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Programmable nano-photonics with electrically controlled phase-change materials

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A dissertation

submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2025

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Electrical and Computer Engineering

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Abstract

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Programmable nano-photonics have the potential to completely transform a range of emerging applications, including optical computing, optical signal processing, light detecting and ranging, and quantum applications. However, implementing energy-efficient and large-scale systems remains elusive because commonly used programmable photonic approaches are volatile and energy-hungry. Recent results on non-volatile phase-change material integrated photonics present a promising opportunity to create truly programmable nano-photonics. The ability to drastically change the refractive index of the PCMs in a non-volatile fashion allows creating programmable units with zero-static energy. By taking advantage of the electrical control, non-volatile reconfiguration, and zero crosstalk between each unit, PCMs can enable both extremely large-scale integrated photonics and metasurfaces.

In this dissertation, we present our main progress in PCM nano-photonics and discuss the challenges and limitations of this emerging technology. We first demonstrated 2×2 electrically programmable units using a well-studied, prototypical PCM $\text{Ge}_2\text{Sb}_2\text{Te}_5$ and scalable doped silicon PIN heaters. These components exhibit low insertion loss (~ 2 dB), high extinction ratio (8 dB), and large endurance ($> 2,800$ cycles), and are critical for large-scale photonic networks and photonic field programmable arrays. We also

designed a three-waveguide directional coupler multiple operation levels by adding a detuning parameter between the center and the other waveguides. To further reduce the loss, we explored an emerging PCM Sb_2S_3 with lower absorption loss and demonstrated phase shifters in both micro-ring resonators and Mach-Zehnder interferometers. An asymmetric directional coupler with two waveguides is also experimentally demonstrated, showing better loss (~ 1 dB) and extinction ratio (~ 15 dB) than the GST one. Interestingly, the device also supported a stepwise multi-level switching behavior, which offered unique opportunity for deterministic tuning, and we showed 32 levels with excellent repeatability. With this multilevel operation, we demonstrate an application of post-fabrication trimming to correct the phase error in a balanced MZI. Beyond the university level, in-house fabrication, which relies on electron beam lithography and has limited scalability, we also cooperated with Intel and showed a scalable process to put PCMs on commercial 300-mm silicon photonic wafers.

Active metasurfaces are another emerging field in nanophotonics. However, current electrically controlled PCM-based metasurfaces are limited to global amplitude modulation, insufficient for SLMs. We demonstrated an individual-pixel addressable, transmissive metasurface using the low-loss PCM Sb_2Se_3 and doped silicon nanowire heaters. The nanowires simultaneously form a diatomic metasurface, supporting a high quality-factor (~ 406) quasi-bound-state-in-the-continuum mode. Global phase-only modulation of $\sim 0.25\pi$ ($\sim 0.2\pi$) in simulation (experiment) is achieved, showing ten times enhancement. 2π phase shift is further obtained using a guided-mode resonance with enhanced light- Sb_2Se_3 interaction. Finally, individual-pixel addressability and SLM functionality are demonstrated through deterministic multilevel switching (ten levels) and tunable far-field beam shaping. Our work presents zero-static power transmissive phase-only SLMs, enabled by electrically controlled low-loss PCMs and individual meta-molecule addressable metasurfaces.

As a perspective, we argue that energy efficiency is a more critical parameter than the operating speed for programmable photonics, making PCMs an ideal candidate. This has the potential for a disruptive paradigm shift in the reconfigurable photonics research philosophy, as slow but energy-efficient and large index modulation can provide a better solution for extremely large-scale integrated photonics than fast but

power-hungry, small index tuning methods. We also highlight the exciting opportunities to leverage wide bandgap PCMs for visible-wavelength applications, such as quantum photonics and optogenetics, and for rewritable photonic integrated circuits using nanosecond pulsed lasers. The latter can dramatically reduce the fabrication cost of PICs and democratize the PIC manufacturing process for rapid prototyping.

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ACKNOWLEDGEMENTS

I would like to extend my heartfelt gratitude to all the committee members for attending my dissertation defense. In particular, I want to express my deepest appreciation to my advisor, Prof. Arka Majumdar, for his unwavering support for my research. Our discussions about new research ideas and perspectives have always been inspiring and intellectually stimulating. He has cultivated a free and encouraging atmosphere for all group members to explore innovative ideas, while also providing exceptional experimental resources and interdisciplinary collaborations to realize and test them. He is particularly inspiring in terms of abstract ideas and philosophy, which has gradually become an important part of my methodology of logic thinking.

I am sincerely thankful to Prof. Mo Li, whose photonics class laid the theoretical foundation for my research. Additionally, I appreciate the assistance of his group members, Dr. Changming Wu and Dr. Bingzhao Li, who have significantly supported my work in nanofabrication and device characterization. I also wish to thank Prof. Sajjad Moazeni for teaching EE 538B: Integrated Photonic Systems, which provided profound insights into state-of-the-art electro-optics integrated systems. The knowledge and skills I gained from this class have become increasingly important as my research focus shifts from device-level to system-level demonstrations. I am also grateful to Prof. David Bergsman for serving as the GSR on my committee and for providing meaningful feedback throughout the process.

I would also like to thank my lab mates and friends from other research groups for their camaraderie, collaboration, and fruitful discussions. Special thanks to Dr. Roger (Zhuoran) Fang, Dr. Jiajiu Zheng, Mr. Virat Tara, Dr. Johannes Fröch, Dr. Jie Fang, Mr. Forrest Miller, Dr. Abhi Saxena, Dr. Quentin Tanguy, Dr. Yueyang Chen, Dr. Changming Wu, Dr. Bingzhao Li, Ms. Jayita Dutta, Mr. Andrew Tang, Dr. Cheng Chang, Dr. Zhendong Wang, Mr. Xi Wang, Mr. Yijie Wang, Mr. Songli Wang, Prof. Keren Bergman, Prof. Alex Gaeta, Prof. Michal Lipson and Prof. Alex (Xiang) Meng for their enormous support in my research and life. In particular, I want to acknowledge Dr. Roger Fang and Dr. Jiajiu Zheng for their countless and invaluable assistance and for their insightful discussions that have greatly enriched my research journey. I want to also express my deepest thanks to Prof. Alex Meng at Columbia University, who have been continuously teaching me both technical knowledge as well as a better view of our life and the world.

I was honored to get an internship opportunity in Meta Platforms, Inc. during the summer of my 4th year and got to work together with several excellent peers and researchers, such as Dr. Zhujun Shi, Dr. Giuseppe Calafiore, Mr. Hanfeng Wang, Mr. Arnab Manna. I truly miss and value the time we spent discussing interesting yet practical ideas. Special thanks to my intern manager Dr. Zhujun Shi, who is extremely inspiring and very informative during my internship.

I am grateful to the University of Washington for providing world-class facilities that made my research possible. A significant portion of my work was conducted at the Molecular Analysis Facility (MAF) and the Washington Nanofabrication Facility (WNF), and I greatly appreciate the resources and expertise the staff has offered, special thanks to Dr. N Shane Patrick, Dr. Darick Baker, and Dr. Mark Brunson for their help.

Finally, I want to express my deepest thanks to my parents and my beloved partner, Ms. Zhaoyi Chen. Their unwavering understanding and support always recharge me and give me the inner strength to overcome seemingly impossible challenges. New journey is ahead of me. Surely they are the ones who are always by my side, and so am I.

Chapter 1. Introduction¹

Nano-photonics is a field that studies light-matter interaction where the structure is of nanometer scales, *i.e.*, typically smaller than the optical wavelengths^{2,3}. Study on such an extreme scale is only made possible in recent decades thanks to the advancements in electromagnetic simulation software⁴, as well as the rapid development of nanofabrication techniques. With nano-photonics technologies, a lot of applications have emerged, including optical imaging^{5–9}, optical communication^{10,11}, optical information processing in both classic^{12–16} and quantum regime^{17–21}, light detection and ranging^{22–25}, hyperspectral imaging^{26–28}, miniaturized spectrometers^{29–32}, just to name a few. At the heart of modern nano-photonics are photonic integrated circuits (PICs)³³ and metasurfaces³. PICs are optical analogy of electronic integrated circuits (EICs), where it is light, instead of electrical current, that is directed on a small chip through various photonic components, such as integrated lasers, waveguides, couplers, phase shifters, amplitude modulators, and on-chip photodetectors. Instead of manipulating light on-chip, metasurfaces are for free-space light wave manipulation, which are made of an array of carefully engineered nanoscale scatterers. One critical aspect of both PICs and metasurfaces is their programmability for their generic usage for optical information processing and optical networking applications. The goal of this dissertation is to provide some advancements in programmability for both PICs and metasurfaces.

PICs are typically application-specific³⁴, *i.e.*, every fabricated chip serves only one particular function. In contrast, recent advancements in silicon photonics urgently call for universally programmable PICs³⁵, adaptable to a wide range of tasks, including optical neural networks³⁶, quantum information processing³⁷, and light detection and ranging³⁸. The fundamental building block constituting such programmable PICs is an electrically controlled 2×2 programmable unit or optical switch, that diverts light to one of two ports. In silicon photonics, the operation of such elements is commonly based on either the thermo-optic³⁹ or free-carrier effect⁴⁰, which are, however, plagued by large footprints (typically $> 100 \mu\text{m}$) and/ or low energy efficiency due to their large static power consumption. Although micro-ring resonators can significantly reduce the footprint (down to the order of tens of μm), the operational optical bandwidth becomes limited

to typically less than 1 nm⁴¹. Moreover, their thermal instability requires an even larger static power consumption, as a constant feedback signal is needed to lock the resonance¹¹. Emerging technologies such as microelectromechanical systems (MEMS)⁴², electro-optic polymer⁴³, and integrated lithium niobate⁴⁴ can potentially provide either a smaller footprint or lower programming energy. Still, they are all based on volatile effects with limited CMOS compatibility. Phase-change materials (PCMs) provide an attractive solution towards compact and energy-efficient programmable units with zero static power^{45–48}, thanks to a non-volatile phase transition⁴⁹, large refractive index contrast ($\Delta n \geq 1$)⁵⁰, and CMOS compatibility⁴⁷. PCMs have two stable states in ambient environments: amorphous (a-PCM) and crystalline (c-PCM). The optical properties of these two states are drastically different. Therefore, by switching between them, the photonic device functionality can be changed. Notably, these two states can be reversibly switched with proper thermal pulses. In general, to change a PCM from the crystalline to the amorphous state, the PCM needs to be heated above its melting temperature T_m and quenched (cooled down with rates higher than $10^9 K \cdot s^{-1}$ ⁵¹). To change from amorphous to crystalline state requires heating the PCM above the glass transition temperature T_g but below T_m . The temperature must be held for a long time (hundreds of ns or longer) to allow crystal nucleation and growth.

We compare different PCMs for three crucial material properties in Figure 1.1, and identify a tradeoff between larger index contrast Δn and increasing loss. For most photonic applications, we need high refractive index contrast Δn but low material absorption (κ_a for amorphous and κ_c for crystalline). Ge₂Sb₂Te₅ (GST), one of the most heavily investigated PCMs, is especially suitable for amplitude modulation in the near-infrared (NIR) or mid-wave infrared (MWIR) wavelengths thanks to the drastic material loss contrast and negligible loss in the amorphous state. On the other hand, emerging transparent PCMs in the NIR, such as Sb₂Se₃ and Sb₂S₃, are excellent candidates for phase-only modulation, because of the drastic index contrast and near zero absorption loss in both phases.

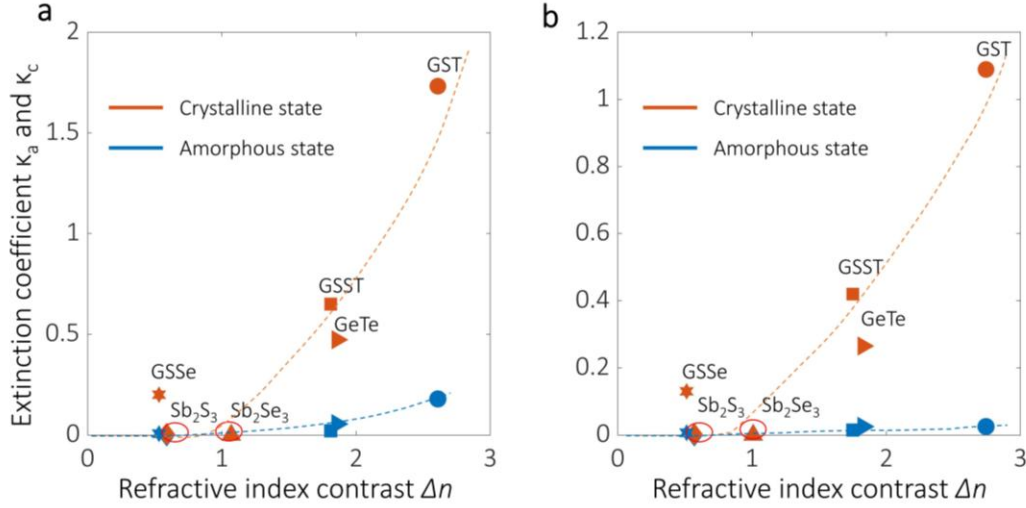


Figure 1.1. **A PCM optical property map.**

Plots for a wavelength of **(a)** 1310nm and **(b)** 1550nm. PCMs with a small extinction coefficient or low loss are circled in red. Different optical PCMs, GST⁵², GSST⁵³, Sb₂S₃⁵⁴, Sb₂Se₃⁵⁵, GeTe⁴⁵ and GSSe⁵⁶ are represented with distinct symbols. The amorphous and crystalline phases are shown in blue and orange, respectively. The dashed trendlines suggest that the PCMs generally exhibit larger absorption losses as the refractive index contrast increases.

To understand how material properties can determine the appropriate application, we define three optical figures of merit (FOM): (1) the refractive index change over the loss in the amorphous state ($FOM_1 = \frac{\Delta n}{\kappa_a}$), (2) the refractive index change over the loss in the crystalline state ($FOM_2 = \frac{\Delta n}{\kappa_c}$) and (3) the loss ratio between the two phases ($FOM_3 = \frac{\kappa_c}{\kappa_a}$). Phase-only modulation ideally requires zero loss. Since crystalline state loss is generally higher than amorphous, FOM_2 is suitable for assessing the worst-case insertion loss and phase tunability of the device. For amplitude modulation applications, FOM_3 can be used to evaluate the tradeoff between extinction ratio and insertion loss. For some devices, *e.g.*, non-volatile beam splitters^{57–59}, it is possible to mitigate the material loss in one of the phases by engineering device geometry. In such cases, FOM_1 should be considered. Table 1 lists three FOM for various PCMs in the visible and telecommunication wavelengths, with red bold highlighting the highest.

Table 1: FOM for different PCMs in 640 nm and 1550 nm

	640 nm						1550nm					
	GST	GSST	Sb ₂ S ₃	Sb ₂ Se ₃	GeTe	GSSe	GST	GSST	Sb ₂ S ₃	Sb ₂ Se ₃	GeTe	GSSe
FOM1	0.10	0.77	∞	1.95	1.26	0.03	109.72	116.73	∞	∞	73.12	78.92
FOM2	0.04	0.24	3.05	0.77	0.47	0.01	2.52	4.17	190.33	∞	6.90	3.95
FOM3	2.47	3.18	∞	2.53	2.67	2.32	43.56	28.00	∞	∞	10.60	20

PCMs have already been widely used in electronics, specifically for memory applications⁶⁰, and was first proposed as optical memories around ten years ago⁶¹. Since then, tremendous efforts have been made in integrating PCMs into nanophotonics^{62,63}, summarized in Figure 1.2. Using fast pulsed lasers (typically fs-lasers⁶⁴), the PCMs can be switched between their crystalline, amorphous or mixed states. Different PCM states then represent distinct bits in optical intensity. Recent works have demonstrated reliable multi-bit operations, large capacity, and reliability^{62,65,66}. Exploiting the reliable multi-bit operation, researchers also used PCMs to realize neuromorphic optical computing^{67–72}, potentially overcoming the von Neumann bottleneck in modern computer architectures. Other than applications in integrated photonics, recent years have also seen significant advancements in using PCMs for active meta-optics^{64,73–81}. Meta-optics can implement arbitrary phase profiles through engineering sub-wavelength scatterers (or meta-atoms). By incorporating PCMs in these meta-atoms, the phase profile can change significantly once the micro-structural phase is switched. Such active tuning capability can enable many demanding applications, *e.g.*, varifocal lens^{78,82–85}, beam steering^{86,87}, spatial light modulator^{22,88,89}, and tunable holography^{90,91}.

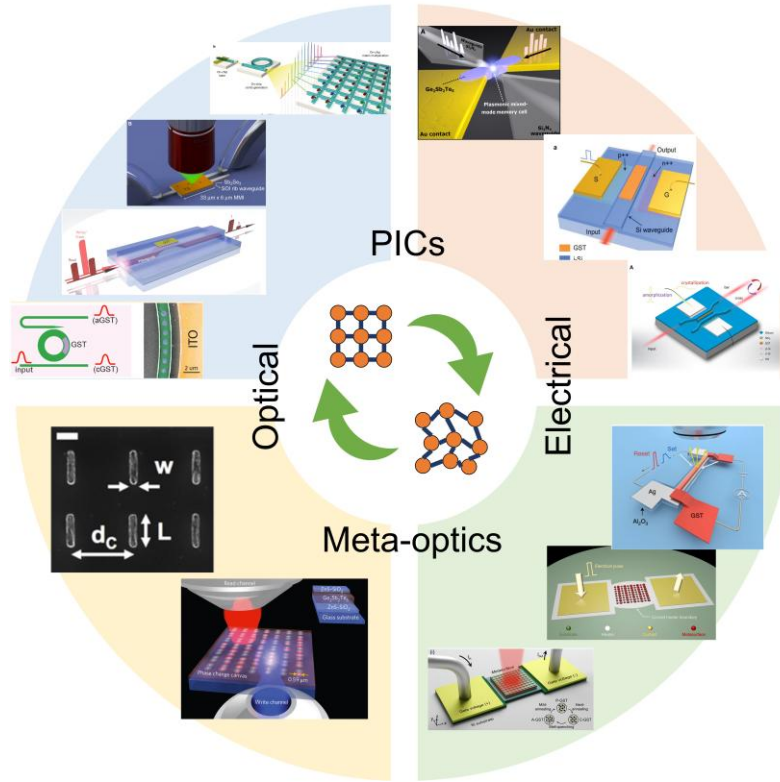


Figure 1.2: **PCM-based reconfigurable integrated photonics (top)^{59,62,92–95} and meta-optics (bottom)^{64,73–76} with optical (left) or electrical (right) controls.**

The device functionality depends on the material phase of the PCM. In optically controlled devices, laser pulses are absorbed to heat the PCM and trigger a phase transition. Complex optical alignment is generally required, limiting this approach to only small-scale applications. A more scalable approach is via electrical control. Short electrical pulses are sent to on-chip heaters to generate heat and subsequently actuate the phase transition. (Reprint from Ref [59, 62, 92-95, 64, 73-76] with permission)

While remarkable progress has been made in optically induced switching of PCMs, the electrical tuning for photonic devices is still in its early stage (the first work was reported only five years back⁹⁶), despite the promised scalability of electrical control. Early works reported limited cyclability (around ten cycles)⁹⁶ and low optical contrast ($< 1\text{dB}$)⁹⁴. Recently, high endurance (over half a million cycles⁹⁷) and large contrast switching ($> 10\text{ dB}$ contrast) have been achieved using external heaters^{55,95,97,98} with high-quality encapsulation.

Yet, broadband electrically controlled 2×2 programmable unit based on GST was still missing at the beginning of my study. While such functionality is ultimately indispensable for large-scale reprogrammable photonic applications, the inherent high absorptive loss of crystalline GST (c-GST)⁹⁹ becomes a severe issue for most designs. Existing electrically tunable GST devices are either designed only for 1×1 switches^{100,101} or rely on ring resonators^{101,102} to circumvent the loss issue. The former is clearly not suitable for encoding information in different optical paths, or spatial information encoding. Thus, it has limited applications in programmable photonics for applications such as optical switch fabric and information processing^{35,36,39,103}. While the latter is suitable for spatial information encoding in a narrow band, a broadband design is preferred to access a wider optical wavelength range.

One direction to achieve the broadband operation is further engineering and optimization of the device geometry. In particular, a three-waveguide directional coupler switch structure was proposed in previous works^{45,57}, which can mitigate the loss in the crystalline GST. However, there was no reversible switching demonstration of such devices, and the demonstrations were limited to either simulations or rapid thermal annealing for crystallization.

The other approach, which provides a more generic solution to the loss problem, is to explore new wide-bandgap phase change materials with lower loss. In that direction, emerging wide-bandgap PCMs, such as GeSbSeTe (GSST)⁵³, antimony selenide (Sb_2Se_3)¹⁰⁴, and antimony sulfide (Sb_2S_3)¹⁰⁵ have recently generated strong interest in the community^{78,106–109}. In particular, Sb_2S_3 shows the widest bandgap among all these PCMs, allowing transparency down to ~ 600 nm in the amorphous phase¹⁰⁵. Moreover, the lack of selenium in Sb_2S_3 makes it less toxic¹¹⁰ and less prone to causing chamber contamination during sputtering or evaporation processes. Thus, Sb_2S_3 is much more amenable to be adapted in a commercial foundry. Despite these promises, high-endurance electrical control of Sb_2S_3 remained unsolved. In Chapter 2 and Chapter 3, we show electrical control of both prototypical PCM GST and emerging low-loss PCM Sb_2S_3 with high endurance ($\sim 1,000$ cycles), low loss (< 1.0 dB), high extinction ratio (> 10 dB) and broadband operation (> 35 nm). The unique material property of Sb_2S_3 further enables a multi-bit operation (up to 5 bits or 32 levels), which is of paramount importance to optical computing applications.

Another challenge in PCM-based programmable PICs is the CMOS compatibility of Chalcogenide PCMs and the system's scalability. Currently, the electrically controlled PCM-based PICs are still either in a single-device level^{59,106,107,111–114}, or a very small system scale¹¹⁵. This can primarily be attributed to the low yield of the in-house fabrication due to the more sophisticated fabrication steps compared to optical actuation schemes, such as multi-stage overlay lithography, doping, annealing, and growth of metal vias. This incurs a significantly prolonged designing and testing cycle. Moreover, inconsistencies in the in-house fabrication process causes difficulty in building a very large-scale PCM-based PIC system. While commercial foundries provide much more reliable silicon photonic components, PCMs are not directly available there yet. In Chapter 4, we present the effort on scaling up the PCM-based PICs, where we developed a simple fabrication process to integrate the PCMs onto Intel large-volume silicon photonic platforms.

On the metasurface side, free-space modulation of light is widely exploited in optical communications, holography, light detection and ranging, and virtual or augmented reality. Traditional spatial light modulators (SLMs) based on liquid crystals (LCs) and micro-electro-mechanical systems (MEMS) are slow, bulky, require large driving voltage, suffer from phase jitters, and only operate in a volatile manner. To address these limitations, recently there has been a lot of effort to realize free-space light control based on metasurfaces integrated with active materials^{116–122}. The metasurfaces support resonances that allow reduction of the optical path length to attain certain phase or amplitude modulation. For example, high-Q metasurfaces based on EO polymers have achieved GHz modulation speed¹¹⁹; LCs combined with Huygen's metasurface can significantly reduce the pixel size and LC thickness required to attain a certain phase shift¹¹⁶; metasurfaces based on plasmonic nano-resonators coupled to epsilon-near-zero materials has achieved full 2π modulation with independent control of amplitude and phase¹¹⁷; large phase-modulation of 237° can be achieved by tuning a plasmonic metasurface using graphene¹²³. Nevertheless, these approaches are all based on volatile changes such as Pockels or carrier depletion/accumulation effects, necessitating a constant power supply at static state. LC-based phase-only SLMs also suffer from temporal phase fluctuations due to constant refreshing^{124,125}. In contrast, nonvolatile control of free-space light can

significantly improve energy efficiency and avoid phase flickering, since it holds steady once reconfigured, leading to a true ‘set-and-forget’ modulation. Particularly, chalcogenide-based phase change materials PCMs can afford a feasible solution¹²⁶, thanks to the nonvolatile microstructural phase transition⁴⁹, large contrast in complex refractive index (typically $\Delta n \geq 1$)⁵⁰, and CMOS compatibility⁴⁷. In fact, PCMs have recently attracted considerable attention to create tunable metasurfaces for applications such as lensing^{122,127}, beam steering^{128,129}, intensity switching^{120,121,130,131}, and spectral filtering¹³².

Despite the progress, nonvolatile phase-only modulation - a highly desirable feature for SLMs – remains elusive. This is because previous works on nonvolatile tunable metasurfaces have used lossy PCMs such as GST^{120,131} or GSST¹²¹ which concomitantly induces large absorption upon phase transition, prohibiting phase-only modulation. The use of metallic heaters further leads to ohmic losses and makes transmissive operation impossible. Although nonvolatile phase-only control has been demonstrated in mid infrared where GST becomes transparent¹³³, laser is used to switch the PCMs which is unscalable⁴⁷ and impractical for SLMs that are normally electrically controlled. In Chapter 5, beyond on-chip light manipulation, we further demonstrate control of free space light using a high-Q BIC resonance and low-loss PCM Sb_2Se_3 . Importantly, this was the first attempt to control individual PCM meta-molecules to realize spatial light modulation.

Finally, we end our dissertation with discussions about the challenges and perspectives about PCM-based programmable PICs in Chapter 6.

Chapter 2. Broadband electrically controlled silicon photonic switches based on GST^{59,134}

Programmable PICs have recently gained significant interest due to their potential in creating next-generation technologies ranging from artificial neural networks and microwave photonics to quantum information processing. The fundamental building block of such programmable PICs is a 2×2 programmable unit, traditionally controlled by the thermo-optic or free-carrier dispersion. Yet, these implementations are power-hungry, volatile, and have a large footprint (typically $> 100 \mu\text{m}$). Therefore, a truly 'set-and-forget' type 2×2 programmable unit with zero static power consumption is highly desirable for large-scale PICs. Here, we report a broadband non-volatile electrically controlled 2×2 programmable unit in silicon photonics based on the PCM GST. The directional-coupler-type programmable unit exhibits a compact coupling length ($64 \mu\text{m}$), small insertion loss ($\sim 2 \text{ dB}$), and minimal crosstalk ($< -8 \text{ dB}$) across the entire telecommunication C-band while maintaining a record-high endurance of over 2,800 switching cycles without significant performance degradation. This non-volatile programmable unit constitutes a critical component for realizing future generic programmable silicon photonic systems.

2.1 Optical refractive index characteristics of GST

GST has a large loss in the crystalline state at 1550 nm in

Figure 2.1, which is measured by ellipsometry (Woollam E-2000) and fitted with Tauc-Lorentz models.

Note that the extinction coefficient κ is proportional to the optical loss $\alpha(\text{dB}/m)$, given by

$$\alpha = 10 \lg(e) \cdot \frac{4\pi\kappa}{\lambda} \quad (2.1)$$

We simulate the fundamental TE mode of a hybrid GST silicon rib waveguide (HW) using Lumerical MODE. The results are shown in Figure 2.3(d), where a high absorption loss of $5.5 \text{ dB}/\mu\text{m}$ when the GST is in the crystalline state is estimated. Directly using GST in photonic switches will introduce huge insertion loss. For example, if GST is used in a Mach-Zehnder interferometer, then to achieve a π -phase shift, a

length of $L = \frac{\lambda_0}{2\Delta n} = 4.2\mu m$ would be required. This will then give a very high loss of 23.1 dB compared to <1 dB loss using the three waveguide structures in the following sections.

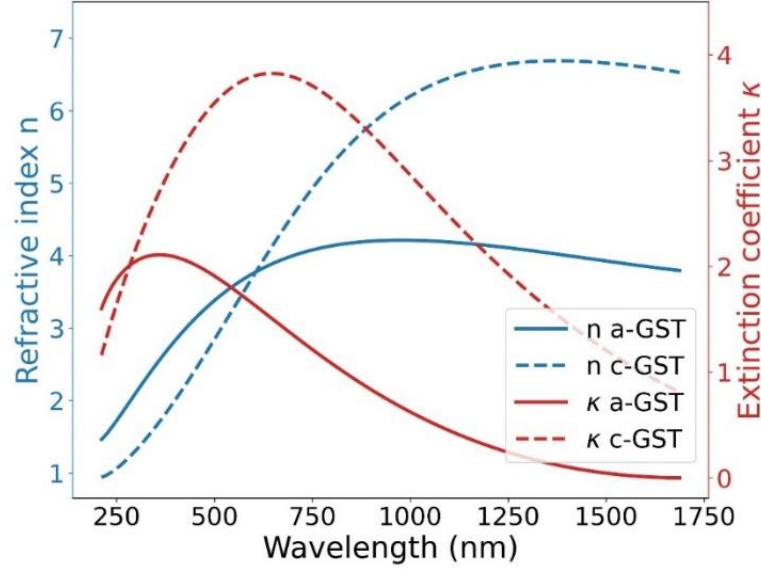


Figure 2.1: The complex refractive index of a/c-GST measured by ellipsometry.

2.2 Design of programmable 1×2 photonic programmable units using GST

We design the 1×2 programmable unit so that the light can only be coupled from the input bare silicon waveguide (SW) to the hybrid (HW) when the GST is in its amorphous state, where only a slight loss is introduced, as shown in Figure 2.2.

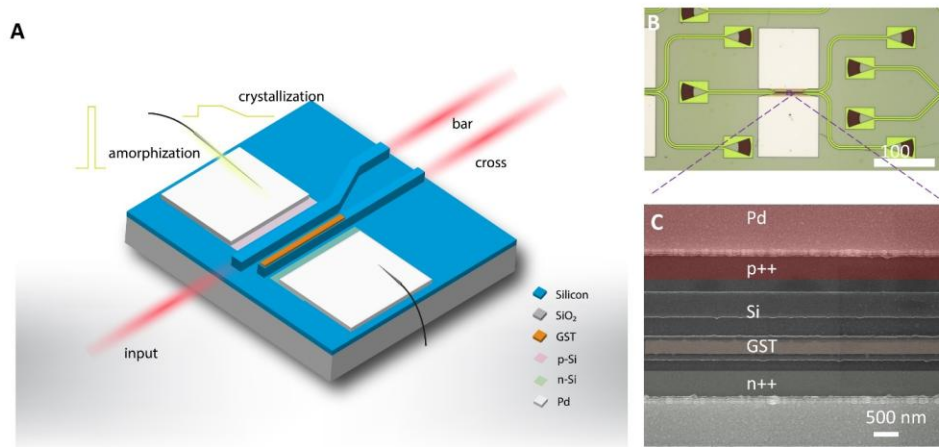


Figure 2.2: **Broadband nonvolatile electrically controlled 1×2 programmable unit schematic and images.**

(a) device schematic (b) The microscope and (c) SEM images of the device. In the SEM image, the GST thin film, p++, and n++ regions are indicated by orange, blue, and green fake colors.

The design procedure of the programmable units is similar to Ref ⁴⁵ as follows. The HW width was optimized so that when GST is in an amorphous state, the HW and SW can couple to each other most strongly, which happens when the two share the same effective index. As shown in Figure 2.3(a), a 408 nm a-GST HW has the same effective index with a 450 nm SW. Due to the significant refractive index change when the GST is switched into a crystalline state, a large phase mismatch would be induced. Thus, the coupling would be weakened.

Then the supermodes of the HW and SW with a gap g are simulated and optimized. The coupling length L_c and the loss when GST is in the amorphous/crystalline state are determined when sweeping g , where the coupling length is determined with coupled mode theory¹³⁵, using the following formula:

$$L_c^a = \frac{\lambda_0}{2(n_{even} - n_{odd})} \quad (2.2)$$

Where λ_0 is the free-space wavelength, n_{even} and n_{odd} are effective index for even and odd mode and L_c^a is the coupling length with a-GST. We note that the loss is determined by decomposing the input field into the supermodes and calculating the loss separately, as below:

$$T^{a,c} = \sum_j T_j^{a,c} = \sum_j \left(A_j^{a,c} \exp \left(\frac{i2\pi\kappa_j^{a,c}}{\lambda} L_c^a \right) \right)^2 \quad (2.3)$$

$$loss^{a,c} = 10 \log T^{a,c} \quad (2.4)$$

Where $T^{a,c}$ is the transmission and the superscript indicates the same formula applies to both amorphous and crystalline GST, $T_j^{a,c}$ is the transmission of the j^{th} supermode, $A_j^{a,c}$ is the expansion coefficient of the input field into the j^{th} supermode field, $\kappa_j^{a,c}$ is the imaginary part of the effective index of the j^{th} supermode. The crosstalk of the device can be calculated with similar formula as well. This formula was implemented in the Lumerical MODE solver. The result is shown in Figure 2.3(c). As g increases, the

coupling length increases, the loss in c-state decreases because of a weaker mode interaction. However, since the amorphous state GST still has a finite amount of loss, a longer coupling length leads to a larger insertion loss. We selected g of 450nm to get an insertion loss smaller than 0.5 dB and a compact device footprint of $L_c = 42 \mu\text{m}$. The supermode simulation results are shown in Figure 2.3(e). With a-GST, the supermode extends in both waveguides, indicating a strong coupling. While with c-GST, the supermodes are highly localized in each of the waveguides, indicating weak coupling. Thus, the light bypasses the high absorption loss of c-GST.

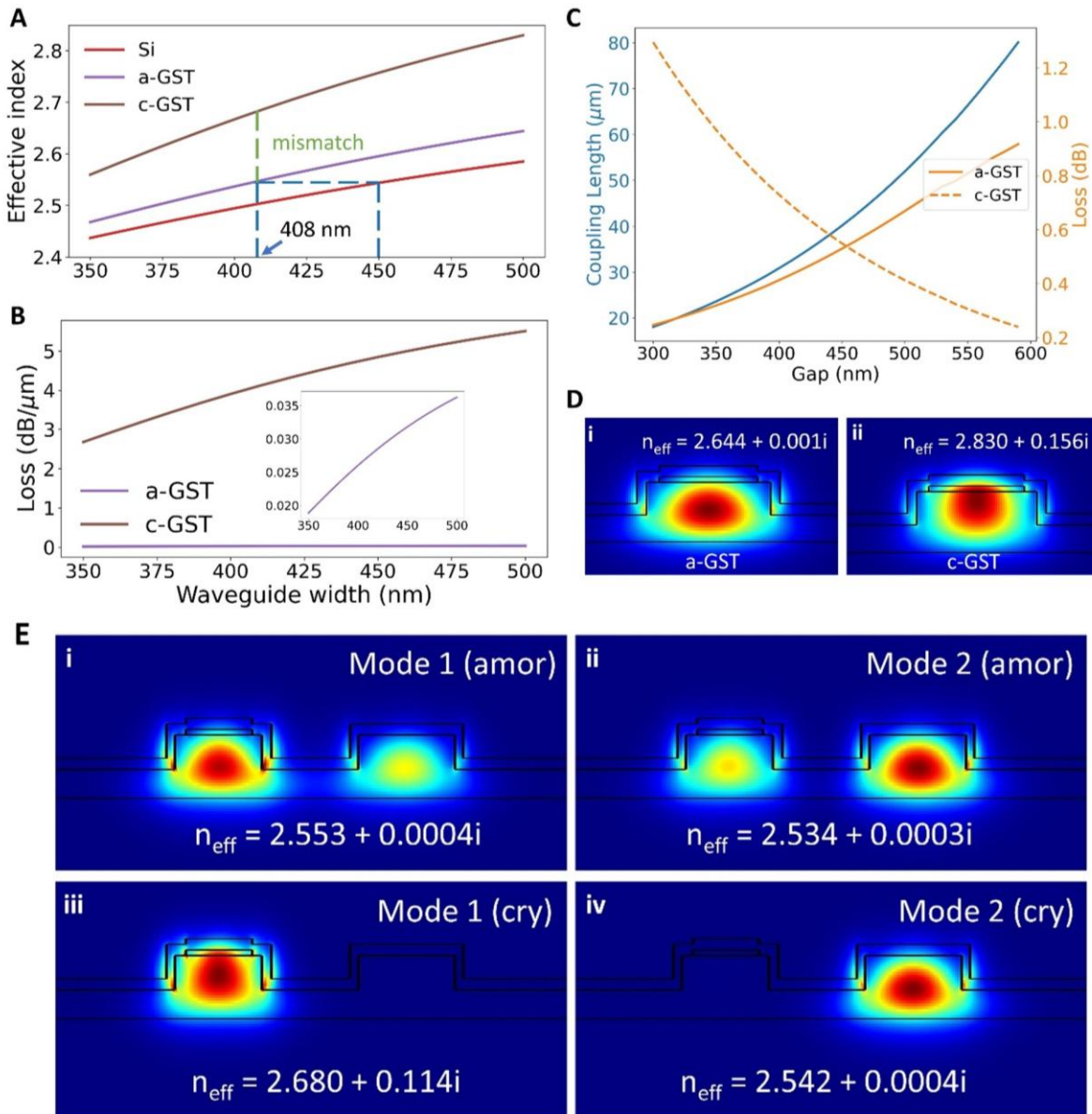


Figure 2.3: **Mode simulation results for the 1×2 programmable unit.**

(a) Effective indices of a bare silicon waveguide, a-GST HW, and c-GST HW changing with the waveguide width. (b) Effective loss of a/c-GST HW, the inset shows the zoomed-in loss of a-GST HW. (c) Mode simulation result of 1×2 programmable unit coupling length and insertion loss with a/c-GST changing with gap. (d) Mode simulation results for (i)a-GST and (ii)c-GST HW. (e) Mode simulation results for 1×2 programmable unit supermodes. (i)(ii) First and second order mode when GST is in amorphous state. (iii)(iv) First and second order mode when GST is in crystalline state.

2.3 Design of the 2×2 programmable photonic units based on GST

The first three TE supermodes are considered for the 2×2 programmable unit design. To achieve the best coupling between the three waveguides, a phase-matching condition needs to be satisfied:

$$2n_2 = n_1 + n_3 \quad (2.5)$$

By fixing the width of SWs to 450 nm and sweeping the width of the middle waveguide, an optimal HW width of 409 nm is determined, as shown in Figure 2.4(a). The minor difference from the previously determined HW width for 1×2 programmable unit can be attributed to numerical error.

The coupling length and the insertion loss are calculated with different gap g , as shown in Figure 2.4(b). An optimal gap of 450 nm is selected for a short coupling length, as well as a small insertion loss of 0.33/0.65dB for a/c-GST, respectively. The coupling length of a three waveguide coupler is calculated by the following formula when the phase-matching condition is satisfied:

$$L_c^a = \frac{\lambda}{2(n_1 - n_2)} \quad (2.6)$$

Finally, we show the optical modes in Figure 2.4(c). One can see a strong coupling between the HW and SW when GST is in amorphous state, as in Figure 2.4(c-i, c-iii). However, when the GST is switched into a crystalline state, the modes are localized in SW or HW, as in Figure 2.4(c-iv, c-v, c-vi), indicating a very weak coupling. Although the effective index of mode 1 (cry) has a large imaginary part, since light can't get coupled into mode 1 if excited from SW, this high loss mode is bypassed.

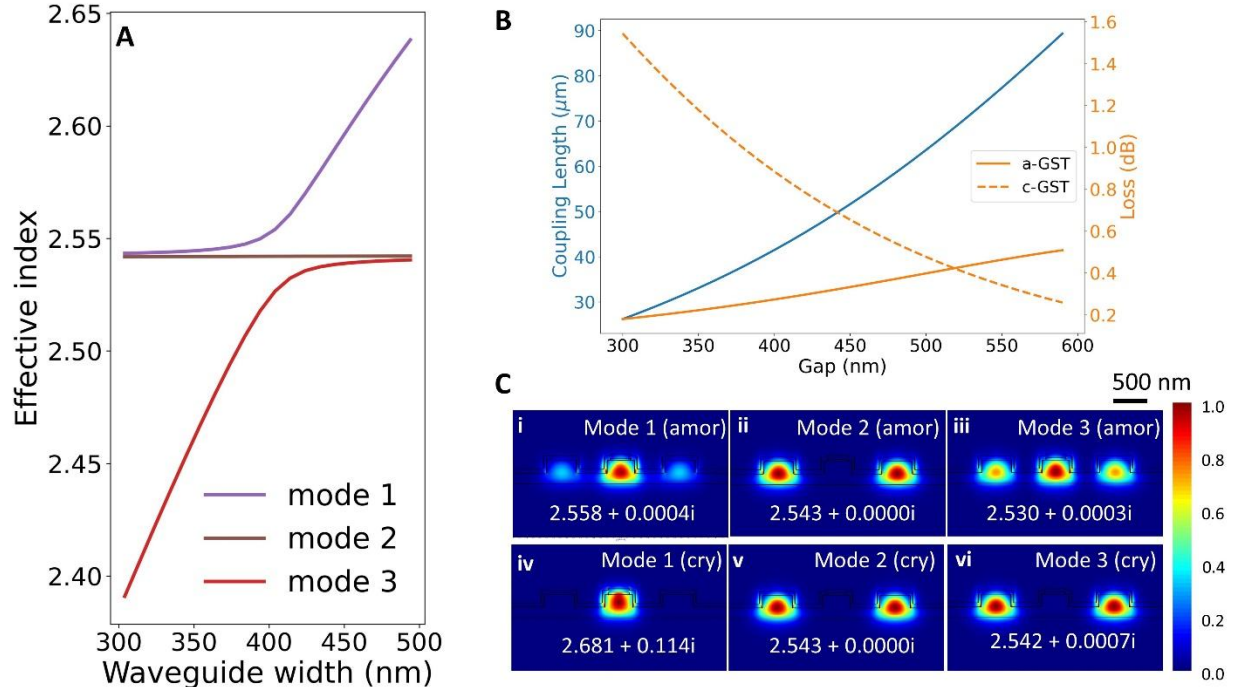


Figure 2.4: **Mode simulation results for the 2×2 programmable units.**

(a) supermode effective indices changing with HW width. (b) coupling length and loss with a/c-GST changing with the gap. (c) Mode simulation results. (i)(ii)(iii) First, second, and third-order modes when GST is in the amorphous state, (iv)(v)(vi) First, second, and third-order modes when GST is in the crystalline state.

The designs of the 1×2 and 2×2 programmable units are verified with Lumerical FDTD as in Figure 2.5. A larger insertion loss of around 1.0 dB compared to the 0.5 dB loss in the MODE solver can be attributed to extra loss introduced by the S-bends and can be further reduced by a better S-bend design.

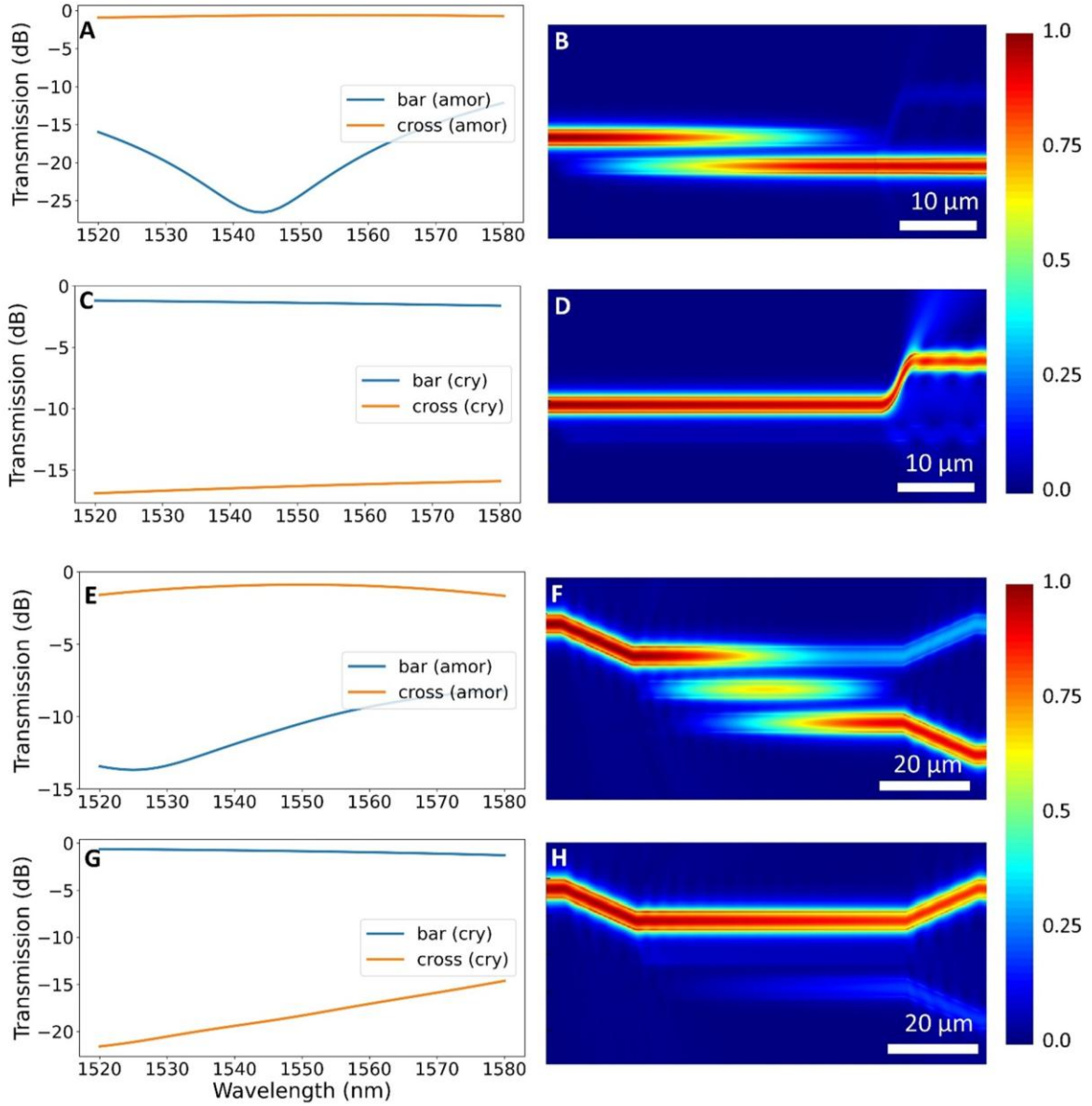


Figure 2.5: FDTD simulation results for both 1×2 and 2×2 programmable units.

(a, b) Transmission spectrum and field distribution of a-GST 1×2 programmable unit, (c, d) Transmission spectrum and field distribution of c-GST 1×2 programmable unit, (e, f) a-GST 2×2 programmable unit, (g, h) c-GST 2×2 programmable unit.

2.4 Fabrication variation tolerance analysis

In this section, we simulate how the insertion loss and extinction ratio in both amorphous and crystalline state changes with respect to various device parameters, such as the waveguide width, the GST width, the GST misalignment, the etch depth and the gap. The results are summarized in Figure 2.6 and Figure 2.7. The fabrication variation in waveguide width, etching depth and GST thickness can lead to significant higher insertion loss and lower extinction ratio.

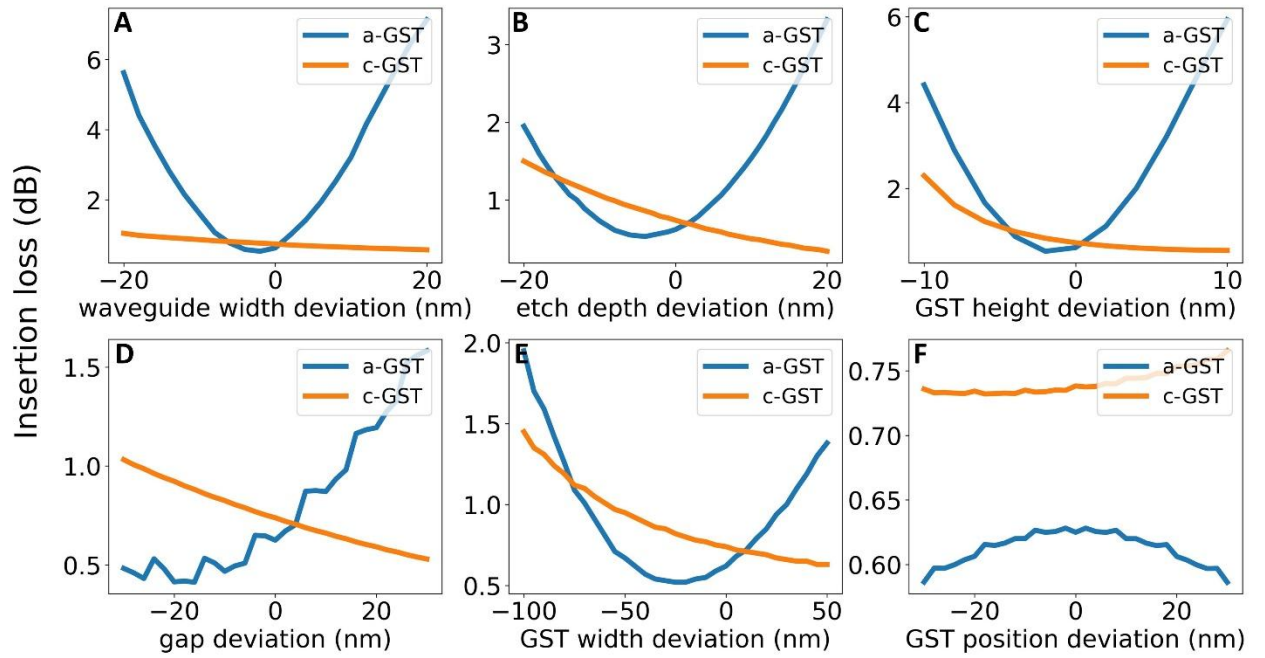


Figure 2.6: **Insertion loss vs. fabrication variation study on the 2×2 programmable unit.**

(a) Waveguide width deviation (b) etch depth deviation (c) GST height deviation (d) gap deviation (e) GST width deviation (f) GST position deviation from the nominal values.

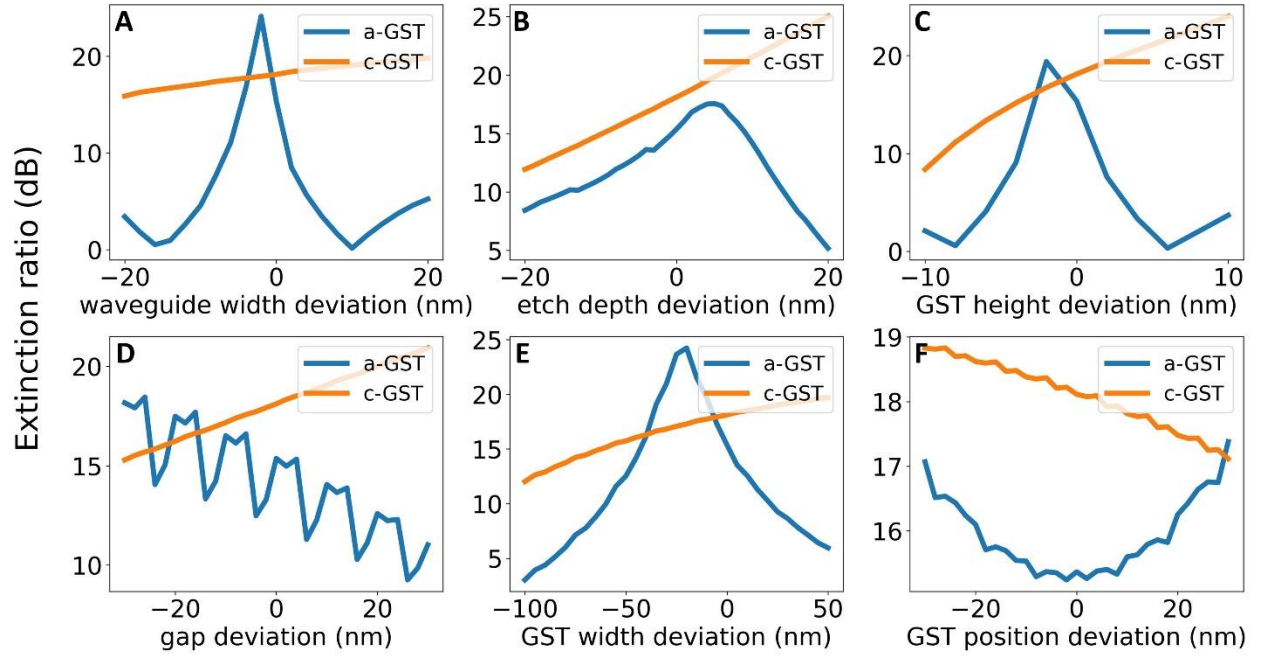


Figure 2.7: **Extinction ratio vs. fabrication variation study on the 2×2 programmable unit.**

(a) Waveguide width deviation; (b) etch depth deviation; (c) GST height deviation; (d) gap deviation; (e) GST width deviation; (f) GST position deviation from the nominal values.

2.5 Heat transfer simulation

The time-dependent heat transfer performance was studied with a cross-coupled electro-thermal model in COMSOL Multiphysics, which includes the semiconductor model for PIN electrical simulation as well as heat transfer in solid model for heating simulation. The detailed description of the model can be found in^{101,136}. For amorphization, a short sharp pulse with high peak voltage is favorable for the melting and quenching process, where the temperature of GST increases above its melting point ($T_m \sim 616^\circ\text{C}$) and decreases rapidly below the glass transition temperature ($T_g \sim 155^\circ\text{C}$) to form the amorphous phase. The amorphous GST can be crystallized through nucleation and growth process, by heating it above the T_g but below T_m , and gradually cooling it down. The amorphization condition was identified as pulse duration of 100 ns, and peak amplitude of 6.8(8.4) V for the 1×2 (2×2) programmable units. To crystallize the GST, a pulse with a duration of 50 μs and peak amplitude of 2.4 (2.8) V. The larger peak amplitude required for

the 2×2 programmable unit is due to the wider intrinsic region, thus a larger resistance and heating volume.

Figure 2.8(a) and (d) show the time dependent temperature result when the amorphization or crystallization pulses are applied. The experimental pulses have higher voltages because of nonideal contact and load impedance mismatch.

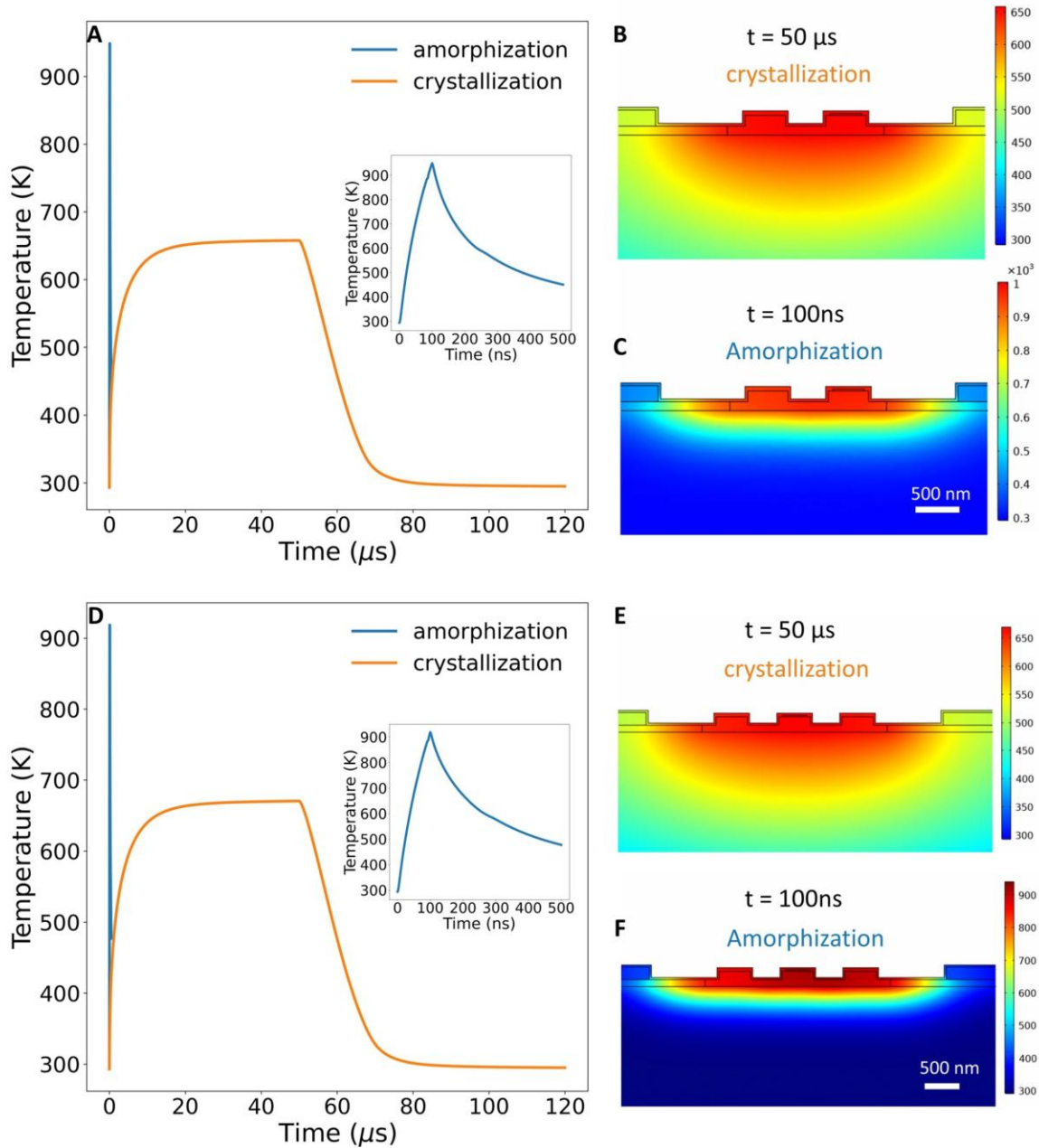


Figure 2.8: Transient heat transfer simulation results.

(a, d) The time-dependent temperature of the GST. The blue and orange lines are amorphization and crystallization pulses, respectively. The insets show zoom-in figures of the amorphization pulse. **(b, e)** Temperature distribution at 50 μ s for crystallization. **(c, f)** Temperature distribution at 100 ns for amorphization. **(a-c)** 1×2 unit; **(d-f)** 2×2 unit.

2.6 Device fabrication

Here we describe the fabrication of our electrically controlled programmable units using GST. The 2×2 programmable unit leverages an asymmetrical three-waveguide directional coupler structure^{45,137,138} fabricated in a Silicon on Insulator (SOI) platform combined with an on-chip P-I-N (p++-doped-intrinsic-n++-doped) heater, as shown in Figure 2.9(a). Compared to previous works, where rapid thermal annealing^{45,139} was used to change the PCM phase, our devices can be reliably and reversibly switched with short electrical pulses via on-chip PIN micro-heaters for more than 2,800 cycles. The design consists of two Si transmission waveguides with a coupling region separated by a truncated transition waveguide. To circumvent the high absorption loss of c-GST, only the transition waveguide is loaded with a 20 nm-thick GST, encapsulated by 40 nm Al_2O_3 to prevent GST oxidation. By design, the phase-matching condition is satisfied only when the GST is switched to the amorphous state (a-GST), which allows light to couple into the transition waveguide and further to the cross port. However, if the GST is in the crystalline state, light barely couples into the transition waveguide due to a significant index mismatch, thus bypassing the high loss of c-GST. The gap between the waveguides is designed to achieve a good tradeoff between insertion loss and device footprint. Our simulations show an insertion loss of less than 1 dB, an extinction ratio of larger than 13 dB at 1520 nm and a 1 dB bandwidth larger than 50 nm. While similar designs have been reported before^{45,137}, it is noteworthy that electrical tunability was not demonstrated in such programmable unit designs, primarily due to the lack of suitable heater designs for large-volume GST switching. A PIN heating element implements the electrical control over the phase switching, which is realized by selectively doping the adjacent regions to the waveguide. We note that this concept directly extends our prior works, where we implemented this concept¹⁰¹ for a 1×1 switch. However, in contrast to the previous 1×1

programmable unit work, this work demonstrates a 2×2 programmable unit which can be used in a lot more applications thanks to its suitability for spatial information encoding. Moreover, the volume of the GST being electrically switched experimentally is $\sim 0.4 \mu\text{m}^3$ in the present work, around ten times larger^{98,100,101,140}. Therefore, prior to fabrication, we optimized the design and operation of the PIN microheater and device transmission using finite element simulations^{101,136}, considering the device's electrical and heat transfer transient performance. We also stress that, compared with resistor-type heaters such as metal, P-I-P, or N-I-N heaters, PIN heaters are more energy efficient. This can be intuitively understood by recognizing the electric current in the PIN diode increases exponentially with voltage, while that of resistor-type heaters only grows linearly.

Our electrically controlled 2×2 programmable unit were fabricated on a commercial SOI Wafer with 220nm-thick Silicon on 3 μm -thick SiO₂ (SOITECH). The rib waveguides and grating couplers were defined with electron-beam lithography (EBL, JEOL JBX-6300FS) using a positive tone E-beam resist (200-nm-thick ZEP-520A) and partially etched by 120 nm in a fluorine-based inductively coupled plasma etcher (ICP, Oxford PlasmaLab 100 ICP-18) using a mixed gas of SF₆ and C₄F₈. The etching rate was calibrated each time before the etching to ensure a correct etch depth. The doping regions were defined by two additional EBL steps with 600-nm-thick poly (methyl methacrylate) (PMMA) resist and implanted by boron (phosphorus) ions for p⁺⁺(n⁺⁺) with a dosage of 2×10^{15} ions per cm² and ion energy of 14 keV (40 keV). A tilt angle of 7° while conducting ion implantation was used to misalign with the silicon lattice and thus achieve uniform deep doping. To activate the dopants, the chips were annealed at 950 °C for 10 min (Expertech CRT200 Anneal Furnace). Before the metal contact deposition, to ensure ideal Ohmic contact, the surface native oxide was removed by immersing the chips in 10:1 buffered oxide etchant (BOE) for 10 seconds. The metal contacts were then immediately patterned by a fourth EBL step using PMMA and formed by electron-beam evaporation (CHA SEC-600) and lift-off of Ti/Pd (5 nm/180 nm) layers. After a fifth EBL defining the GST window, a 20-nm GST thin film was deposited using a GST target (AJA International) in a magnetron sputtering system (Lesker Lab 18), followed by a lift-off process. The deposition rate was calibrated on a silicon chip using Ellipsometer (Woollam alpha-SE). The GST is then

encapsulated by 40-nm-thick Al_2O_3 through ALD (Oxford Plasmalab 80PLUS OpAL ALD) at 150 °C. To ensure good contact between the electric probe and metal pads while measuring, the Al_2O_3 on the metal contacts were removed by defining a window using a sixth EBL with 600nm PMMA, then etching in a chlorine-based inductively coupled plasma etcher (ICP-RIE, Oxford PlasmaLab 100 ICP-18). Finally, rapid thermal annealing (RTA) at 200 °C for 10 min was conducted to completely crystallize the GST.

The fabricated device's optical and scanning electron microscope (SEM) images are shown in Figure 2.9(b) and (c), respectively. In detail, the PCM phase is switched by an on-chip P-I-N heater, defined by doping the 100-nm-thick silicon slab via ion implantation while leaving the three waveguides intrinsic¹⁰¹ to reduce the insertion loss. The doped regions and metal pads are designed to maintain a distance of 200 nm and 1 μm , respectively, from the directional coupler to reduce excess loss from the free carriers.

We also fabricated 10- μm -long GST on silicon waveguide switches, as shown in Figure 2.11(a) and (b).

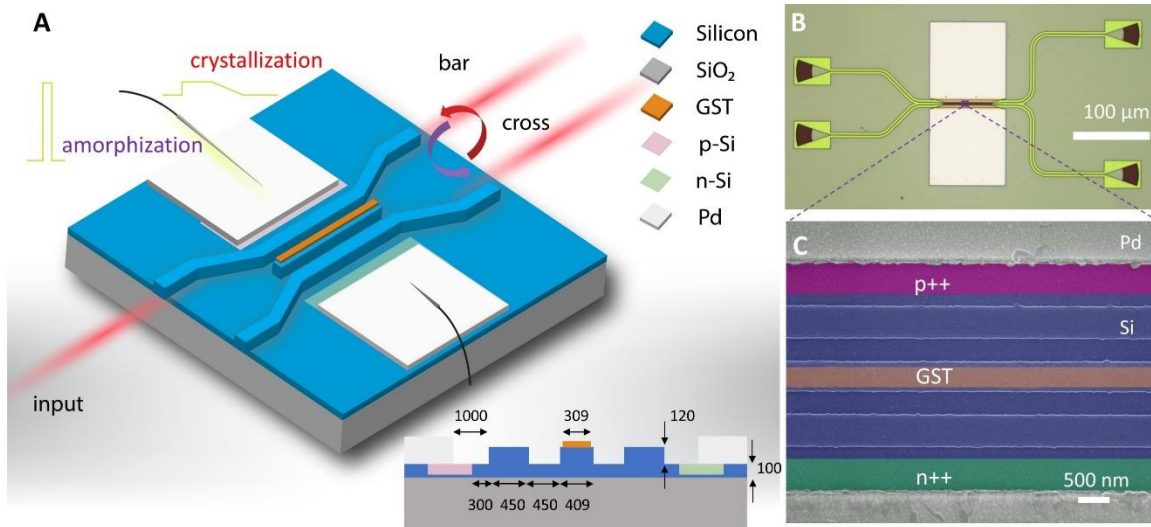


Figure 2.9: **Broadband non-volatile electrically controlled 2×2 programmable unit in silicon photonics.**

(a) Device schematics. Inset: the cross-sectional view at the center of the device. The 40 nm encapsulation Al_2O_3 is not shown. (b) The optical micrograph and (c) SEM images of the device. In the SEM image, the GST thin film, p++, and n++ regions are indicated by false colors.

2.7 Device characterization

2.7.1 Characterization setups

The fabricated devices were characterized in a customized vertical fiber coupling setup. The programmable units were measured with a vertical fiber-coupling setup using a coupling angle of 25° , shown in Figure 2.10(a). The stage temperature was fixed at 26°C controlled by a thermoelectric controller (TEC, TE Technology TC-720). A tunable continuous-wave laser (Santec TSL-510) provided the input light. The polarization was controlled by a manual fiber polarization controller (Thorlabs FPC526) to match the TE mode of the rib waveguides. A low-noise power meter (Keysight 81634B) was used to measure the static optical transmission from the output grating couplers. The transmission spectra of the devices were obtained by normalizing to the closest reference waveguide spectra. For the I–V characterization and on-chip electrical switching, electrical pulses were applied to the on-chip metal contacts via a pair of electrical probes controlled by two probe positioners (Cascade Microtech DPP105-M-AI-S). In particular, the I-V curve measurement was performed using a source meter (Keithley 2450), which is later used to estimate the power of the applied pulses. The crystallization and amorphization pulses were generated from a pulse function arbitrary generator (Keysight 81160A). The tunable laser, power meter, thermal controller, source meter, and pulse function arbitrary generator are controlled by a laptop with a National Instrument interface.

The transient response of the programmable units was measured under the same vertical fiber coupling setup but with a faster light detection instrument as shown in Figure 2.10(b). Instead of the power meter, we used a switchable gain balanced amp photodetector (Thorlabs, PDB450C) with 150MHz bandwidth to obtain the fast time response. An optical amplifier (Amonics AEDFA-30-B-FA) was used to amplify the optical signal to $\sim 1\text{ mW}$ before the photodetector so that the photodetector is operating in its linear range. The photodetector response was captured by an oscilloscope, triggered by the applied electrical signal.

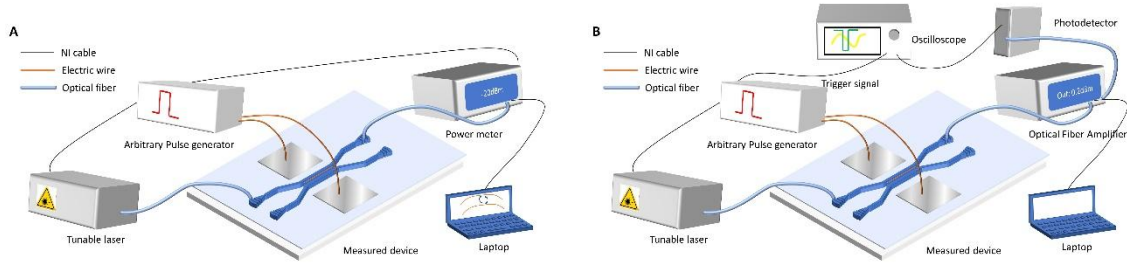


Figure 2.10: **Measurement setup schematics.**

Setup for **(a)** optical transmission measurement setup; **(b)** transient response measurement.

2.7.2 Results for 1×1 waveguide switch

By switching the GST between amorphous/crystalline (low-loss/high-loss) states, the optical switch is controlled on/off, with an extinction ratio larger than 15 dB. We show that this device can be switched to ten distinct transmission levels. This was accomplished by first complete crystallizing (2.2 V peak voltage, 30 μ s duration and 10 μ s falling edge) the GST and then applying gradually increased voltage (peak volage starts from 6.5V, with an increment step of 0.1V, and 10 total steps, 200 ns pulse duration and 8 ns falling edge) for partial amorphization, as in Figure 2.11(c). We repeated the multilevel switching test three times at a wavelength of 1550 nm, and each time a multilevel performance can be observed, shown in Figure 2.11(e). We further demonstrate more than 2000 switching events via sending in amorphization (2.2V) and crystallization (7.4V) pulses alternately, and the results are shown in Figure 2.11(d). The waveguide switch exhibits a large extinction ratio between the ON and OFF state after more than 2000 switching events, showing excellent endurance. We note that the transmission level becomes stable after around 600 switching events due to the larger crystalline domain forming from the initial ‘conditioning’ steps⁶².

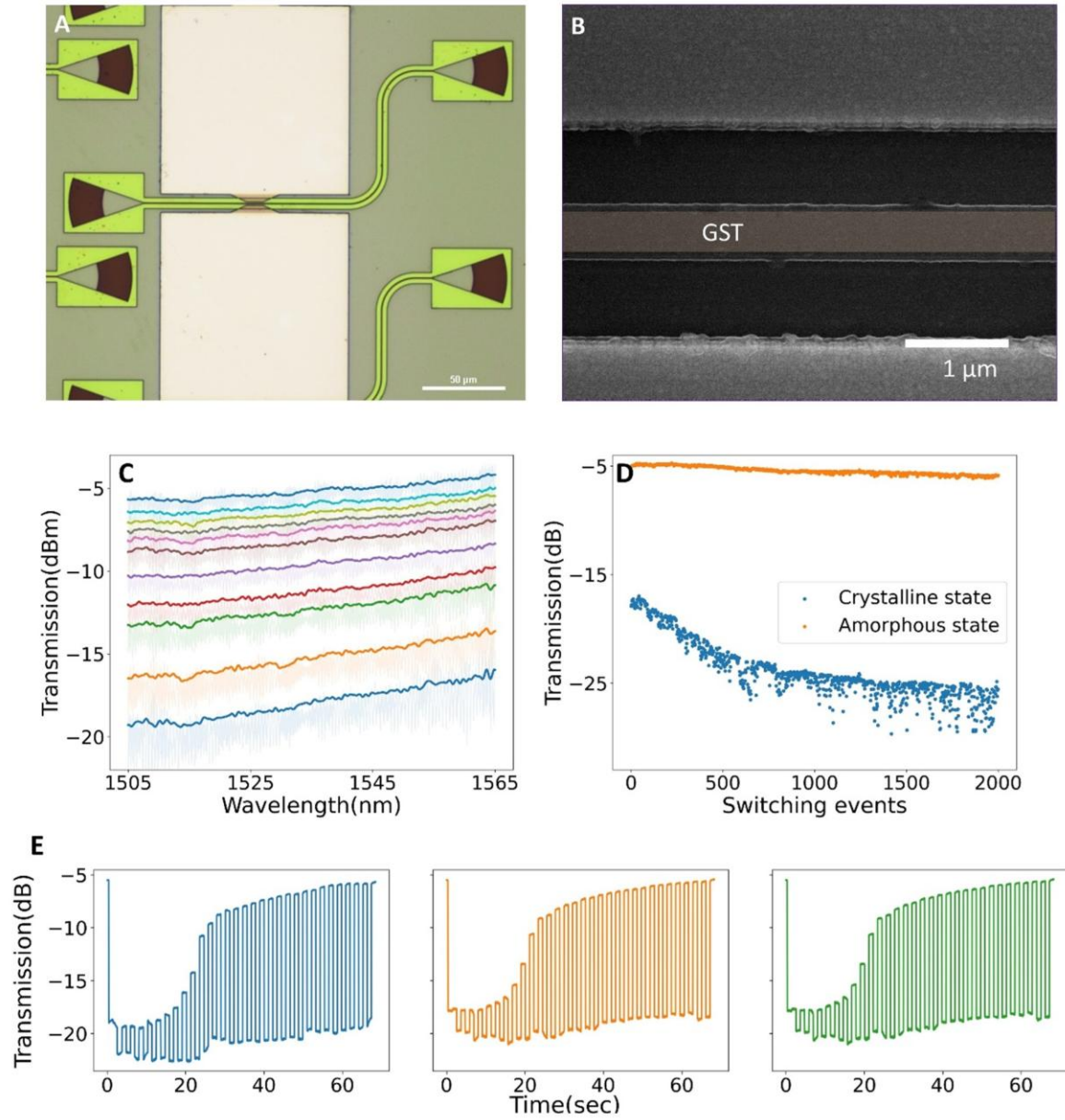


Figure 2.11: Measurement results for the waveguide switch.

(a) Microscope and (b) SEM image of the waveguide, where the GST thin film is indicated by the orange fake color. (c) Multilevel switching results. (d) Cyclability test results. (e) Three rounds of multilevel switching results.

2.7.3 Results for 1×2 silicon photonic programmable units

We first show the characterization results for the 1×2 programmable unit. It has an extinction ratio of 9 dB, a larger insertion loss of 4 dB than simulation, nonvolatility, and large endurance of 8,000 switching events, as in Figure 2.12 and Figure 2.13. The high loss in this design can also be attributed to fabrication imperfection. We also note that 1×2 design inherently has a higher overall loss than 2×2 design, as shown in Figure 2.3(c) and Figure 2.4(b).

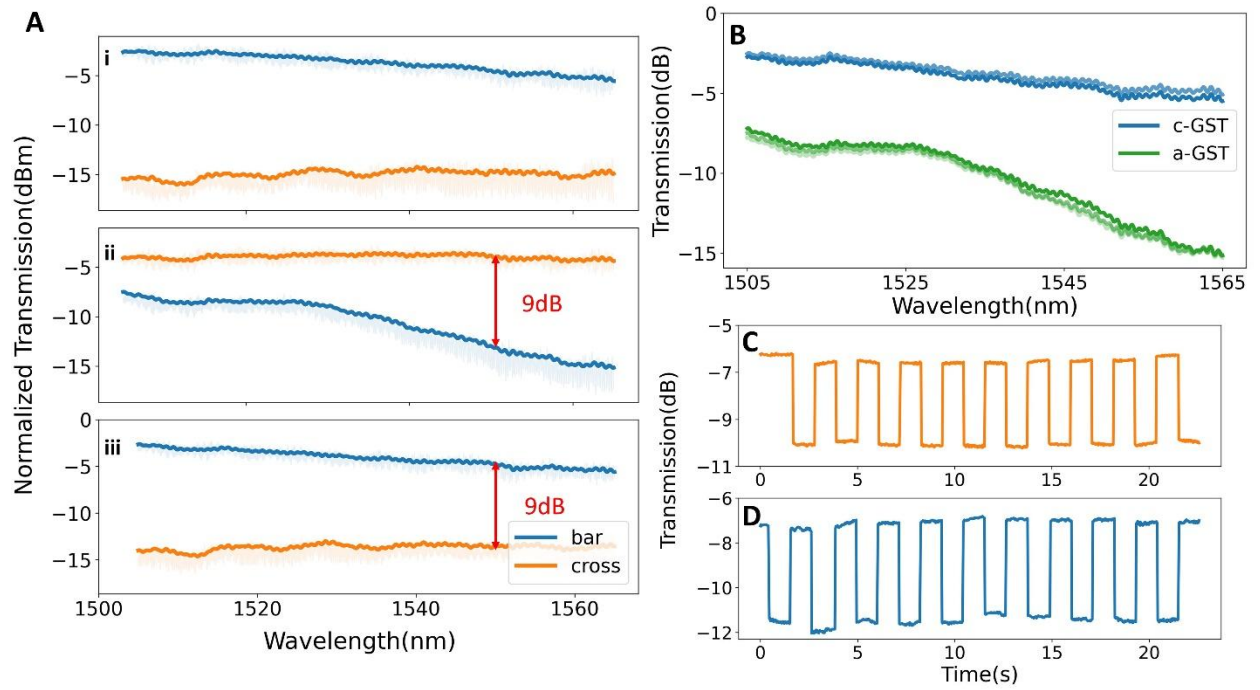


Figure 2.12: Optical transmission spectra measurement results for the 1×2 programmable unit.

(a) The transmission spectrum (i) initially when GST is in the crystalline state, (ii) after sending an amorphization pulse, (iii) after sending a crystallization pulse. (b) Transmission spectrum of 3 cycles amorphization and crystallization at the bar port. The spectra overlap well, showing a reliable and reversible switching performance. (c, d) The continuous-time measurement result for (c) cross and (d) bar ports.

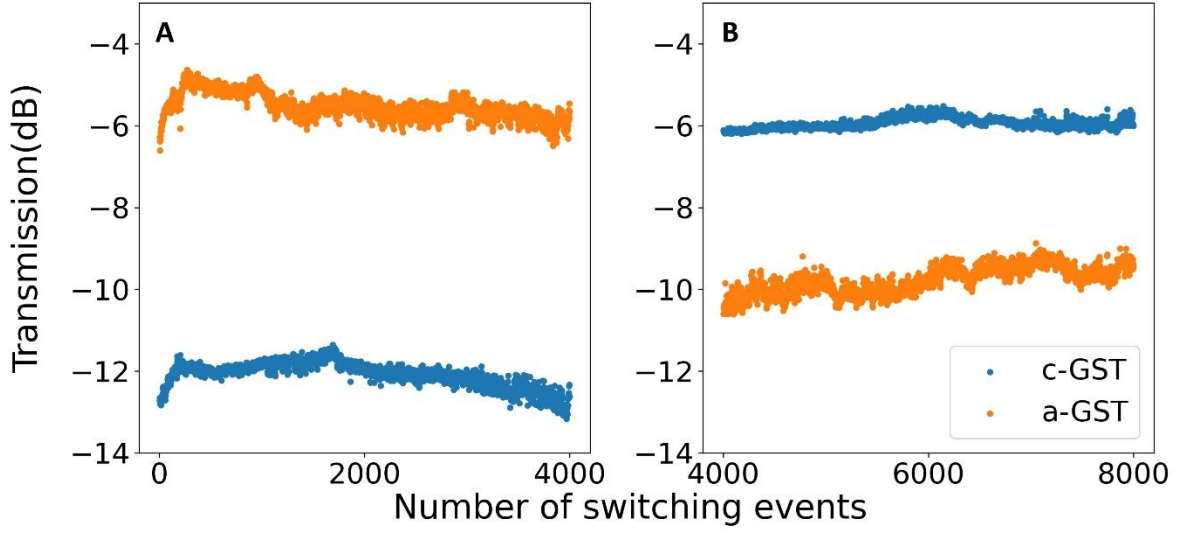


Figure 2.13: **The endurance test results for the 1×2 programmable unit.**

(a) cross and (b) bar port. 8000 switching events are shown without significant performance degradation at 1550nm. The degradation in extinction ratio and insertion loss compared to Figure 2.12 is mainly due to material ablation when testing the switching pulse conditions.

2.7.4 Results for 2×2 silicon photonic programmable units

The reversible operation of the electrically controlled 2×2 programmable unit is demonstrated by measuring the transmission of a tunable laser through the bar and cross port at two different phases of GST, summarized in Figure 2.14(a). Initially, the GST is prepared in the crystalline state (c-GST), for which the light passes through the bar port with an extinction ratio over 10 dB at 1550 nm and over 8 dB across the entire C-band in Figure 2.14(a-i). After applying a short, high amplitude pulse (13.6 V, 8 ns leading/falling edge, 200 ns pulse width with 380 nJ pulse energy) to induce amorphization (a-GST), the transmission spectrum flips, resulting in a high transmission through the cross port with over 10 dB extinction ratio at 1550 nm and over 8 dB across the entire C-band in Figure 2.14(a-ii). Subsequently, we applied a longer but lower amplitude pulse (3.2 V, 8 ns leading edge, 50 μ s pulse width with 6.83 μ J pulse energy) to trigger crystallization, returning the switch to the original high bar transmission state in Figure 2.14(a-iii). Crosstalk less than -8 dB is observed across the entire telecommunication C-band (1530 to 1565 nm) in cross and bar

states. We estimate the switching energy density to be 0.95/1.63 fJ/nm³ for amorphization/crystallization. This is comparable with ¹⁰¹, where an energy density of 0.2/1.95 fJ/nm³ for the phase transition was demonstrated. The cycle-to-cycle reproducibility was verified over three consecutive switching cycles, as shown in Figure 2.14(b), where transmission spectra for a-GST and c-GST at bar port overlap nearly perfectly. We then established the long-term retention of the device states by performing several measurements over a period of one month, as shown in Figure 2.14(c). A good match between the transmission spectra for devices in the a-GST configuration after putting the device in an ambient environment for 132 hours and 720 hours indicates that the switching is indeed non-volatile. Slight variations among the spectra are likely due to minor differences in the optical alignment during the different measurements.

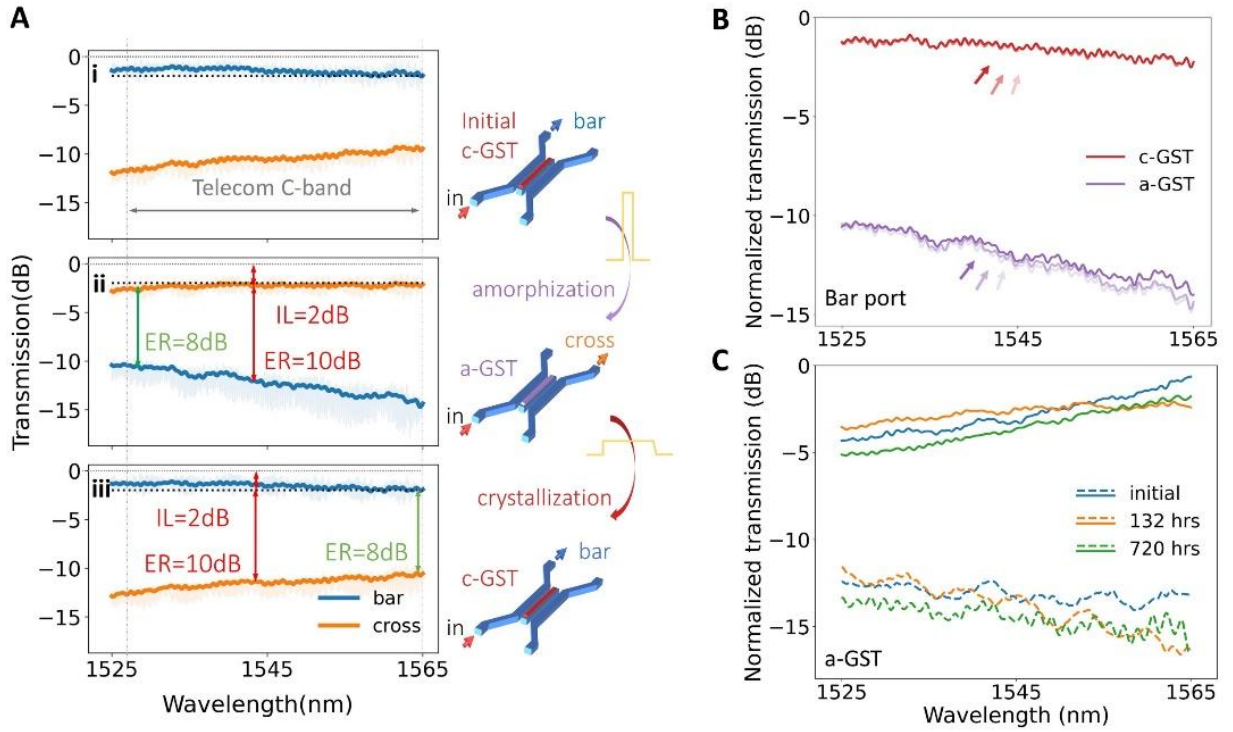


Figure 2.14: **Characterizations of the electrically controlled 2 × 2 programmable unit.**

(a) Transmission spectrum of the device (i) initially, (ii) after applying an amorphization pulse (iii) after applying a crystallization pulse. The shaded areas are measured raw spectra, and the solid lines are spectra after a low pass filter. IL and ER are insertion loss and extinction ratio, respectively. (b) Transmission spectra measured over three cycles at bar port. Each cycle is indicated with different color saturations. (c) Device

functionality over an extended period of one month with a-GST. The solid and dashed lines correspond to the bar and cross port transmission.

Finally, we demonstrate reversible operation over 5,750 switching events measured at 1550 nm without significant performance degradation, presented in Figure 2.15, thanks to the optimized PIN heater design. We note that due to limitations in our measurement setup, the cross and bar ports are measured consecutively, as shown in Figure 2.15(top) and (bottom), respectively. The two distinct transmission levels arising from switching between the crystalline and amorphous state are indicated by the shaded regions, whereas transmission contrasts of 8 dB and 11 dB are obtained for the cross and bar ports, respectively. The measured insertion loss at beginning is around 1 dB higher compared to Figure 2.14, which can be attributed to fiber alignment variation as well as device performance degradation due to previous measurement steps. Interestingly, although the cross-port transmission contrast reduces from 8 dB to 6 dB at the 2,750th event, the bar port contrast remains around 11 dB throughout the measurement. We attribute this reduction in the cross-port transmission contrast to thermal reflowing and material degradation of GST after multiple cycles. The performance degradation is less pronounced for the bar port because even if the GST shape changes due to thermal reflowing, a significant index mismatch still exists between the transition waveguide and input waveguide so that light still does not couple to the transition waveguide. We note that some data points are removed around the 600th, 800th, and 1,900th events because the same amorphization condition failed to trigger the phase change, and larger voltages of 13.8, 14.1, and 14.4V were used after that, respectively. This could result from drifting contacts of electrical probes and/or GST degradation. The contact drift issue could be solved by wire-bonding the chip to a carrier.

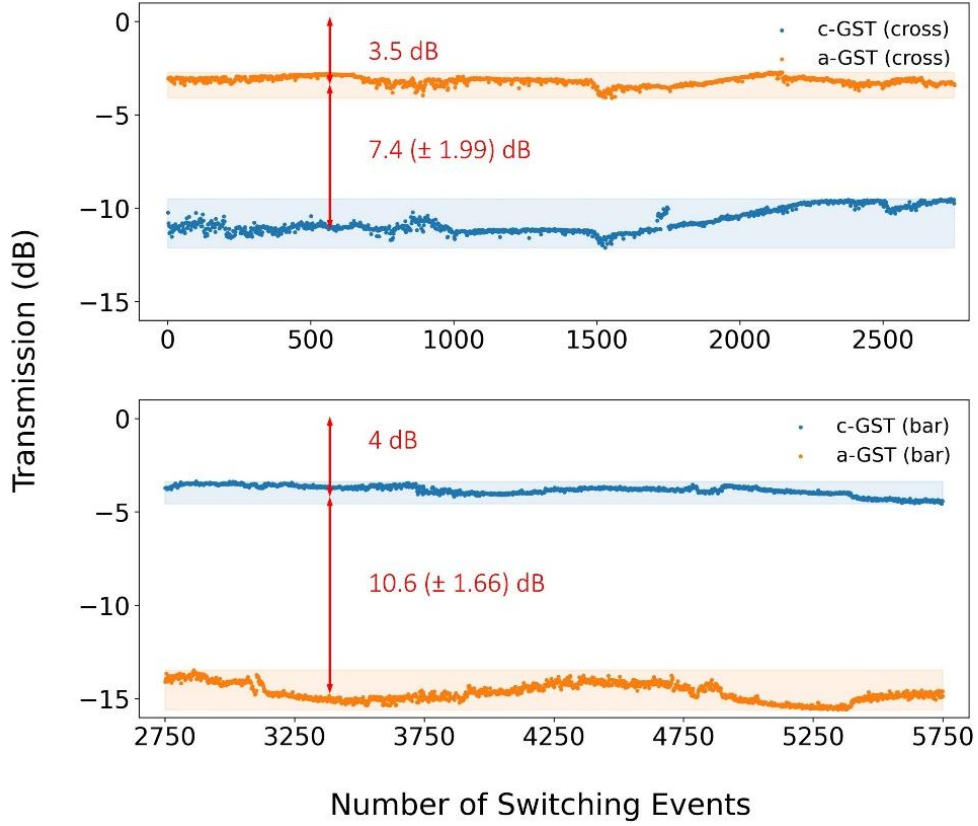


Figure 2.15: Cyclability test of the electrically controlled 2×2 programmable unit.

(Top) Transmission measured at the cross port. **(Bottom)** Transmission measured at the bar port. The blue/orange dots represent the measured transmission at 1550 nm after sending in a crystallization/amorphization pulse (with the same pulse condition in Figure 2.14). The shaded regions correspond to variations of the two distinct transmission levels. A larger insertion loss of 3 dB at both ports at the beginning can be attributed to fiber alignment variation as well as the material degradation and thermal reflowing of the GST thin film in previous measurement steps, see Discussion Section.

To understand the failure mechanisms after the cyclability test, we show the SEM image of the devices after the cyclability test. In Figure 2.16(a) and (c). The GST thin film shrinks and exhibits a wavy edge. This is likely due to the reflowing^{67,102} while GST was melted or due to non-uniform heating (as can be seen in Figure 2.16(c)). Some bubbles can also be observed, as in Figure 2.16(b) and (d), which indicates some of the phase change materials are damaged.

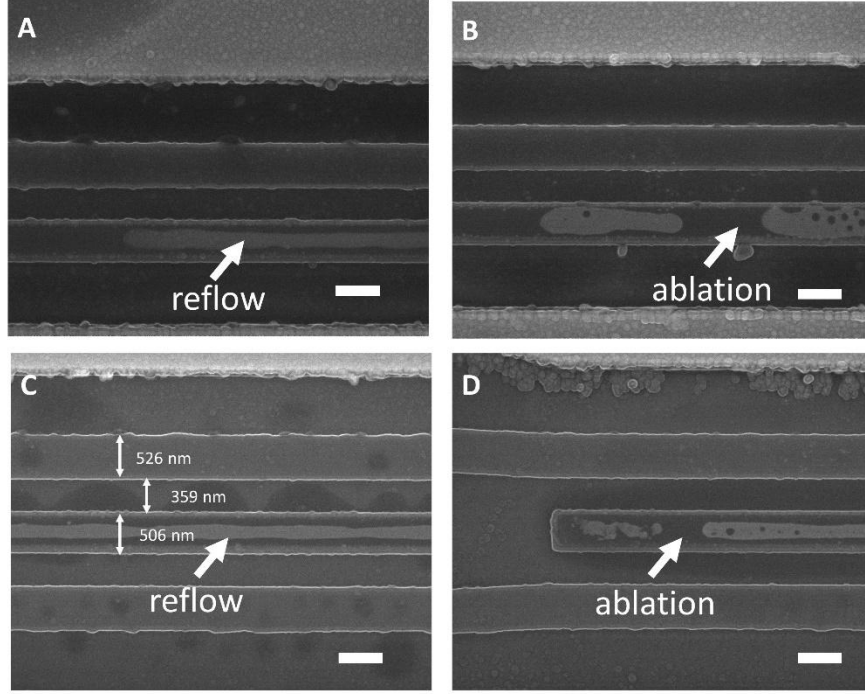


Figure 2.16: SEM of the devices after multiple cycles.

(a, b) 1×2 programmable unit reflowing and ablation. (c, d) 2×2 programmable unit reflow and ablation. All scale bars are 500 nm.

2.7.5 Transient response of the 2×2 programmable unit

The results are shown in Figure 2.17, and we analyze the transient performance. A high transmission is expected at the bar/cross port when GST is in the crystalline/amorphous state. Indeed, the measurement results in Figure 2.17(a) and (c) show that around $1 \mu\text{s}$ or $2 \mu\text{s}$ after sending in the 200 ns amorphization pulse, the transmission at bar port decreases while at cross port increases to a steady level. In this case, the longer transient response time than electrical pulse duration can be attributed to the finite response time of the PIN junction in the forward bias mode due to the slow process of minority carrier injection. We also found a sudden transmission drop right after the electrical pulse due to the carrier effect, which significantly increased the loss of the waveguides. From Figure 2.17(b) and (d), we can conclude that in the process of crystallization, the response time of the programmable unit is almost the same as the total pulse duration due to the small voltage and the relatively long electrical pulse applied ($50 \mu\text{s}$ steady time and $30 \mu\text{s}$ falling

edge, total pulse duration 80 μs). The bar-port changes into a high transmission level, while the cross-port goes to a low transmission level.

Interestingly, in Figure 2.17(b), we observed a two-step transmission rise. We can attribute such a phenomenon to carrier injection into the middle transition waveguide, which introduces an effective index imaginary part mismatch. The light then stays in the input waveguide. Thus, a higher bar-port transmission can be observed¹⁴¹.

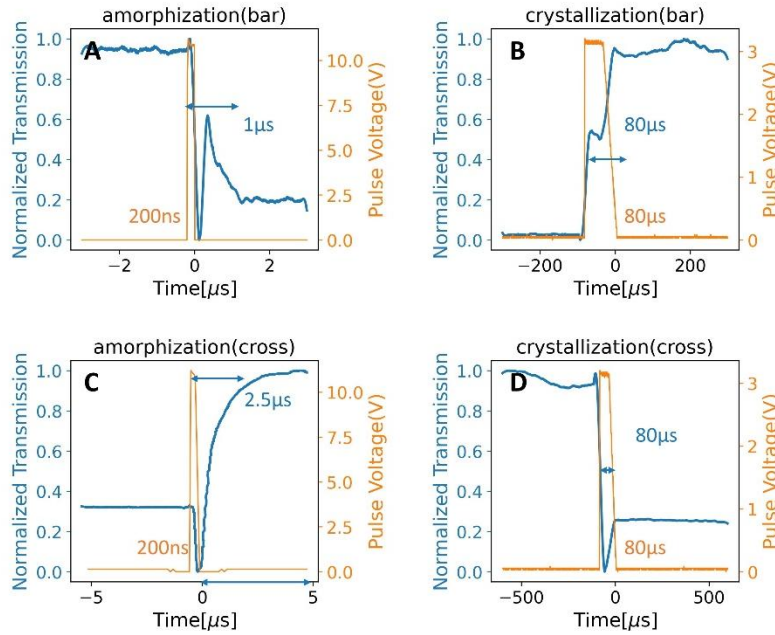


Figure 2.17: **Transient response measurement results for electrically controlled 2×2 programmable unit.**

(a) amorphization and (b) crystallization at the bar port, and (c) amorphization and (d) crystallization at the cross port. The blue curve shows optical transmission while the orange line provides the electrical pulse for pulse-change actuation. The amorphization response time is around 1 or 2.5 μs while the crystallization time is around 80 μs .

2.7.6 Thermal stability test results

One advantage of a broadband device is its thermal stability. Here we measured the transmission spectrum of the 2×2 programmable unit after the cyclability test at 25, 30, and 35 $^{\circ}\text{C}$ when the GST is in the crystalline state as shown in Figure 2.18. The excellent match among the curves offers good thermal stability.

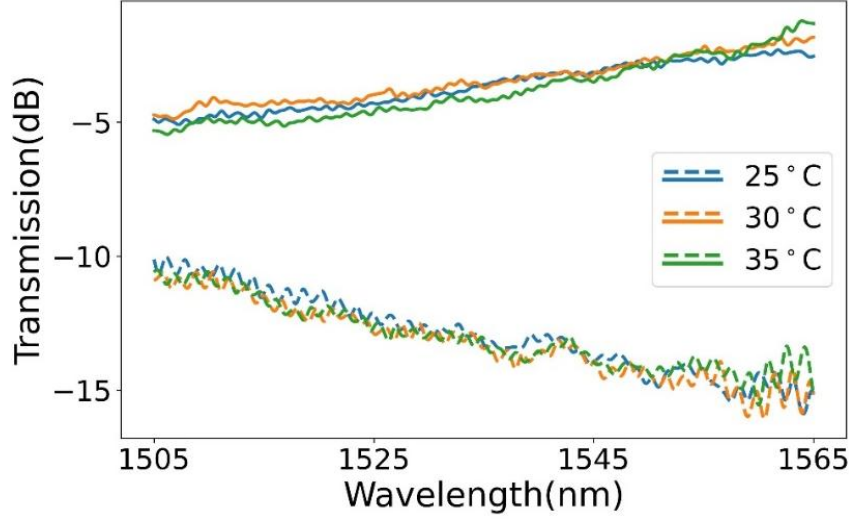


Figure 2.18: **Thermal stability test measurement.**

The temperature varies from 25°C to 35°C. No significant spectrum shift is observed. The cross and bar port transmission are represented by solid and dashed lines, respectively.

2.8 Deterministic multilevel operation with multiple GST segments

2.8.1 Multilevel 1×2 programmable units

Figure 2.19 shows the simulation result for a 1×2 optical programmable unit, for which the optical design is similar to Ref. ⁵⁹. One change is that two individually controlled GST segments, instead of one, are used to achieve multi-level operation. The achievable low-loss states are, however, not 2^N as in the 1×1 programmable unit case, but $N + 1$, since any a-GST segment before c-GST segment results in light coupling to the GST-loaded waveguide, which then gets completely absorbed by the highly lossy c-GST segments. Our simulation results agree with this intuition. We denote the phase sequence from left to right as {phase of segment 1, phase of segment 2} and show the electric field distribution and the transmission spectrum for all four possible phase sequences. Figure 2.19(b) and (c) shows that Sequence {a, c} exhibits a high insertion loss of ~ 3 dB due to high absorption of the c-GST segment 2. This is verified by the electric field distribution image, where the light first couples into the cross port along the a-GST segment 1, then

gets completely absorbed by c-GST segment 2. Since the length of the first segment is half of the coupling length, exactly half of the light is coupled and absorbed, agreeing well with the simulation.

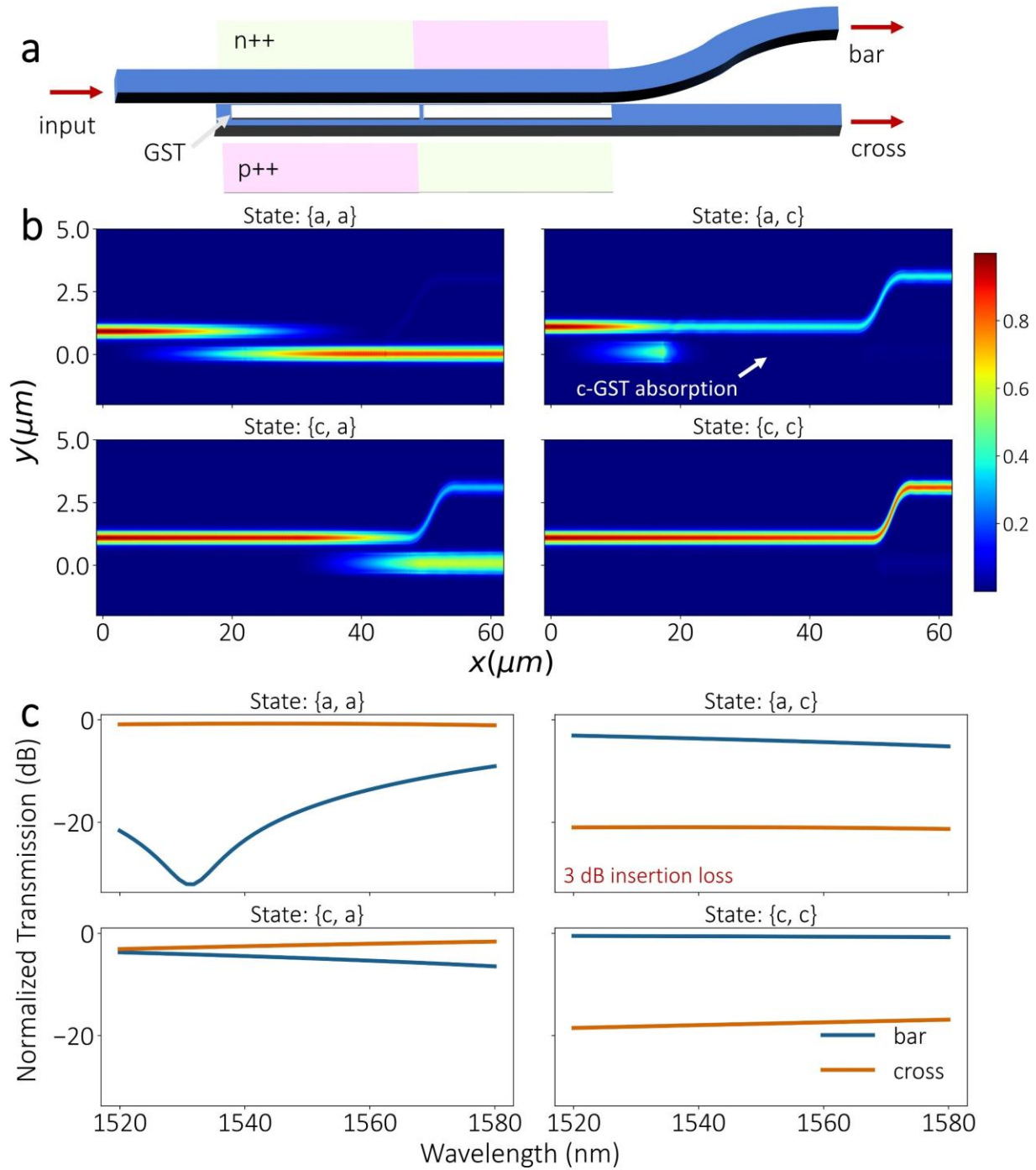


Figure 2.19 FDTD simulation for a deterministic three-level 1×2 programmable unit using GST.

(a) Schematic. (b) Intensity distribution and (c) the corresponding transmission spectra for different GST phase combinations. GST sequence {a, c} introduces an insertion loss of ~ 3 dB due to c-GST absorption loss, pointed by a white arrow in the field distribution map.

2.8.2 Multilevel 2×2 programmable unit

Previous GST-based low-loss 2×2 programmable unit leveraged a PM-TDC structure to circumvent the loss of c-GST.^{57–59} In these works, an extra transition WG is placed between two silicon waveguides with 20-nm-thick GST deposited on top for active switching. When the GST is in the a-phase, the transition WG is designed to phase match with other two WGs. Therefore, the input light can be coupled into the transition WG, and then to the cross port. On the contrary, once switching the GST to the c-phase, a large effective index difference is introduced, and the light can barely couple to the high loss transition WG. This bypasses the high loss of c-GST. Unfortunately, a straightforward extension of this PM-TDC method to multi-level operation does not work as we will show in the following analysis.

Challenges of multiple segments switching using the phase-matched TDC approach

Figure 2.20 shows a simulation using a similar design to Ref.⁵⁹ but with two GST segments. It shows that both {a, c} and {c, a} phase sequences have a high loss of ~ 3 dB. The former can be explained based on the same concept as in the 1×2 programmable unit case: no c-GST should be placed after an a-GST segment when finite light is still in the transition WG, defined as the Type I absorption loss. Besides, the transition WG, which is open at the end, adds another constraint for low-loss operation: no light can remain in the transition WG at the end of this transition waveguide. Otherwise, that portion of light will radiate and get lost, defined as Type II radiation loss.

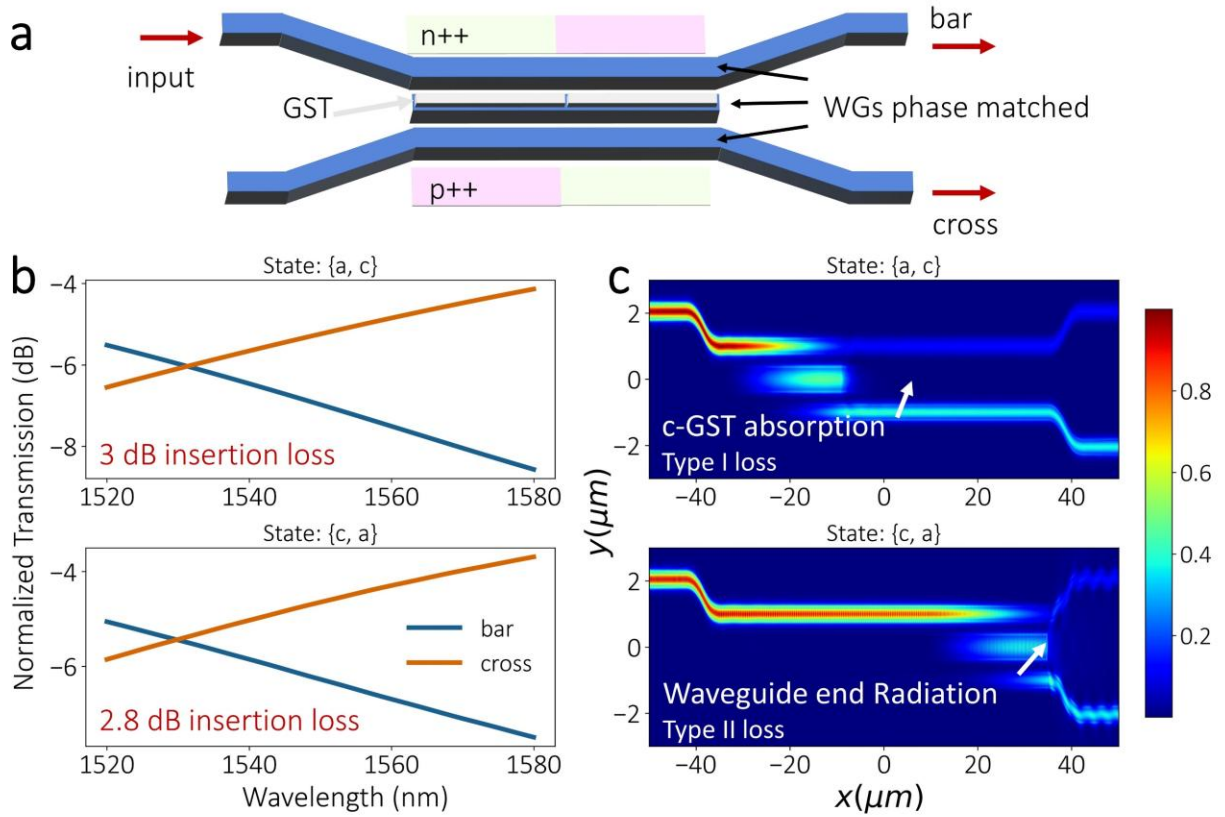


Figure 2.20: **Phase-matched three-WG 2×2 directional couplers have high loss for intermediate levels.**

(a) Schematic. (b) the transmission spectra for different GST phase sequences and (c) the corresponding intensity distribution. Both sequences {a, c} and {c, a} introduce an insertion loss of ~ 3 dB. The former is due to c-GST absorption loss (Type I loss), while the latter is due to the radiation loss at the end of the transition WG (Type II loss), both indicated by white arrows.

Analytical and numerical study of the three-waveguide directional coupler systems

To tackle this loss issue, it is crucial to understand the intensity dynamics inside of each WG in this coupled-waveguide system. We describe the coupled three waveguide system using the following coupled partial differential equation¹⁴²:

$$\begin{cases} \frac{da_0}{dz} = i\kappa^*(a_1 + a_2) \\ \frac{da_1}{dz} = i\kappa a_0 - i\delta a_1 \\ \frac{da_2}{dz} = i\kappa a_0 - i\delta a_2 \end{cases} \quad (2.7)$$

where z is the distance in light propagation direction, $a_{i,i=0,1,2}$ is the amplitude in three WGs in Figure 2.21(a), $\kappa = \Delta n_{eff,c} \cdot \frac{2\pi}{\lambda_0}$ and $\delta = \Delta n_{eff,i} \cdot \frac{2\pi}{\lambda_0}$ are the coupling coefficient and detuning between the center and other WGs, $\Delta n_{eff,c}$ is the effective index difference between the super-modes formed by coupled WG0 and WG1 (or WG2), $\Delta n_{eff,i}$ is the effective index difference between the modes in WG0 and WG1 (or WG2) assuming they are isolated, and λ_0 is the vacuum wavelength of light. We note that only the nearest coupling is considered in this model, which is usually a valid assumption in a 2D photonic WG array. We also assume that WG1 and WG2 have the same geometry to simplify the model and neglect the loss term for simplicity. To quickly capture physics, we show the numerical analysis below.

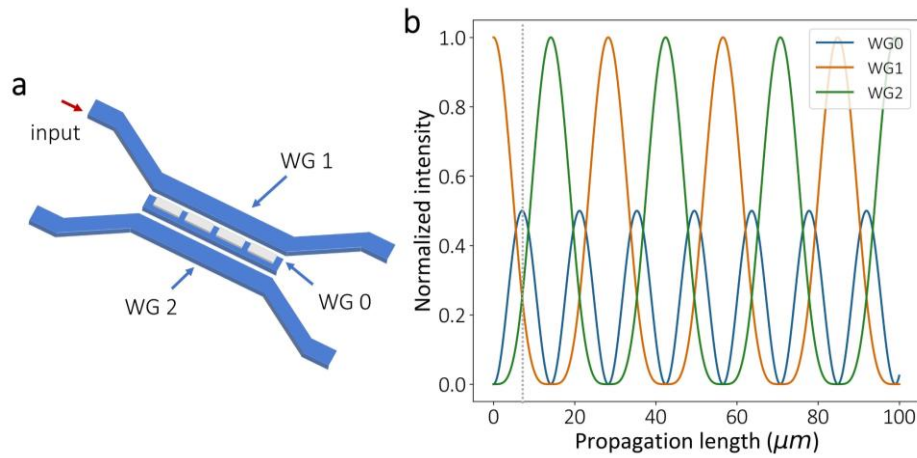


Figure 2.21: **Analytical model reveals that phase-matched three-WG couplers can never have low-loss intermediate levels.**

(a) Schematic for a generic GST three-waveguide coupler. The GST patches are denoted in white. In all the discussions, we assume the WG1 the input port. **(b)** Numerically calculated light intensity in three WGs. Blue, orange and green colors denote WG0, WG1, and WG2, respectively. In the case of two GST segments, phase sequence {c, a} would lead to a propagation distance of $L_c/2$, indicated by the gray dotted line. It is clear that finite energy still remains in WG0, causing Type II radiative loss.

First, to analyze the case where WG0 is phase matched with WGs 1 and 2, we set δ to zero and solve this equation numerically. We found that the middle WG intensity is zero only when the light is completely in the cross or bar port in Figure 2.21(b). Therefore, Type I loss occurs in the $\{a, c\}$ state, while Type II loss occurs in the $\{c, a\}$ state. Therefore, we summarize the requirements for low-loss multilevel operation in a three-waveguide directional coupler as (1) no light can be in the middle waveguide at a c-GST segments to avoid Type-I loss, and (2) no light can be at the end of the middle waveguide to avoid Type-II loss, and (3) there must exist some intermediate splitting ratios (except from complete bar or cross) when the intensity of light in WG0 is zero. Obviously, the last requirement can never be fulfilled in a phase-matched TDC.

New degree of freedom: phase-detuned three-waveguide directional couplers

To solve this issue, a new degree of freedom must be introduced. We deliberately designed WG0 to have a phase detuning δ with WG1 and WG2, *i.e.*, a phase-detuned TDC scheme. The phase detuning between WGs can be quantitatively represented by the detuning rate δ , where $\beta = 2\pi/\lambda$ is the vacuum wavevector and Δn_{eff} is the effective index difference between WGs. To intuitively understand the wave dynamics in this system, we performed a numerical simulation as shown in Figure 2.22, where different plots show the intensity in the three WGs versus propagation length under different detuning rates δ . It can be clearly seen that different splitting ratios between WG1 and WG2 can be obtained when zero light is in WG0. We note that Eqns. (2.7) are analytically solvable, and the solution is presented in Appendix I of ref¹³⁴.

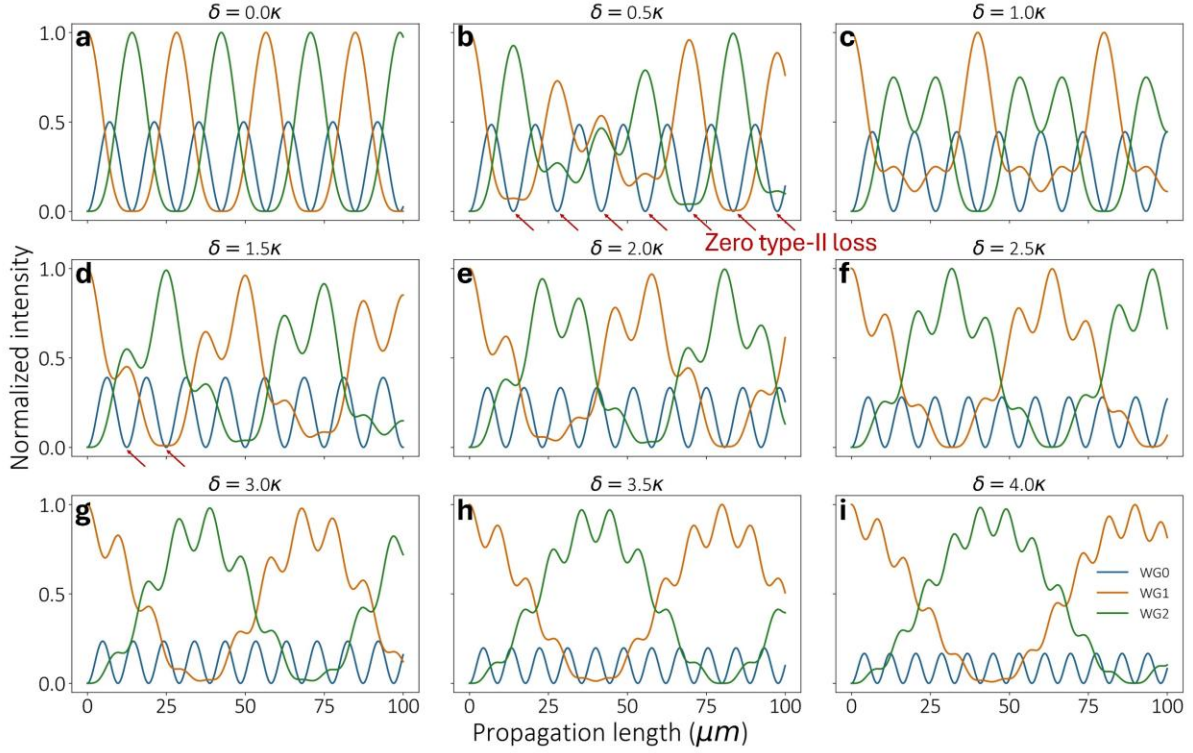


Figure 2.22: **Detuning the middle waveguide provides rich optical intensity dynamics, enabling low-loss intermediate levels.**

(a)-(i) Intensity dynamics in the three waveguides as the detuning δ varies from 0 to 4κ . As the detuning gets larger, the intensity in WG0 becomes smaller and that in the other two is smoother. As δ increases from zero, multiple zeros in blue curve emerge (such as pointed by red arrows in (b)), overcoming Type II loss. Note that this simulation assumes a coupling length L_c of $10\ \mu\text{m}$ between WG0 and WG1 (or WG2) when $\delta = 0$.

A tradeoff must be considered when choosing detuning rate δ . A large detuning δ generally creates more zeros in the middle waveguide within the same coupling region length, hence more achievable intermediate levels. However, a large δ also leads to a longer device (for complete power transfer to the cross port) and hence larger overall loss when GST is in c-phase. To compensate for this, a thicker GST can be used to provide a larger Δn . However, the loss due to a-GST also increases. Furthermore, this also makes the reversible electrical switching more difficult.

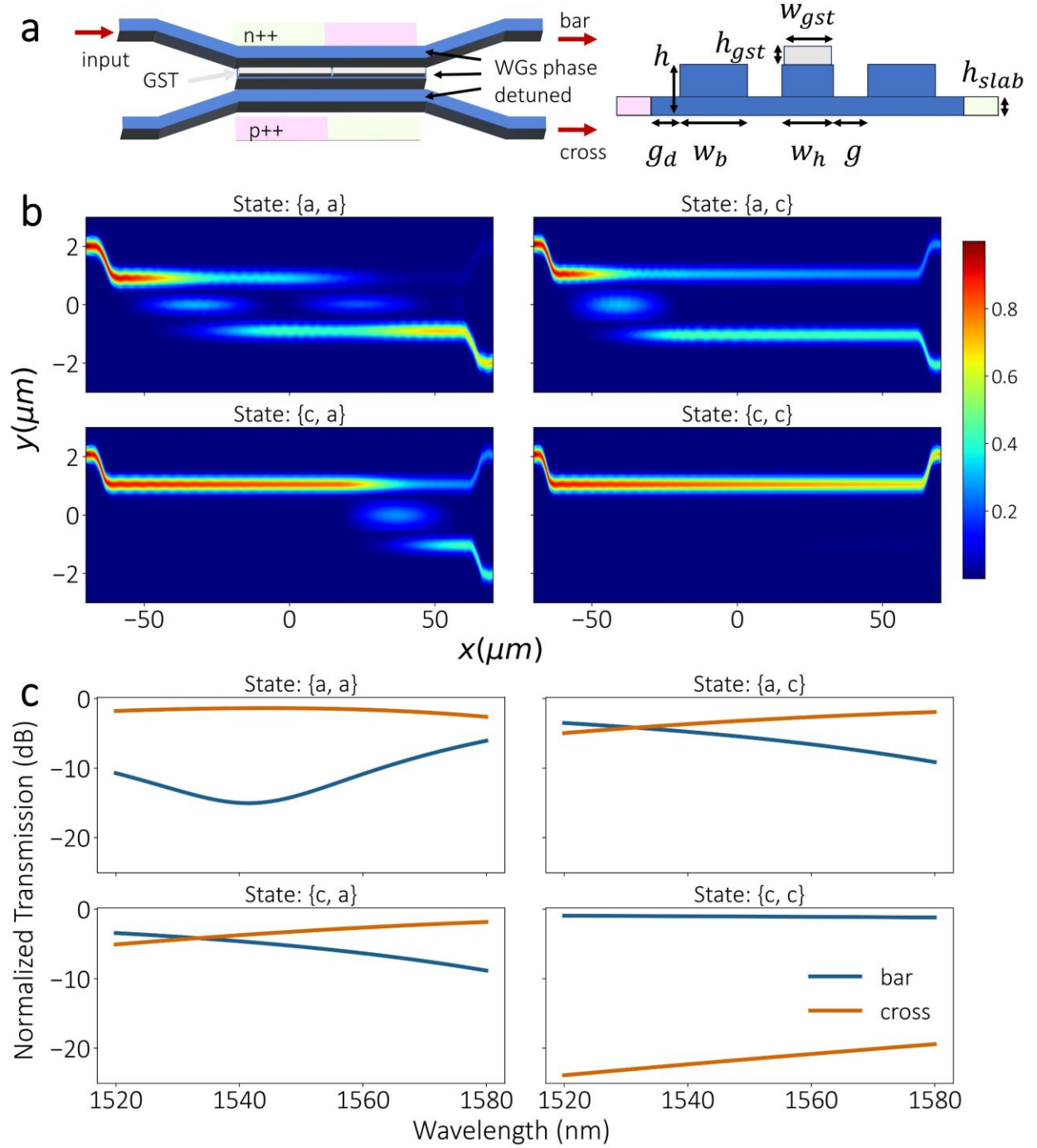


Figure 2.23: Optimized deterministic three-level 2×2 programmable units with phase-detuned TDC design ($\delta = 1.5\kappa$).

(a) Schematic (left) and the cross-sectional view (right). Designed geometry parameters are listed in Table 1. (b) Simulated intensity distribution and (c) the corresponding transmission spectra for different GST phase sequences. The insertion loss is reduced to ~ 1.2 dB compared to ~ 3 dB in traditional phase-matched TDC designs.

Based on the above discussion, we choose $\delta = 1.5\kappa$ and design a multi-level 2×2 programmable unit with ellipsometry measured GST refractive index, (see Appendix II of ¹³⁴ for detailed design procedures). Figure 2.23 shows the FDTD simulation results with a low insertion loss (~ 1.2 dB) and three achievable splitting ratios of 100:0, 50:50 and 0:100. The designed parameters are summarized in Table 2 below.

Table 2: **Designed parameters for the multi-level 2×2 GST programmable unit with $\delta = 1.5\kappa$. Unit: nm except for l_c .**

h	h_{slab}	g_d	w_b	w_h	g	h_{gst}	w_{gst}	l_c (μm)
220	100	200	630	500	315	30	450	115

Figure 2.24 shows the insertion loss and extinction ratio of the optimized 2×2 programmable unit. The insertion loss is low (~ 1.2 dB) across a broad wavelength (60 nm) for all three levels (four configurations). We emphasize that this insertion loss is mainly due to the relatively thick GST film used in the design, which introduces absorption loss in its amorphous state. By replacing GST with lower loss PCMs such as GSST, we can potentially further reduce the loss. However, the index contrast Δn of GSST is much smaller than GST, which may result in a thicker PCM and longer devices. The extinction ratios of the complete cross and bar states remain high across 60 nm, but the intermediate states are more wavelength-sensitive with a 3 dB variation bandwidth of ~ 22.6 nm.

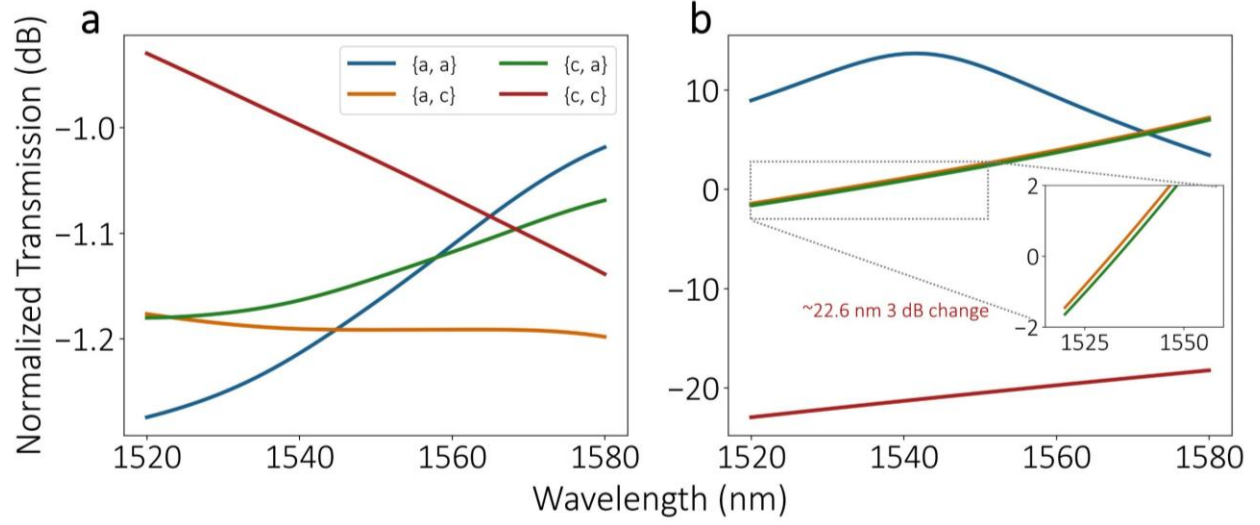


Figure 2.24: Simulated transmission spectrum of the designed three-level 2×2 TDC programmable unit ($\delta = 1.5\kappa$).

The device shows (a) a low loss (< 1.2 dB) for all four GST sequences and (b) a bandwidth of ~ 22.6 nm with less than 3 dB extinction ratio variation.

2.9 System-level applications envision

The presented nonvolatile 2×2 programmable unit, along with the 1×2 and 1×1 switches, render an energy-efficient and scalable solution to programmable integrated photonics. First, these are nonvolatile devices, and zero static energy is required to hold the state. This is very desirable for low-frequency programmable photonics, as shown in **Table 1**. Second, our device can be switched electrically. System-level and automatic solutions can be envisioned by interfacing with mature electronic technologies. Lastly, the programmable units are broadband devices, which will enable full use of the parallelism operation of light by wavelength division multiplexing (WDM). Also, the device is relatively insensitive to thermal drifts and fabrication errors because of its broadband nature.

The 2×2 programmable unit can be utilized in large-scale nonvolatile optical switching fabric¹³⁷, as in Figure 2.25(a). An 8×8 non-blocking optical switching fabric using the classical Benes topology is presented. More applications can be envisioned if the 2×2 programmable unit can operate in a multilevel switching fashion, which can be potentially implemented by introducing a detuning between the SW and

HW. For example, such devices are essential building blocks for a nonvolatile optical programmable gate array (OPGA). We propose to connect our 2×2 programmable unit with each other to form a mesh array, such as in Figure 2.25(b). By configuring the optical programmable unit into different states, diverse types of functions can be realized for optical on-chip information processing. Most OFGAs were demonstrated with thermal-optics effect^{39,41,143}. But due to its volatile nature, a significant amount of energy is consumed to hold the configuration. PCM-based OPGA can significantly save energy thanks to its self-holding property and thus zero static energy consumption.

Another possible application is optical computing. Recently there have been works on using phase change materials for on-chip non-Von Neumann optical computing^{68,69,67}. These works mainly apply optical pulses to actuate the phase transition, limiting the device's scalability due to complicated optical alignment. We propose the structure in Figure 2.25(c), which can function as an optical forward neural network. Although only reliable binary-level operations are feasible using the reported 2×2 programmable unit, this very similar design idea can be directly extended to using transparent PCMs such as Sb_2Se_3 and Sb_2S_3 , which will support multi-bit operation¹⁴⁴. The reliable operation of these devices can be achieved by a segmented heater and PCM design¹⁴⁵. Also, similar to⁶⁸, an optical convolutional neural network comprising 1×1 multilevel switches with electrical control can be envisioned, as shown in Figure 2.25(d). We expect a large-scale, nonvolatile, and in-memory optical computing platform using electrical controls.

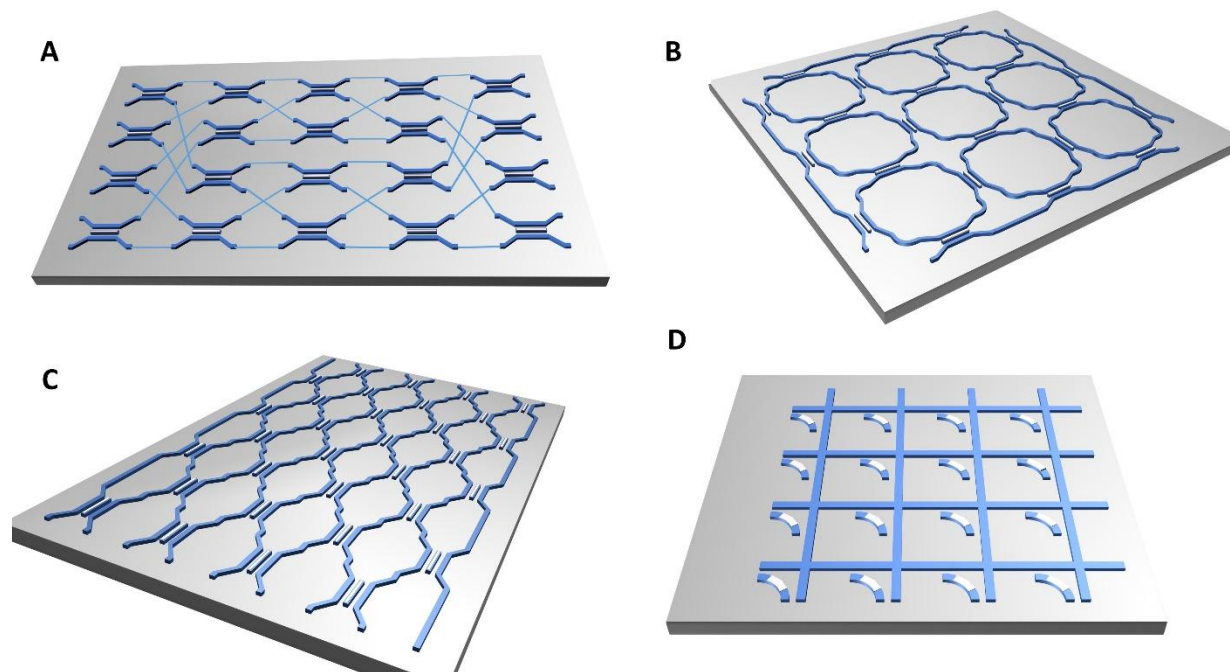


Figure 2.25: **PIC schematics for various applications.**

(a) on-chip optical switching fabric. **(b)** multipurpose programmable PICs. **(c)** On-chip optical forward neural networks. **(d)** convolutional neural networks.

Chapter 3. Electrically programmable multi-level PICs with Sb_2S_3 ¹¹³

Although the GST-based programmable unit in the previous Chapter was carefully designed, the loss in experiment was still high due to the slight fabrication variation. Moreover, the previous device is only suitable for binary operation due to the strict phase matching condition. In this Chapter, we aim to solve these longstanding problems through wide-bandgap PCMs such as antimony sulfide (Sb_2S_3) and antimony selenide (Sb_2Se_3). Because of their intrinsically lower optical absorption loss, a traditional two waveguide directional coupler design is suitable for the broadband optical switches, and we achieved low loss (<1.0 dB), high extinction ratio (>10 dB), high cyclability ($>1,600$ switching events), and 5-bit operation. These Sb_2S_3 -based devices are programmed via on-chip silicon PIN diode heaters within sub-ms timescale, with a programming energy density of $\sim 10 \text{ fJ}/\text{nm}^3$. Remarkably, Sb_2S_3 is programmed into fine intermediate states by applying multiple identical pulses, providing controllable multilevel operations. Through dynamic pulse control, we achieve 5-bit (32 levels) operations, rendering 0.50 ± 0.16 dB per step. Using this multilevel behavior, we further trim random phase error in a balanced MZI. Our work opens an attractive pathway toward large-scale energy-efficient programmable PICs with low-loss and multi-bit operations.

3.1 Characterization of Sb_2S_3 thin films

We started with characterizing the thin film Sb_2S_3 using ellipsometry, X-Ray diffraction, and Raman spectroscopy (Figure 3.1). A layer of 60-nm Sb_2S_3 was sputtered on a silicon wafer. The as-deposited Sb_2S_3 was characterized first and then switched to the crystalline phase by annealing at 325°C for 10 minutes under nitrogen flow. The Sb_2S_3 was characterized by ellipsometry, and the data is fitted with Cody-Lorentz models with low mean square error (~ 5). The fitted complex refractive indices in Figure 3.1(a) show a drastic change in the real part n (~ 0.7 at 1310 nm), while almost zero κ (0.0003 for amorphous and 0.03 for crystalline phases at 1310 nm) across the entire telecommunication O- and C-band. Therefore, switching the Sb_2S_3 produces a phase-only modulation. The micro-structural phase transition after annealing and the stoichiometry were verified under X-ray diffraction (XRD) and Raman spectroscopy¹⁴⁶, as shown in Figure

3.1(b) and (c), by the characteristic lattice constants in the XRD and wavenumber shifts in the Raman spectrum. These characteristics show good agreement with existing literature¹⁴⁷.

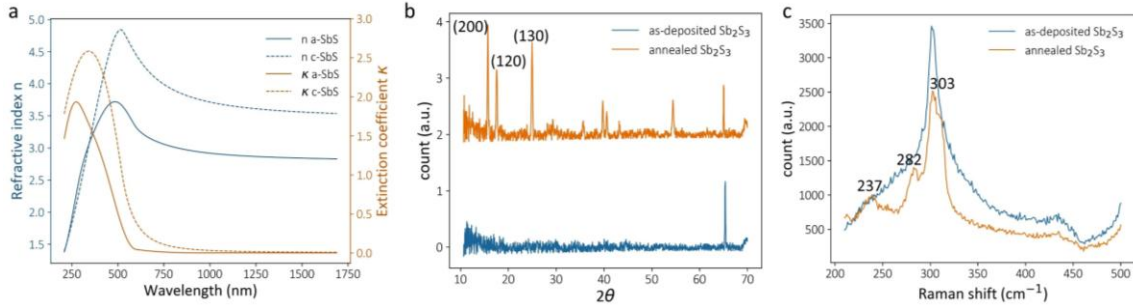


Figure 3.1: **Sb_2S_3 material characterization.**

(a) Broadband complex refractive index fitted from ellipsometry measurement. **(b)** X-ray diffraction and **(c)** Raman spectroscopy measurement for the as-deposited (blue) and annealed (orange) Sb_2S_3 samples. The peak at $2\theta = 65^\circ$ for as-deposited Sb_2S_3 comes from the silicon substrate. The characteristic lattice constants and Raman shifts are marked.

In Figure 3.2, we took a micrograph image of 60-nm-thick Sb_2S_3 on a blanket silicon chip, where the Sb_2S_3 films were annealed under 325°C and in the crystalline phase. The micrograph image shows a non-uniform surface with a lot of local crystal grains and even flower-shaped patterns (circled in red), which could lead to unintended scattering loss for in-plane light propagation. We hypothesize that the crystal grains form because crystalline Sb_2S_3 has a density reduction of around 24% compared to its amorphous form¹⁰⁵. Hence, a significant strain is induced during the phase transition, and results in a non-uniform surface. We also speculate that flower-like patterns occur near the nuclei.

It is unclear what the c- Sb_2S_3 surface looks like on our devices because those 20-nm-thick, 450-nm-wide Sb_2S_3 films are too small to image optically. The 40-nm-thick encapsulation alumina further prevents the accurate usage of SEM. Advanced material study is required to quantitatively understand the crystalline patterns formed.

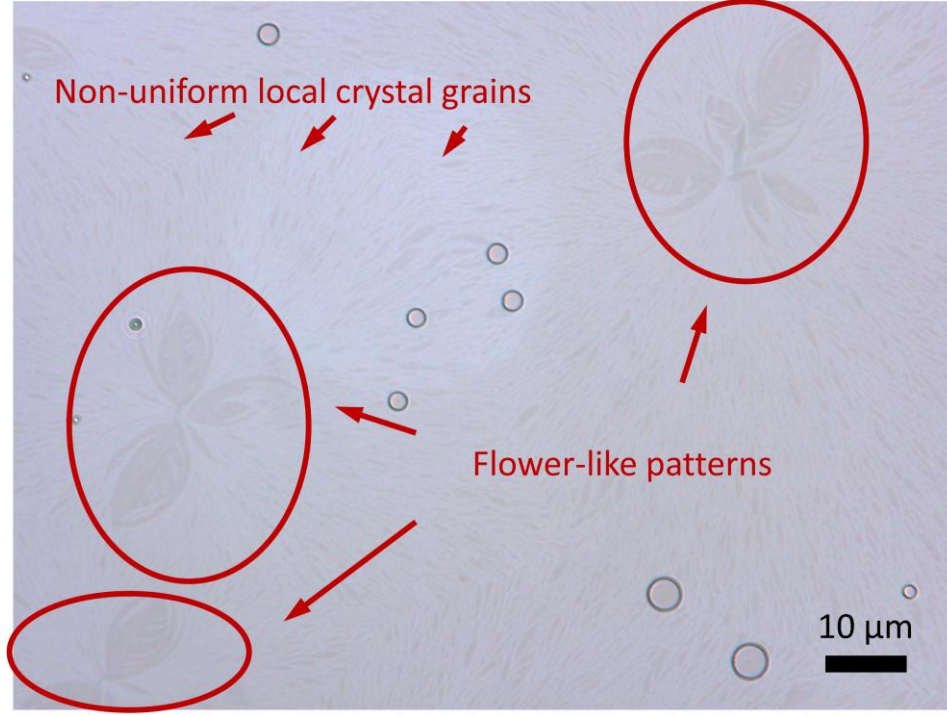


Figure 3.2: **Non-uniform surface forms after the annealing due to the density difference between amorphous and crystalline Sb₂S₃.**

Some flower-shaped patterns are observed. We speculate the nonuniform surface is due to the large density difference between a- and c-Sb₂S₃, and the flower-shaped patterns occur near the nuclei.

3.2 Simulation and design of Sb₂S₃-based silicon photonic components

3.2.1 Sb₂S₃-based silicon phase shifters

Figure 3.3 shows the simulated π phase shift length L_π and insertion loss for the Sb₂S₃-based phase shifters. The refractive indices of Sb₂S₃ used here were obtained experimentally in the previous section. For a generic 500-nm-wide, 220-nm-high SOI waveguide with 20-nm-thick, 450-nm-wide Sb₂S₃ on the top, an effective index contrast of 0.018 is obtained at 1310 nm in Figure 3.3(a) and (b), indicating a π phase shift length $L_\pi \approx 38 \mu\text{m}$. Figure 3.3(c) and (d) shows that a wider and thicker Sb₂S₃ film reduces L_π and does not impact the insertion loss much ($\sim 0.23 \text{ dB}/\pi$). We adopted a generic waveguide width of 500 nm to avoid any extra taper structure, which renders $L_\pi \approx 38 \mu\text{m}$. The calculated mode coupling between the bare

silicon waveguide mode and the c-Sb₂S₃-Si hybrid waveguide mode is 99.7% (or -0.013 dB), which is negligible.

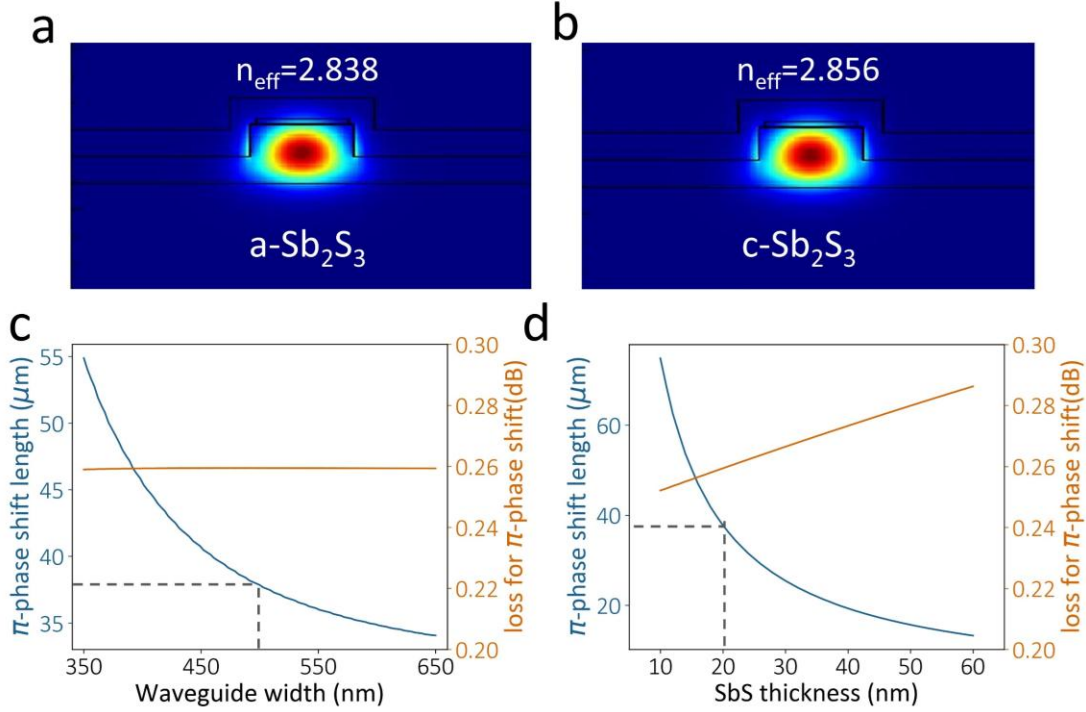


Figure 3.3: **Simulations for Sb₂S₃-on-SOI phase shifters.**

(a, b) Mode simulations for (a) amorphous and (b) crystalline Sb₂S₃. An effective index contrast of 0.018 is obtained at 1310 nm, indicating a π phase shift length $L_\pi \approx 38 \mu\text{m}$. (c, d) L_π (blue) and excess loss for π phase shift (orange) versus (c) the hybrid waveguide width and (d) Sb₂S₃ thickness. L_π decreases as the increase of both waveguide width and Sb₂S₃ thickness, while the excess loss remains almost invariant. The dashed gray lines represent that we used a waveguide width of 500 nm and an Sb₂S₃ thickness of 20 nm in our experiments.

We note that L_π could be further reduced by exploiting a wider or thicker Sb₂S₃. Although thick Sb₂S₃ gives a more compact device footprint, the complete phase transition is more difficult. The vertical temperature gradient at thick Sb₂S₃ films could lead to Sb₂S₃ ablation at the bottom while not high enough temperature for amorphization at the top. Unintentional re-amorphization could also happen with a thick Sb₂S₃ layers. Moreover, recrystallization could also occur because of the crystallization kinetics and finite heat diffusion time¹⁴⁸. To accommodate this tradeoff, we pick 20 nm as the experimental thickness, providing both a complete, repeatable Sb₂S₃ phase transition and a relatively compact L_π of 38 μm . Since

this is the first experiment to switch Sb_2S_3 electrically, we chose a conservative thickness of 20 nm. Considering the good switching behavior observed in our experiment, a thicker Sb_2S_3 could be used in future experiments to provide even more compact devices. The largest thickness of Sb_2S_3 films that could be switched completely require more experimental exploration.

3.2.2 Sb_2S_3 -based silicon asymmetric directional coupler

The asymmetric directional coupler is designed using the Lumerical Mode simulator and the coupled-mode theory. The idea has been depicted in the main text and the literature^{58,59,144}. Figure 3.4(a) and (b) show two main optimization steps: (i). find the Sb_2S_3 -loaded waveguide width with a fixed Sb_2S_3 thickness so that it is phase matched with a bare SOI waveguide; (ii). obtain a high transmission at the bar port when switching the Sb_2S_3 by optimizing the gap between two waveguides to allow the coupling length in the bar state to be an even multiple of the coupling length in the cross state¹⁴⁴. Unlike the 1×2 coupler in ref¹⁴⁴, here we consider a 2×2 directional coupler, where light comes in from both input ports. To achieve an input port independent performance, the Sb_2S_3 -SOI hybrid waveguide and the bare SOI waveguide are phase matched when Sb_2S_3 is in the crystalline phase. Intuitively, the light interacts with the slight loss of the Sb_2S_3 waveguide half of the L_c regardless of the input port in this configuration.

After accomplishing the optimization in the Lumerical MODE simulator, we ran a Finite Difference Time Domain (FDTD) simulation to verify the design, and the results are in Figure 3.4(c) - (f). The transmission spectra in Figure 3.4(c) and (e) show that a bar (cross) state is achieved by controlling the phase of Sb_2S_3 to amorphous (crystalline). At 1310 nm, the insertion loss is around 0.1 dB and 0.3 dB for the bar and cross state, respectively, and the extinction ratio is larger than 15 dB in both states. The higher insertion loss for the cross-state is mainly due to the slight material absorption of c- Sb_2S_3 . The inset in Figure 3.4(e) shows that our device performance is symmetric and independent of the input port. Figure 3.4(d) and (f) shows the field propagation profile corresponding to Figure 3.4(c) and (e). Again, we can verify the input-port independent performance.

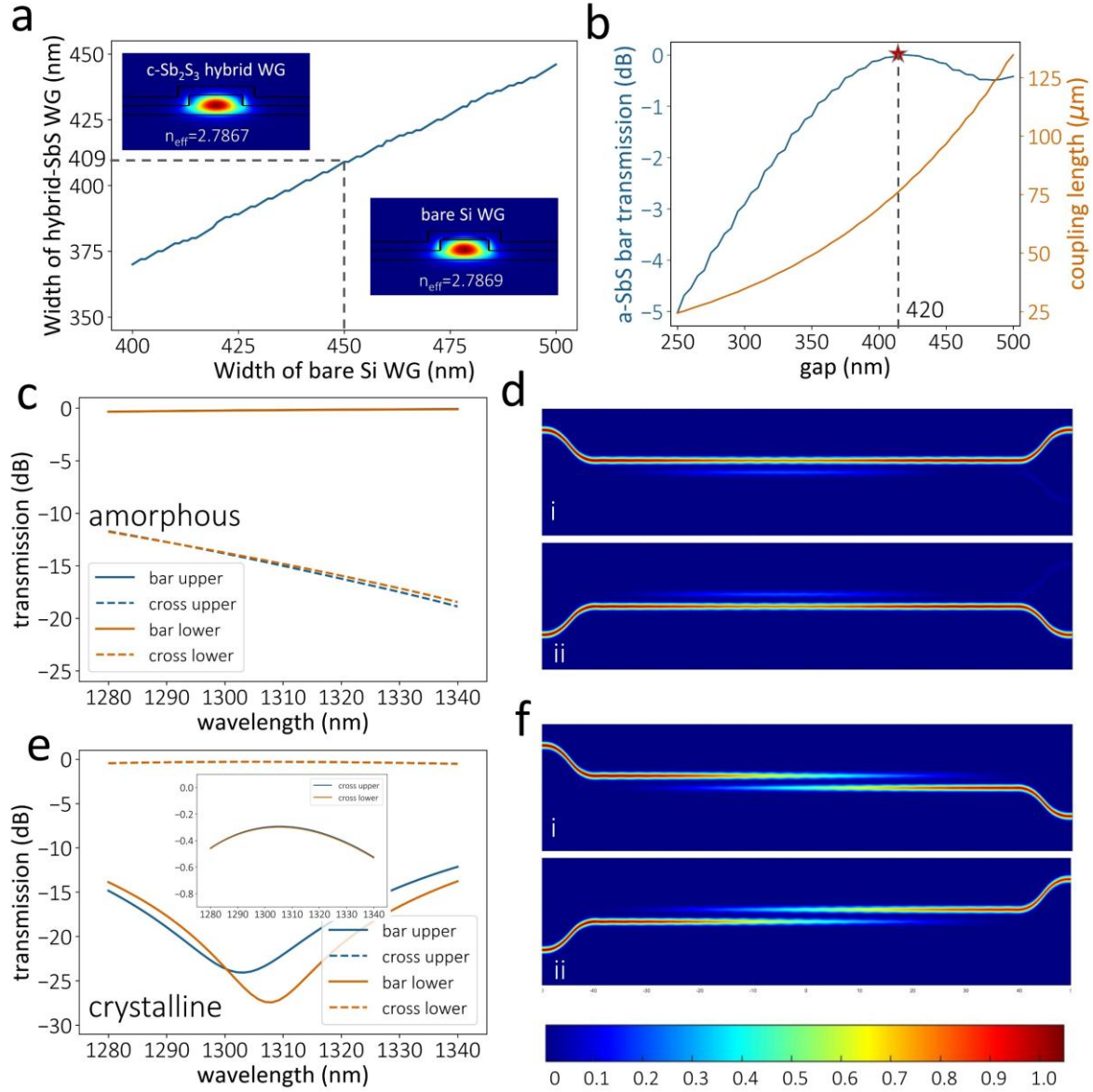


Figure 3.4: **Simulations for Sb_2S_3 -on-SOI 2×2 tunable directional couplers with low insertion loss and large extinction ratios.**

(a) Phase-matching widths for c- Sb_2S_3 -SOI and bare SOI waveguide. The dashed gray line shows that a 450-nm-wide bare SOI waveguide is phase matched with a 409-nm-wide c- Sb_2S_3 -SOI waveguide. Their mode profiles are shown in the insets with a similar effective index, indicating good phase matching. **(b)** The gap (blue) is optimized to maximize bar port transmission when the Sb_2S_3 is switched into its amorphous phase. The coupling length L_c for the cross state (orange) is also obtained based on the MODE simulation and coupled-mode theory. An optimal gap of 420 nm is picked, corresponding to $L_c \approx 79 \mu\text{m}$. **(c - f)** FDTD simulation results. (c, e) Transmission spectrum and (d, f) field profile for (c, d) amorphous- and (e, f) crystalline- Sb_2S_3 . (i) and (ii) show the field profile when inputting light from the upper and lower port, respectively. The inset in (e) shows an input-port independent performance for the cross-state.

On the contrary, if the waveguides are phase matched for a-Sb₂S₃, the loss would be much higher when light inputs from the Sb₂S₃ waveguide. Figure 3.5 shows the simulated spectrum of an optimized design, where 20-nm a-Sb₂S₃ is phase-matched with a bare SOI waveguide. As shown in the zoomed-in bar transmission plot in Figure 3.5(b), a difference of 0.3 dB between two input ports is observed when Sb₂S₃ is in its crystalline phase. This seemingly slight asymmetry could lead to undesired, unbalanced optical response for different light paths in a large-scale PIC system.

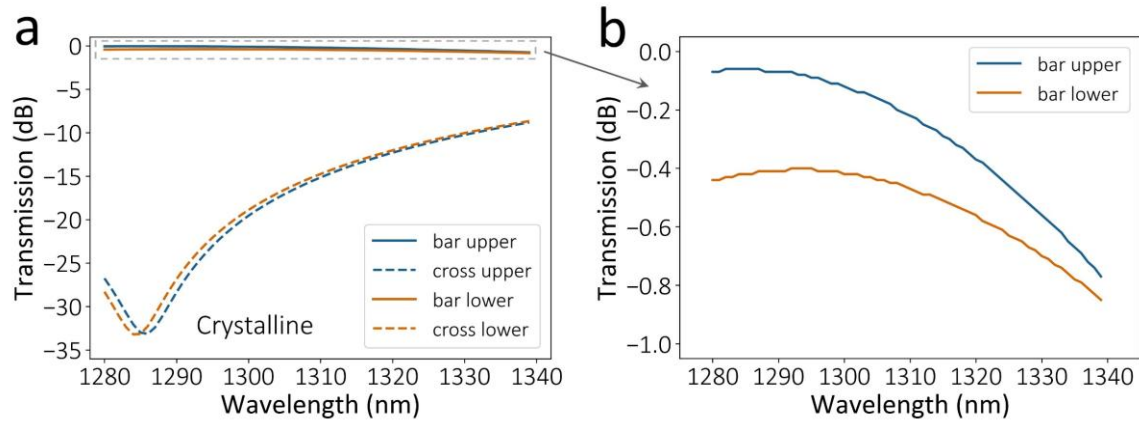


Figure 3.5: Phase matching a-Sb₂S₃-SOI waveguide with bare SOI waveguide results in an asymmetric (input port dependent) bar state when switching the Sb₂S₃ to its crystalline phase.

(a) Transmission spectrum for c-Sb₂S₃. **(b)** Zoomed in transmission spectrum at the bar port shows a transmission difference of 0.3dB between two input ports.

We adopted the relatively thin Sb₂S₃ with 20 nm thickness to ensure a complete phase transition. However, such a thin PCM layer provides limited tunability, resulting in a large device footprint. Fortunately, we note the slow crystallization speed of Sb₂S₃ could potentially enable a much thicker PCM layer to crystallize, which will shrink the device size. Using the same design methodology, we numerically designed asymmetric directional couplers with Sb₂S₃ thickness ranging from 30 nm to 50 nm in Table 3. Remarkably, the designed directional coupler with 50-nm-thick Sb₂S₃ shows a significantly reduced coupling length ($\sim 34 \mu\text{m}$).

Table 3: Performances of Sb₂S₃ directional couplers using different Sb₂S₃ thicknesses

t_{SbS} (nm)	W_b (nm)	W_h (nm)	gap (nm)	L_c (μm)
20	450	409	420	79
30	450	395	370	55
40	450	383	330	41
50	450	373	305	34

Note: t_{SbS} , W_b , and W_h represent the Sb₂S₃ thickness, and widths of bare SOI and hybrid Sb₂S₃-SOI waveguide, respectively.

3.3 Fabricated devices and characterization results

The silicon photonic devices were designed to operate at the telecommunication O-band (1260 – 1360 nm) and fabricated on a standard silicon-on-insulator (SOI) wafer with 220 nm silicon and 2 μm buried oxide. The 500-nm-wide waveguides are fabricated by partially etching 120-nm silicon. We then deposited 450-nm-wide Sb₂S₃ onto the SOI chip via sputtering. The slightly smaller width than the waveguide is to compensate for electron beam lithography (E-beam) overlay tolerance. The Sb₂S₃ films are electrically controlled via on-chip silicon PIN micro-heaters^{59,95}. The p⁺⁺ and n⁺⁺ doping regions were designed 200 nm away from the waveguide to avoid free-carrier absorption loss⁹⁵, indicated in the scanning electron microscope (SEM) images with false colors in Figure 3.6(c), Figure 3.9(c), and Figure 3.11(c). The Sb₂S₃ stripes are encapsulated with 40 nm of Al₂O₃ grown by atomic layer deposition (ALD) under 150 °C. This conformal encapsulation is critical to prevent Sb₂S₃ from oxidation and thermal reflowing and is essential to attain high endurance. To show that our Sb₂S₃-clad silicon photonic platform is versatile and compatible with most PIC components, we demonstrate three widely used PIC components: (1) a micro-ring resonator to show low-loss tuning of cavities, (2) a balanced MZI to demonstrate a full π phase shift and a broadband operation, and (3) an asymmetric directional coupler to create a compact programmable unit.

The fabrication process of the designed Sb₂S₃ on SOI devices is similar to what we described in Section 2.6 and we shall not repeat it in too much detail here.

3.3.1 Trench effect of PCM liftoff

Notably, it was found that a narrow resist trench for Sb_2S_3 deposition and liftoff leads to a reduced Sb_2S_3 thickness than blanket Sb_2S_3 deposition. This could be attributed to that part of Sb_2S_3 was blocked by the resist due to a deep trench. We fabricated a chip with different patch width (300, 400, 500 nm) and measured the thickness after Sb_2S_3 liftoff. The measured results (Table 4) show a reduction factor of around 0.5 compared to blanket deposition. We also measured the widths of the Sb_2S_3 widths which agree reasonably well with the Ebeam defined widths. Since this is not the main interest of this measurement, we only measured part of the Sb_2S_3 stripes, and the ones not measured are denoted as '- '.

Table 4: Sb_2S_3 thickness reduces after liftoff measured by AFM (Unit: nm)

Deposited width	Width after Liftoff	Deposited thickness	Thickness after liftoff
300	373	30	13.8
300	354	30	14
400	471	30	16.9
400	471	30	17
300	-	40	16.4
400	413	40	19.5
300	-	50	21
400	-	50	26
400	471	50	25.9

3.3.2 Nonvolatile micro-ring switch integrated with Sb_2S_3 phase shifter

The characterization setup is similar to the one we described in Section 2.7.1, and we do not repeat it here. We deposited 10- μm -long, 20-nm-thick Sb_2S_3 on a micro-ring resonator with 30 μm radius, shown in Figure 3.6(a)-(c). The free spectral range (FSR) is ~ 2.42 nm in Figure 3.6(d), and the bus-ring gap is 280 nm to achieve a near-critically coupled device. We switched the as-deposited a- Sb_2S_3 to c- Sb_2S_3 on the micro-ring resonator by applying three 1.6 V, 200-ms-long pulses with ~ 3.4 mJ energy (or SET pulses) separated by 1 second and then re-amorphized the material via three 7.5 V, 150-ns-long pulses with ~ 56 nJ

energy also separated by 1 second (RESET pulses). The unit energy density (energy/total Sb_2S_3 volume) for switching Sb_2S_3 is then estimated as $0.6 \text{ fJ}/\text{nm}^3$ ($38 \text{ pJ}/\text{nm}^3$) for amorphization (crystallization). We note that the 200-ms-long SET pulse is indeed significantly longer than other reported PCMs, such as GST ($50 \mu\text{s}^{95}$ or $100 \mu\text{s}^{107}$) and Sb_2Se_3 ($5 \mu\text{s}^{106}$ or $100 \mu\text{s}^{107}$), and causes a large crystallization energy and energy density. But we found that the SET pulse duration can be reduced to around $100 \mu\text{s}$ after the first few cycles. Therefore, the crystallization energy is reduced to $\sim 1.7 \mu\text{J}$ ($19 \text{ fJ}/\text{nm}^3$) after the initial conditioning, comparable to other PCMs^{95,106}. With the $100 \mu\text{s}$ crystallization pulse condition, this device could be operated at $\sim \text{kHz}$ speed for a complete SET/RESET cycle. The slow crystallization, however, can allow amorphizing a large volume of Sb_2S_3 . Figure 3.6(d) shows a resonance shift of $\sim 0.394 \text{ nm}$ upon switching the $10 \mu\text{m}$ Sb_2S_3 from the a- (blue) to the c-phase (orange), corresponding to a π -phase shift length L_π of $\sim 30.7 \mu\text{m}$, significantly shorter than the 1-millimeter L_π of ferroelectric non-volatile phase shifter¹⁴⁹. Our simulation results show a change in effective index $\Delta n_{eff} \approx 0.018$ between a- and c- Sb_2S_3 in Figure 3.3, which gives a theoretical π phase shift length of $L_\pi = \frac{\lambda_0}{2\Delta n_{eff}} = 36.4 \mu\text{m}$. The slightly shorter L_π in the experiment can be attributed to a slightly thicker Sb_2S_3 deposited. The SET and RESET processes were repeated for 10 cycles. The shift in resonance is highly repeatable, as suggested by the slight standard deviation in Figure 3.6(d). The excess loss from a- Sb_2S_3 is negligible¹⁴⁶, and in c- Sb_2S_3 -clad waveguides the loss is estimated to be $0.024 \text{ dB}/\mu\text{m}$ ($0.72 \text{ dB}/\pi$), which is three times larger than our simulation result ($0.26 \text{ dB}/\pi$). We attribute this excess loss to the scattering from the Sb_2S_3 thin film due to non-uniform deposition/liftoff and local crystal grains in c- Sb_2S_3 . We verified that the loss due to mode mismatch at the transition between the bare silicon waveguide and the Sb_2S_3 -loaded waveguide is small ($\sim 0.013 \text{ dB}/\text{facet}$), consistent with the fact that the thin Sb_2S_3 film should not significantly change the mode shape.

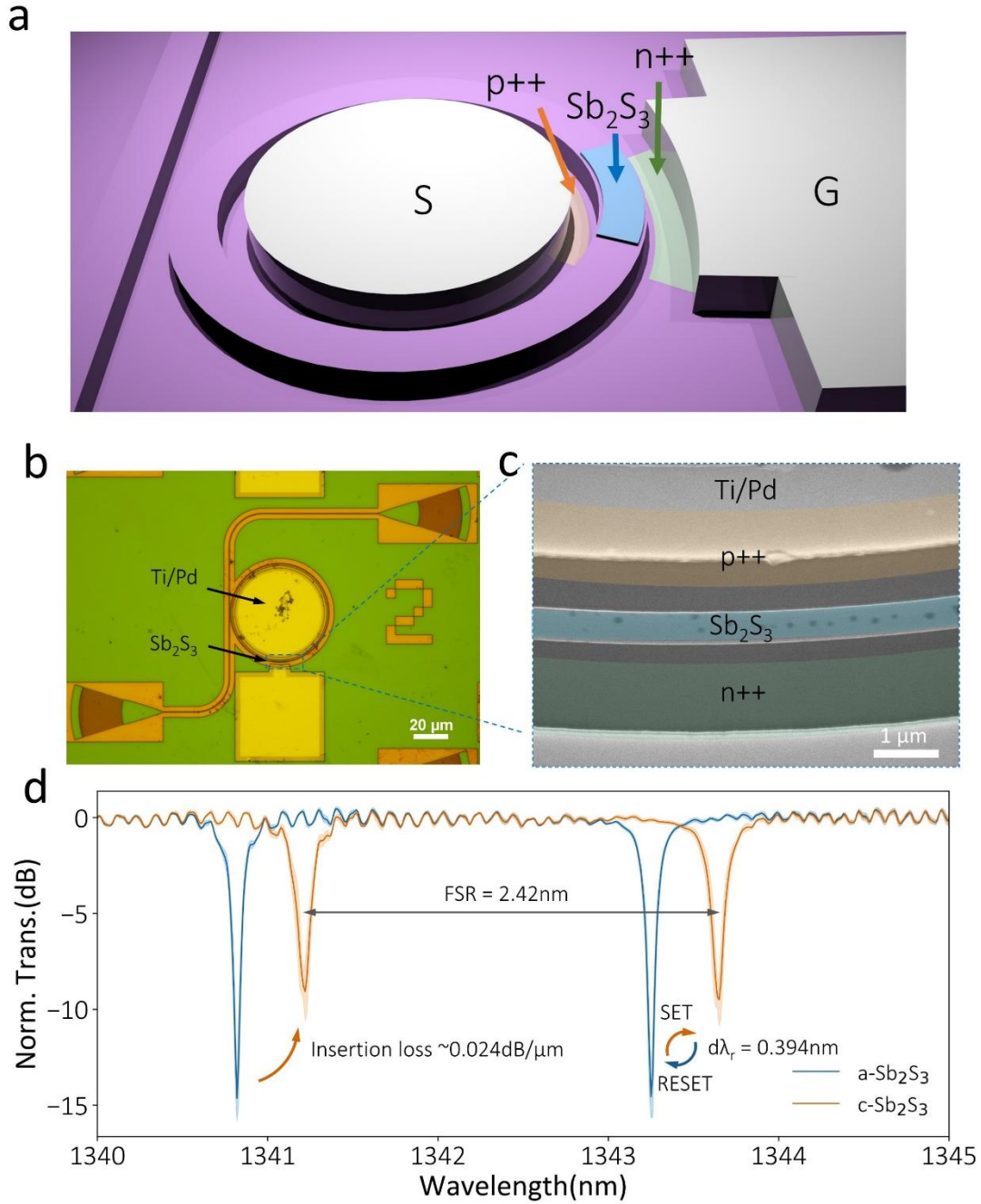


Figure 3.6: A high-Q ring resonator loaded with 10 μm long 20-nm-thick Sb_2S_3 .

(a) Schematic of the device (the encapsulation ALD Al_2O_3 layer is not shown), (b) optical, and (c) Scanning-Electron Microscope (SEM) images of the micro-ring resonator. The Sb_2S_3 thin film, n^{++} , and p^{++} doped silicon regions are represented by false colors (blue, orange, and green, respectively). (d) Measured micro-ring spectra in two phases (SET: three 1.6 V, 200-ms-long, 3.4 mJ pulses to change Sb_2S_3 to the crystalline state; RESET: three 7.5 V, 150-ns-long, 56 nJ pulses to change Sb_2S_3 to the amorphous state). The spectra are averaged over ten cycles of reversible electrical switching, and the shaded area shows the standard deviation. Norm. Trans. Stands for normalized transmission, normalized to a reference waveguide on the same chip.

In our experiment, single pulses could not trigger a reliable, complete phase transition. We sent in a single pulse for SET/RESET. The final state shows a significant variation in Figure 3.7(a). This could be attributed to multiple crystalline phases and incomplete thermal process due to the relatively thick Sb_2S_3 . We tackled this issue by sending two or three pulses to trigger a complete phase transition. The resulting transmission spectra of another ring resonator is shown in Figure 3.7(b). This multi-pulse switching scheme achieved a much more consistent performance across ten cycles. We emphasize that this behavior is distinctly different compared to GST or Sb_2Se_3 , where we were able to actuate the phase transition under a single shot, in a very similar PIC. While we provided a hypothesis for such behavior, more material studies are warranted to explain the behavior.

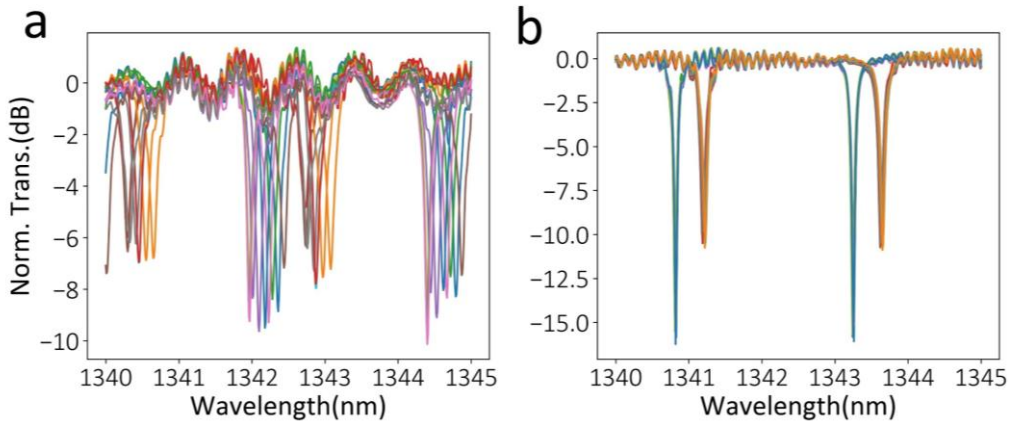


Figure 3.7: **Single SET (RESET) pulses could not reliably trigger complete crystallization or amorphization.**

(a, b) Transmission spectra of a ring resonator switched with (a) single SET(RESET) pulses and (b) three identical SET(RESET) pulses with one-second intervals. Different colors represent different experiments.

3.3.3 Nonvolatile Mach-Zehnder switch integrated with Sb_2S_3 phase shifter

A 120-nm partially etched MMI was designed using the Lumerical Eigen-Mode Expansion (EME) Method. The design was further tweaked and verified with 3D FDTD simulations. The optimized multimode device parameters are annotated in *orange* in Figure 3.8(a). Figure 3.8(a) and (b) show the

simulated electric field propagation profile and the transmission spectra at both output ports. The optimized MMI exhibits an insertion loss < 0.1 dB at 1310 nm and a 1-dB bandwidth > 60 nm, as shown in Figure 3.8(b). The measured transmission spectrum is presented in Figure 3.8(c). The slight spectral fluctuation (~ 0.1 dB) is attributed to the interference between back-reflected light at the interface between the single mode tapers and the multimode region.

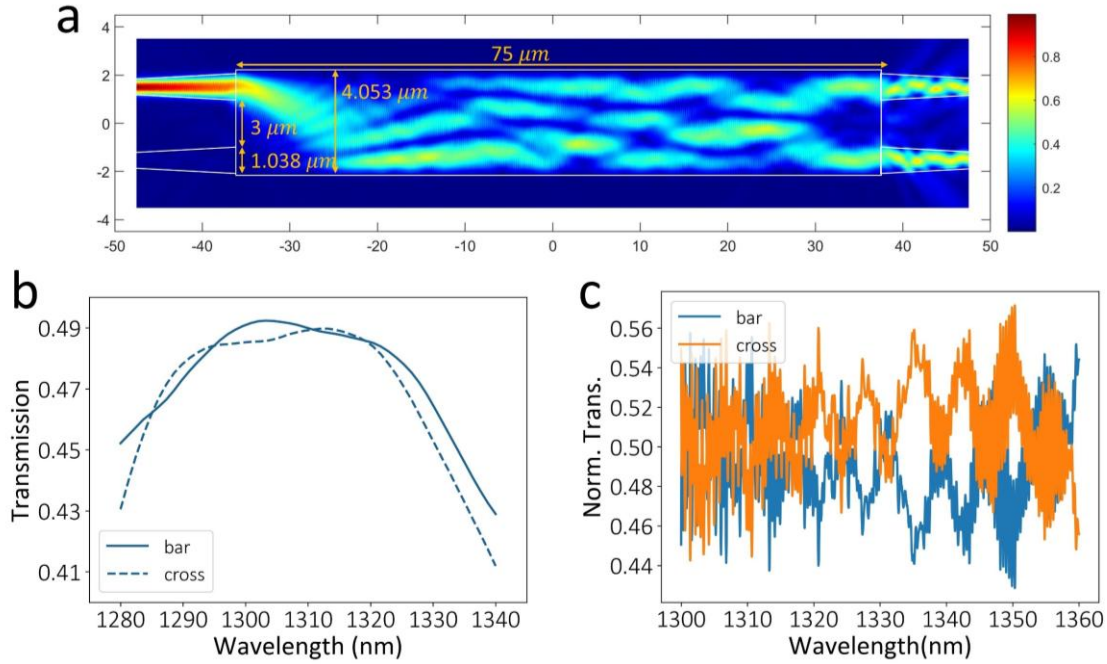


Figure 3.8: **Low-loss 50:50 multimode interferometer (MMI) at 1310 nm.**

(a) Field profile and (b) transmission spectrum using FDTD simulation. The white dotted line outlines the device shape. (c) Measured transmission spectrum of the fabricated device.

Figure 3.9(a)-(c) shows a balanced MZI with the 50:50 MMI in Figure 3.9(d) and both arms covered with 30- μm -long 20-nm-thick Sb_2S_3 , which operates at wavelengths between 1,320 nm and 1,360 nm. Initially, the light comes out mainly from the bar port with an extinction ratio of ~ 13 dB in Figure 3.9(e). The light comes out from the bar port instead of the cross port in this balanced MZI, which can be explained by the random phase errors between two arms due to fabrication imperfections, especially in the S-bend and PCM segments. One can overcome these fabrication imperfections by exploiting a wider waveguide to

improve fabrication robustness¹⁵⁰. Alternatively, this random phase error can be post-fabrication trimmed using Sb₂S₃, as we show later in Section 3.5.

We measure the current-voltage (IV) response on an MZI arm with a doped region length of 30 μm by applying a voltage from -0.5 to 1.0 Volt in Figure 3.10(a). The measured IV-curve shows a typical rectified shape and has a turn-on voltage of around 0.8 V and resistance of 50 Ω . The Sb₂S₃ on one arm was switched by two 1.7 V, 200-ms SET electric pulses with an energy of 11.6 mJ (density: 42 pJ/nm^3) to provide a full π phase shift. An 8.1 V, 150-ns short RESET electric pulse with an energy of 197 nJ (density: 0.73 fJ/nm^3) switched the device back to the initial state. Figure 3.9(e) and (f) show the transmission spectra normalized to a reference waveguide when the Sb₂S₃ film is in the amorphous and crystalline phases, respectively. The c-Sb₂S₃ displays a complete spectrum flip, showing a bar state with an extinction ratio of 15 dB.

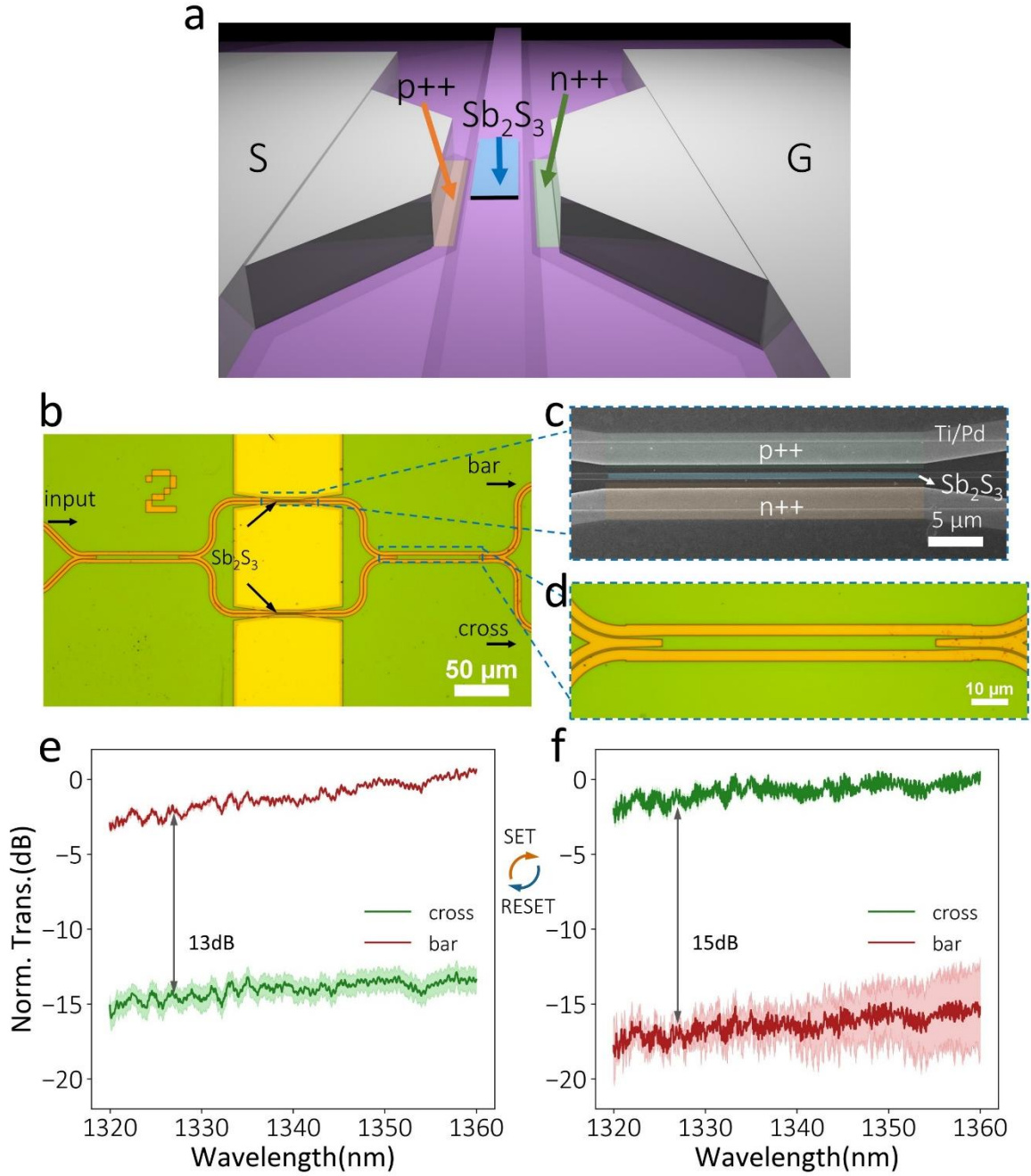


Figure 3.9: A Mach-Zehnder interferometer with both arms covered with 20-nm-thick Sb_2S_3 .

(a) Sb_2S_3 phase shifter schematic (the encapsulation ALD Al_2O_3 layer is not shown). (b) Optical and (c) SEM images of the Sb_2S_3 phase shifter. (d) Optical micrograph of the 50:50 splitting ratio multi-mode interferometer. (e, f) Transmission spectra at both bar and cross ports for (e) a- Sb_2S_3 (RESET: an 8.1 V, 150 ns, 197 nJ pulse) and (f) c- Sb_2S_3 (SET: two 1.7 V, 200 ms, 12 mJ pulses). The green and red lines represent the measured transmission at cross and bar ports. The shaded region indicates the standard deviation of transmission for 5 cycles of measurements.

The Sb_2S_3 phase shifter in an MZI was switched reversibly by alternatively applying SET and RESET pulses. We note this cyclability test was performed with a single pulse scheme, so a significant variation was observed. In the later characterization for asymmetric directional coupler, we instead used three pulses that were used for each amorphization or crystallization, providing much better repeatability. Yet, we found 100 consecutive switching events in Figure 3.10, where the device was switched with a high extinction ratio of ~ 15 dB.

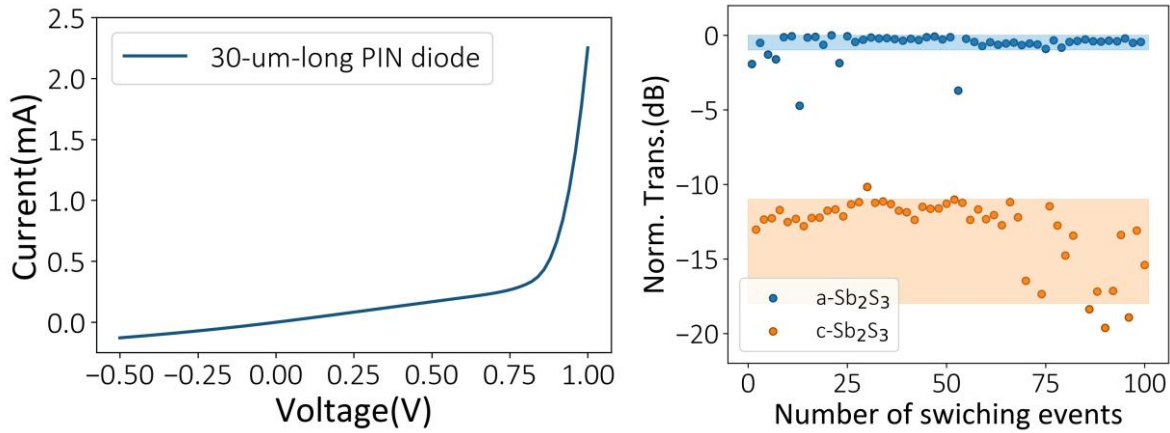


Figure 3.10: Extra measurement results on MZIs.

(Left) I-V characteristics of the 30- μm -long PIN diode, showing a turn on voltage of 0.8 V and a resistance of 50 Ω . **(Right)** The Sb_2S_3 -based phase shifter in an MZI is experimentally switched between amorphous (blue) and crystalline (orange) phases for 100 switching events. Each switching event was triggered with a single pulse.

3.3.4 Asymmetric directional coupler silicon switch with Sb_2S_3

We also designed and fabricated a compact asymmetric directional coupler (coupling length $L_c \approx 79$ μm), as shown in Figure 3.11(a)-(c). The coupler consists of two waveguides with different widths. The narrower 409-nm-wide waveguide (hybrid waveguide) was capped with 20-nm-thick Sb_2S_3 and designed to allow phase match with the wider 450-nm-wide waveguide (bare waveguide) for c- Sb_2S_3 ¹⁴⁴. As such, the input light could completely couple to the cross port in one coupling length. Once Sb_2S_3 is switched to the amorphous state, the effective index of the hybrid waveguide changes while the bare waveguide remains the same. The resulting phase mismatch changes the coupling strength and coupling length. Then, co-

optimizing the gap and waveguide length permits a complete bar transmission. The unique c-Sb₂S₃ phase matching approach, instead of a-Sb₂S₃^{57,59,144,151}, allows a more symmetric performance regardless of the input port, crucial for a 2×2 device. If phase mismatch happens in the c-Sb₂S₃ state, the slight loss of c-Sb₂S₃ on one of the waveguides will result in different bar state insertion loss when the light goes from different input ports. We note that the 79- μm coupling length can be potentially reduced ($\sim 34 \mu\text{m}$) by depositing a thicker (50 nm) Sb₂S₃ to provide stronger refractive index modulation.

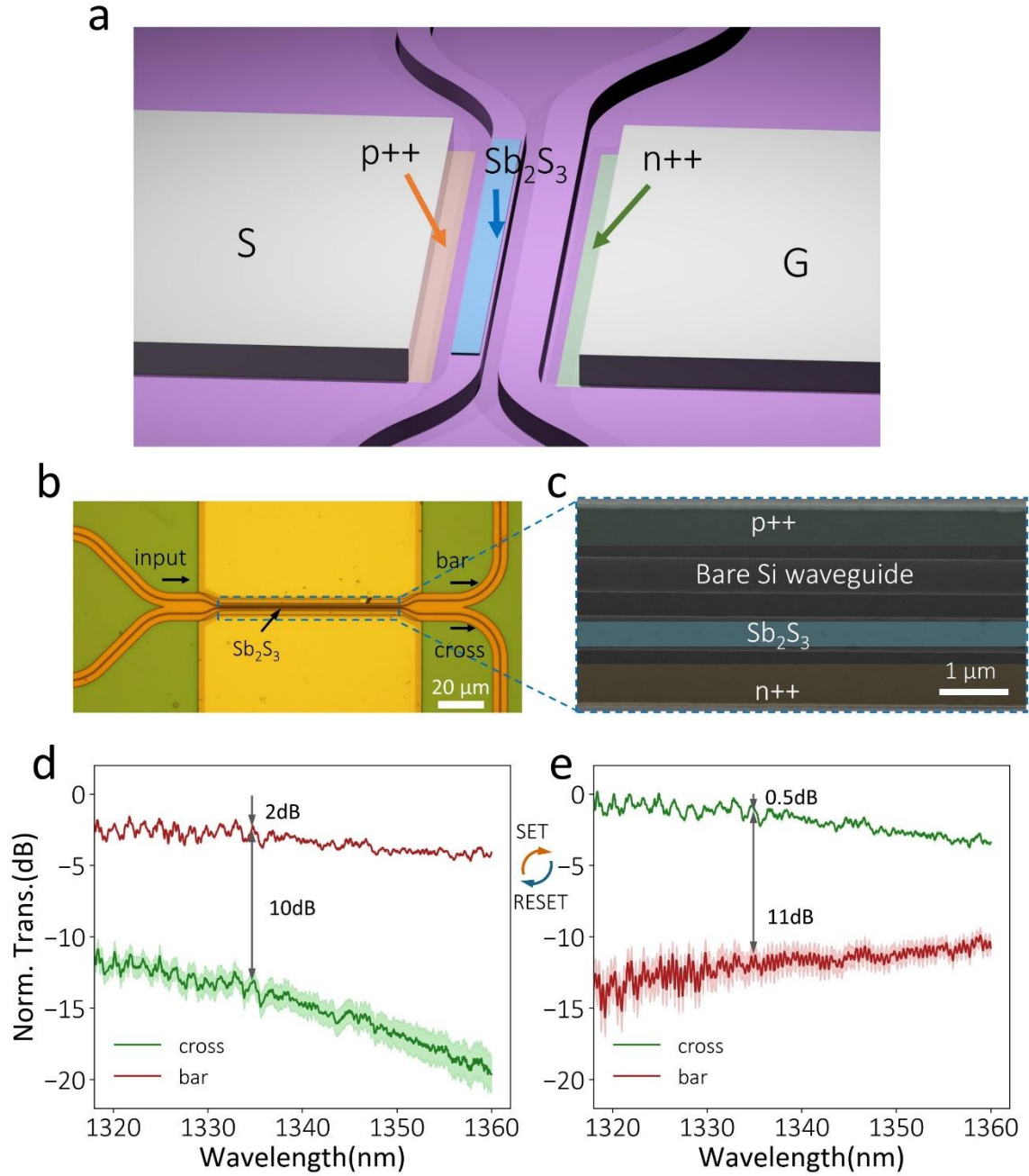


Figure 3.11: An asymmetric directional coupler with Sb_2S_3 -Si hybrid waveguide.

(a) Schematic (the encapsulation ALD Al_2O_3 layer is not shown), (b) optical, and (c) SEM images of the asymmetric directional coupler. (d, e) Transmission spectra at bar and cross ports for (d) a- Sb_2S_3 (RESET: three 9.6 V, 500 ns, 922 nJ pulses) and (e) c- Sb_2S_3 (SET: three 2.7 V, 200 ms, 29.2 mJ pulses). The result was averaged over five measurements, and the shaded region indicates the standard deviation.

Figure 3.11(d) and (e) show the transmission spectra for a- and c-Sb₂S₃, switched with three 9.6 V, 500 ns, 922 nJ RESET, and 2.7 V, 200 ms, 29.2 mJ SET pulses, respectively. The energy density for amorphization (crystallization) is 1.28 fJ/nm³ (40 pJ/nm³). The insertion losses are 2 dB (0.5 dB), and the extinction ratios are around 10 dB (11 dB) for a (c)-Sb₂S₃. The unexpected high insertion loss when the Sb₂S₃ is in an amorphous state can be attributed to several factors, including deviation of the gap size from the design, Sb₂S₃ overlay alignment error, or the cross-port grating coupler fabrication imperfection. To estimate the actual loss of the device, we apply the c-Sb₂S₃ loss extracted from the ring resonator to the simulation, which includes the crystal grain scattering loss, by matching the loss measured in the high-Q resonator (0.76 dB/μm) with MODE simulation. We obtained an extinction coefficient $\kappa' \approx 0.015$, compared to ellipsometry measurement result of $\kappa = 0.005$ at 1310 nm. We then estimate the actual loss of the asymmetric directional coupler using the new complex refractive index. Figure 3.12 shows the simulation results, where the insertion loss is around 0.85 dB, and the extinction ratio is 25 dB. This loss taking into consideration of the grain boundary scattering is similar to what we observed in device characterization, which emphasizes the importance of further optimizing the material for a smaller scattering loss by reducing grain size of crystalline PCMs¹⁵². We note that the amorphous Sb₂S₃ loss is very small in the experiment, so the initial simulation result still holds (0.1 dB insertion loss and 15 dB extinction ratio).

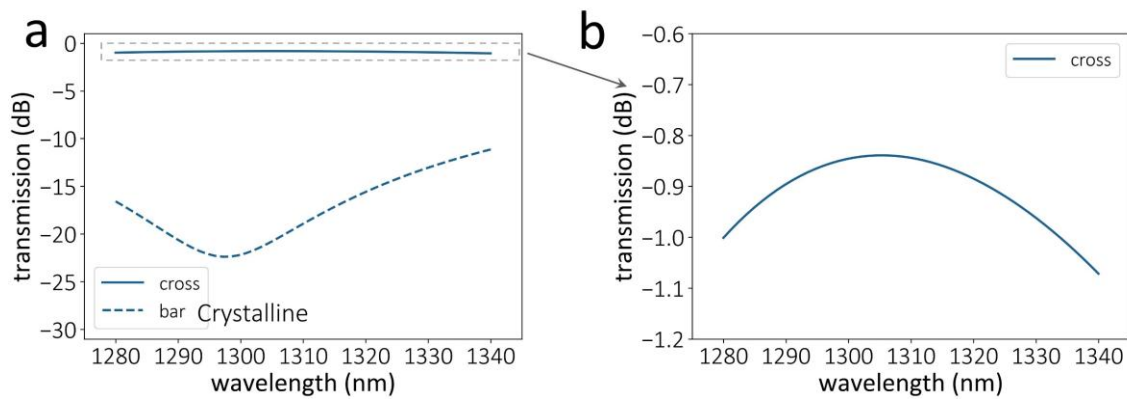


Figure 3.12: Simulated transmission spectrum for asymmetric directional coupler.

- (a) Simulation results with the ring resonator measured c-Sb₂S₃ loss, showing high extinction ratio > 20 dB.
- (b) Zoomed-in plot to show the insertion loss. The insertion loss increases from 0.3 dB to 0.85 dB due to the high material absorption loss used.

Figure 3.13 shows more than 1,600 switching events for the asymmetric directional coupler, a first demonstration of large-endurance electrical switching of Sb₂S₃ at the time of the work. We note that very few electrical controls of Sb₂S₃ had been experimentally demonstrated^{105,146} and no work had previously shown reversible electrical switching of Sb₂S₃. Limited by our measurement setup, we separately measured the cross and bar ports in Figure 3.13(a) and (b), respectively. The higher insertion loss (~1 dB) at around event 500 was due to optical fiber misalignment. We note that almost no performance degradation occurred at the end; hence, 1,600 switching events are not the limit of this device. We stopped the experiment at that point due to the long duration of the experiment. The cross-port transmission shows a relatively large variation for a-Sb₂S₃ (from ~ -15 dB to ~ -35 dB) in Figure 3.13(a), which was caused by incomplete amorphization or thermal reflow of the Sb₂S₃ film. Since the plot is on a logarithmic scale, such a large variation in a-Sb₂S₃ (due to higher transmission) is not visible in Figure 3.13(b).

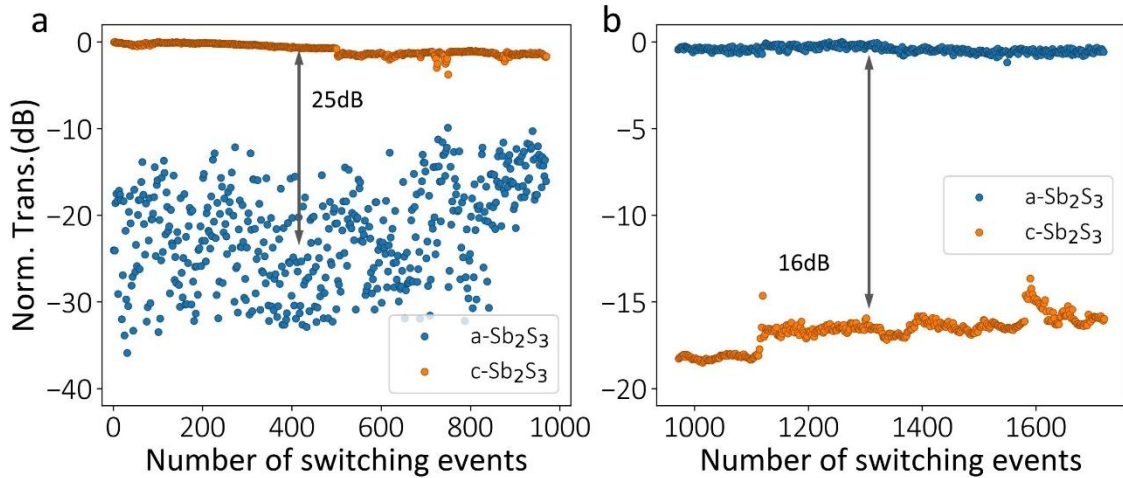


Figure 3.13: **Cyclability test for a-Sb₂S₃-based asymmetric directional coupler.**

Measured transmission at the (a) cross and (b) bar ports. The blue and orange scatterers represent the normalized transmission when Sb₂S₃ is in the amorphous and crystalline phases. The phase change condition is the same as in Figure 3.11. The device was switched for over 1,600 events with no significant insertion loss and performance degradation.

Experimentally, we observed a very slow Sb_2S_3 crystallization for the first time, where even 500 μs pulses could not trigger crystallization. The devices were then crystallized with DC voltage or pulses with very long durations such as 200 ms. This could be explained by the small enthalpy of fusion of Sb_2S_3 ($\sim 40.64 \text{ kJ/mol}^{153}$, compared to fusion enthalpy¹⁵⁴ of GST 625 J/cm^3 or $\frac{625}{\rho} M = \frac{625 \text{ J/cm}^3}{5.87 \text{ g/cm}^3} \cdot 1026.8 \text{ g/mol} = 109.3 \text{ kJ/mol}$, where ρ is the density¹⁵⁵ and M is the molar mass of GST), which necessitates a large critical nuclei size to overcome the crystallization energy barrier. After the first crystallization, however, the successive crystal growth process happens without any requirement for overcoming the energy barrier. We were able to see partial crystallization using much shorter 100- μs pulses, as shown in Figure 3.14. We note this slow crystallization guarantees larger volumes of Sb_2S_3 amorphized again without recrystallization and thus could be beneficial for photonic applications. In the next section, we experimentally show that indeed the amorphization could be triggered with very long pulses.

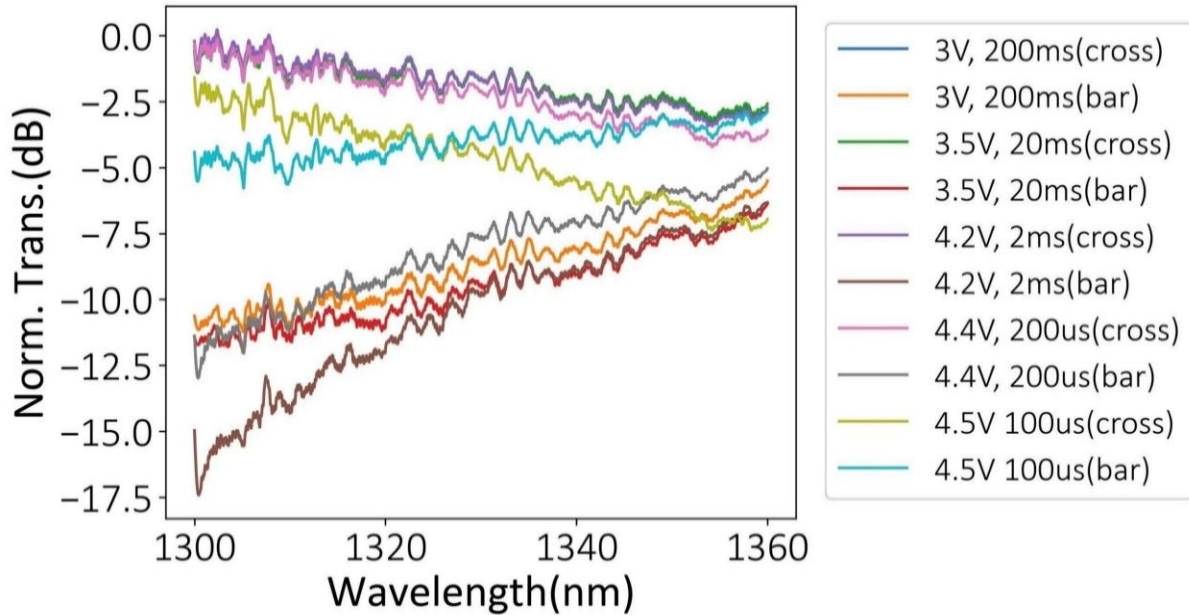


Figure 3.14: **The slow crystallization nature of Sb_2S_3 limits the pulse duration longer than 100 μs .**

The 100- μs -long pulses were not able to trigger complete crystallization even after the first time. We note again that during the first few cycles of crystallization, only pulses with even much longer duration, such as

200 ms, could trigger crystallization. This indicates the difficulty in forming initial Sb_2S_3 nuclei and the substantially faster rate of crystal growth compared with nucleation.

One appealing aspect of using "slow" PCMs, such as Sb_2S_3 , is that the slow crystallization process could avoid any unintentional recrystallization during the melt-quench process, hence could ensure the amorphization for a large volume of PCM. This capability of completely switching large volumes of PCMs is crucial in photonics, where the volume (typically orders of μm^3) are much larger than in electronic applications (typically orders of $(10\text{ nm})^3$) and takes precedence over the phase transition speed¹.

Here, we verify Sb_2S_3 's resistance to unintentional recrystallization by comparing the longest amorphization time of an asymmetric directional coupler to other reported PCM devices. Figure 3.15 shows that the Sb_2S_3 on the directional coupler could be amorphized under different pulse durations, ranging from 500 ns to 10 μs . A large degree of amorphization was observed even when we increased the pulse durations to 10 μs . This 10- μs pulse duration is much longer than in the reported GST^{59,107,111} ($< 200\text{ ns}$) or SbSe¹⁰⁶ ($< 1\text{ }\mu\text{s}$, but the thickness is 30 nm) switching experiments. This successful amorphization with long pulses supports that Sb_2S_3 is inherently more suitable for large volume amorphization because recrystallization is suppressed. Moreover, the long amorphization pulses relaxed the requirements of high voltage from $\sim 10\text{ V}$ down to 5V, showing a potential path towards CMOS compatible voltage levels (1~2 V).

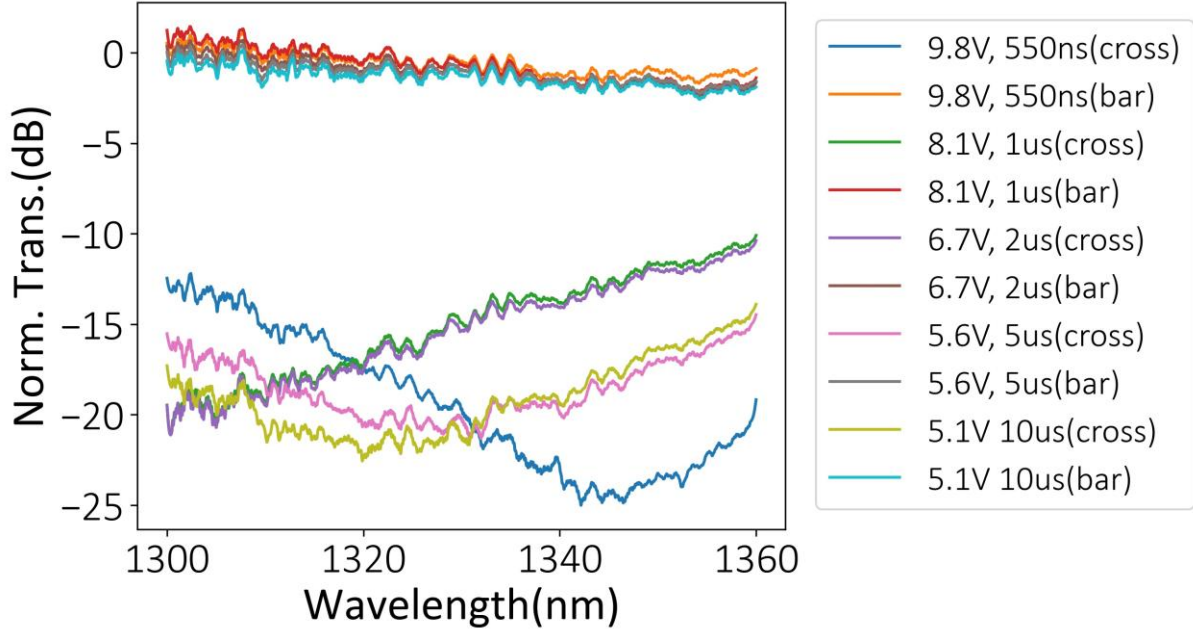


Figure 3.15: **Complete amorphization was triggered with relatively long, 10- μ s pulses because of the slow crystallization nature of Sb_2S_3 .**

High-level port (bar port) transmission is consistent among all the pulse conditions. The low-level port (cross port) transmission variation could be attributed to a tiny portion of the Sb_2S_3 not being switched completely, which could be potentially overcome by optimizing the heater design.

We switched the asymmetric directional coupler for 2,300 switching events. However, some drift in the optical measurement setup occurred and we only reported 1,600 cycles in Figure 3.13. Here, we compare the SEM image and the transmission spectrum before and after 2,300 switching events and explain the performance degradation or the transmission drifting. Figure 3.16(a) and (b) show the SEM images of Sb_2S_3 directional couplers before and after the cyclability test. We note that the black dots on the lower waveguide in Figure 3.16(a) are likely the crystalline Sb_2S_3 nuclei formed during the rapid thermal annealing. The rough Sb_2S_3 edge in Figure 3.16(b) indicates that switching the relatively large volume of the Sb_2S_3 stripe many times results in a distorted Sb_2S_3 . This is because the thin film always tends to minimize the surface energy during melt-quench process, hence leads to sinusoidal edge. This phenomena is known as Rayleigh instability of fluid motions¹⁵⁶. The result of such surface-energy-induced instability could be discrete circular patterns, having been used for advanced nano-fabrication¹⁵⁷. Therefore, to further improve the

endurance of our devices, one possible approach is to pattern the long Sb_2S_3 stripes to subwavelength gratings to ensure a lower initial surface energy and a low excess loss. We note that this subwavelength grating idea has been experimentally demonstrated in other works using GST^{92,158,159}, hence could be a future direction to improving the presented work.

The transmission spectra before and after the cyclability test are shown in Figure 3.16(c). A minor drift in the spectra could be attributed to the thermal reflowing, which changes the Sb_2S_3 shape, hence breaking the phase matching condition. Nevertheless, the device still shows a low insertion loss (< 1 dB degradation) and high extinction ratio (~ 15 dB).

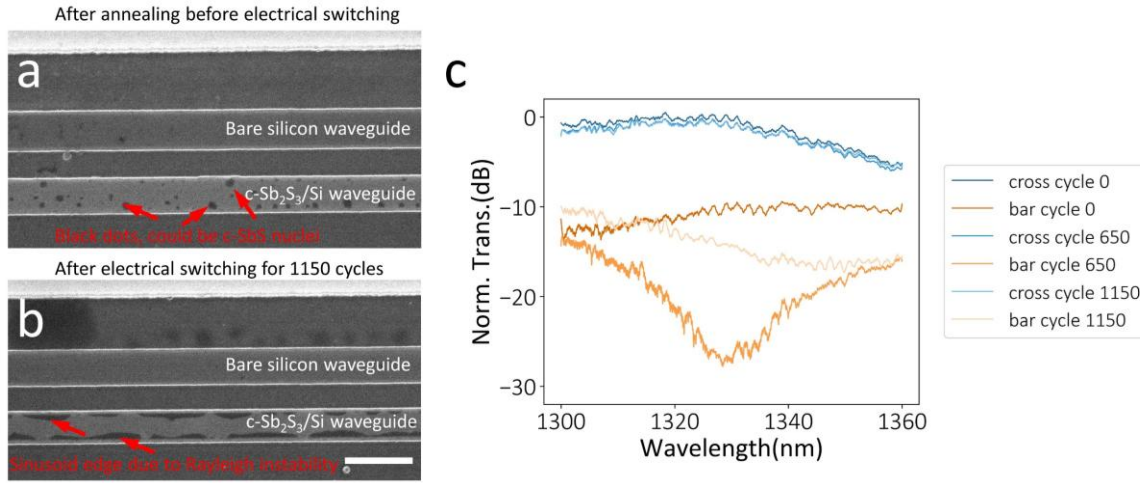


Figure 3.16: **Only slight device degradation occurred after 1,150 cycles (2,300 switching events), and the SEM images suggest it is due to thermal reflowing.**

(a, b) SEM images of a device after (a) a single rapid thermal annealing and (b) 1,150 cycles. Scale bar: 1 μm . (c) Transmission spectra before, in the middle, and at the end of the cyclability test. No significant performance degradation in the cross port (blue) was observed after switching the asymmetric directional coupler for more than 1,150 cycles. The variation in the bar port could be attributed to the change in Sb_2S_3 distribution due to the thermal reflowing or Rayleigh instability issue.

3.4 Multilevel 5-bit operation with dynamic electrical control

Our Sb_2S_3 -Si integrated structures further show a stepwise multilevel operation up to 32 levels with dynamic pulse control. In Figure 3.17(a), we show the multilevel transmission at both cross and bar ports

of an asymmetric directional coupler while sending in RESET 10 V, 550 ns, 1.1 μ J pulse every other second to amorphized the Sb_2S_3 . We started the experiment with “coarse” tuning, where unoptimized, identical pulses were sent to partially amorphize the c- Sb_2S_3 device to demonstrate multiple levels. The asymmetric directional coupler was originally in the “cross state” (red region). After one partial amorphization pulse, it was reconfigured into an intermediate state (orange region), where light comes out from both cross and bar ports. After six pulses, a complete “bar state” (green region) was achieved. We repeated this experiment five times for each port and plotted the average transmission levels and the standard deviation. The variation is attributed to the stochastic phase change process using electrical controls¹⁶⁰. Partial crystallization is briefly discussed in Figure 3.18. In the following experiments, we mainly focused on partial amorphization because of lower energy consumption and more operation levels with finer resolution.

Such stepwise multilevel operation by applying identical pulses is distinctly different from previously reported multilevel operations in GST^{59,95} and Sb_2Se_3 ^{106,107}, where different voltage amplitudes or pulse duration were used to access multiple levels during amorphization. The pulse-number-dependent behavior is quite counterintuitive: one expects that after the first amorphization pulse, the thin Sb_2S_3 film would have reached its new equilibrium phase. Moreover, since the thermal processes relax within 10 μ s, each pulse is independent due to the relatively long one-second interval. As a result, the subsequent identical and separated pulses should not further change the material phase. To understand the origin of the multi-level operation, we closely inspected four partially amorphized Sb_2S_3 devices under the microscope. We observed a few separate patches and a region that grew with more voltage pulses. As reported in some literature, one possibility could have been that a- and c- Sb_2S_3 have significantly different thermal conductivities and specific heat capacities. But we measured the thermal conductivities to be similar (a- Sb_2S_3 : 0.2 W/m/K; c- Sb_2S_3 : 0.4 W/m/K), and hence, we ruled out this as a possible explanation. We hypothesize that this unique behavior comes from Sb_2S_3 ’s multiple crystalline phases. Sb_2S_3 has at least two distinct crystalline phases¹⁶¹, which may differ in the amorphization conditions. The partial amorphization pulse can cause amorphization in the hottest region, but at the lower temperature region, it

may cause phase transition to the other crystalline phase. These regions get amorphized in subsequent pulses, resulting in multilevel operation.

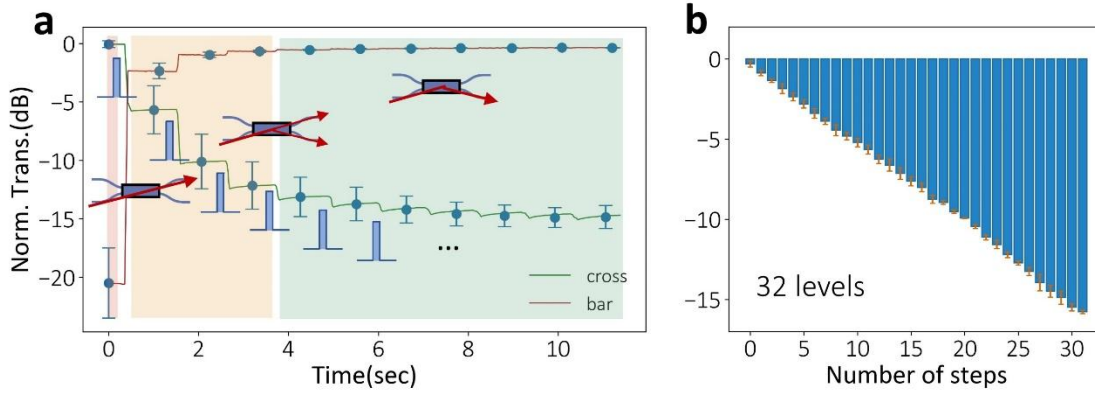


Figure 3.17: **A quasi-continuously tunable directional coupler based on multilevel Sb_2S_3 .**

(a) (Coarse tuning applying identical electrical pulses) Time trace measurement of the directional coupler when sending in an amorphization pulse (10 V, 550 ns, $1.1 \mu\text{J}$) each second. Green (red) curves represent cross (bar) transmission. The result is averaged over five experiments for each port, and the error bar shows the standard deviation. Depending on the pulses, a “bar”, “intermediate”, and “cross” state can be achieved as indicated by the red, orange, and green regions. **(b)** (Fine tuning using dynamically controlled near-identical electrical pulses) Normalized transmission at 1,340 nm at the bar port shows 5-bit operation (32 distinct levels), achieved by dynamically controlling the number, amplitude, and duration of pulses sent in (near-identical, 9.65 V $\sim$ 9.85 V, 550 ns, $1.02 \mu\text{J}$ to $1.06 \mu\text{J}$). A precise transmission level of 0.50 ± 0.16 dB per step and 32 levels were simultaneously achieved. The only slight difference between the target and achieved transmission demonstrates an on-demand operation. The error bars represent the standard deviation over five experiments.

An even finer multilevel operation was realized by monitoring the transmission level and dynamically changing the pulse conditions slightly. Here, we demonstrate on-demand 5-bit operation in a quasi-continuously tunable directional coupler, as shown in Figure 3.17(b). We dynamically controlled the partial amorphization pulses to have slightly lower, near-identical voltages (ranging from 9.65 V to 9.85 V) and obtained up to 32 levels. Figure 3.17(b) demonstrates 5-bit operation (32 distinct levels) with a target resolution of 0.5 dB per level step at 1,340 nm. We emphasize that dynamic control is necessary to mitigate the stochastic nature of electrically controlled PCMs¹⁶⁰, hence essential for a reliable many-level operation. Furthermore, the stepwise multi-level operation allows precise control by gradually approaching the desired

operation level, whereas the voltage or pulse duration dependent approaches result in unrepeatable multi-level operation, limited by PCM's stochastic nature. In Figure 3.17(b), a linear fit shows a slope of -0.50 dB per step and a standard deviation of 0.16 dB among five experiments, indicating a repeatable operation. While the 5-bit operation of GST was shown using laser pulses¹⁶², our demonstration is thus far the highest number of operating levels reported using electrical control in PCMs-based photonics. Moreover, our multilevel operation does not require sophisticated heater geometry engineering, such as the segmented doped silicon heater design¹⁰⁶, and solely relies on the unique phase-change dynamics of Sb_2S_3 . We note that the deviation from the ideal level mostly comes from the over-amorphization of the device, and the error can be reduced by incorporating a “backward” tuning using partial crystallization pulses. Implementing a more sophisticated heater geometry^{106,114} could also potentially increase the number of levels.

We also experimentally tested the partial crystallization of the device and multilevel operation, which is based on the growth-dominant nature of Sb_2S_3 crystallization process¹⁴⁴. By sending in relatively low voltage crystallization pulses (voltage 3.1 V, duration 200 ms, leading-edge 10 ms, falling edge 100 ms), we obtained partial crystallization performance in Figure 3.18. Such behavior could be explained by the growth-dominant nature of Sb_2S_3 ¹⁴⁴. The growth rate could be controlled by the temperature (pulse voltages); the total crystallization volume could be controlled with the duration of crystallization pulses. Further engineering the pulse parameters could potentially achieve more operation levels.

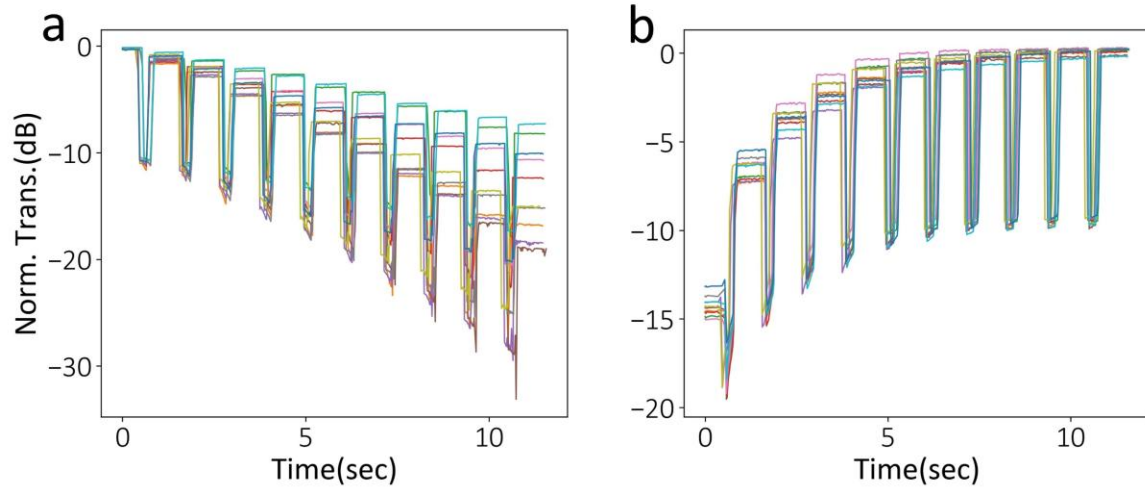


Figure 3.18: **Stepwise partial crystallization using identical, low amplitude, and long duration pulses with a one-second interval.**

Continuous time trace measurement at **(a)** bar and **(b)** cross port of an asymmetric directional coupler. The experiment was repeated 10 times at each output port, represented by different colors, and the multilevel characteristic occurred in all experiments.

We inspected devices at different intermediate levels under the microscope in Figure 3.19. One can see a gradual increase of amorphous Sb_2S_3 as the degree of amorphization increases. The amorphous Sb_2S_3 is not located precisely in the center of the long strip, where the temperature is the highest. We attribute this to the possible non-uniform doping profile and recrystallization of Sb_2S_3 near the center.

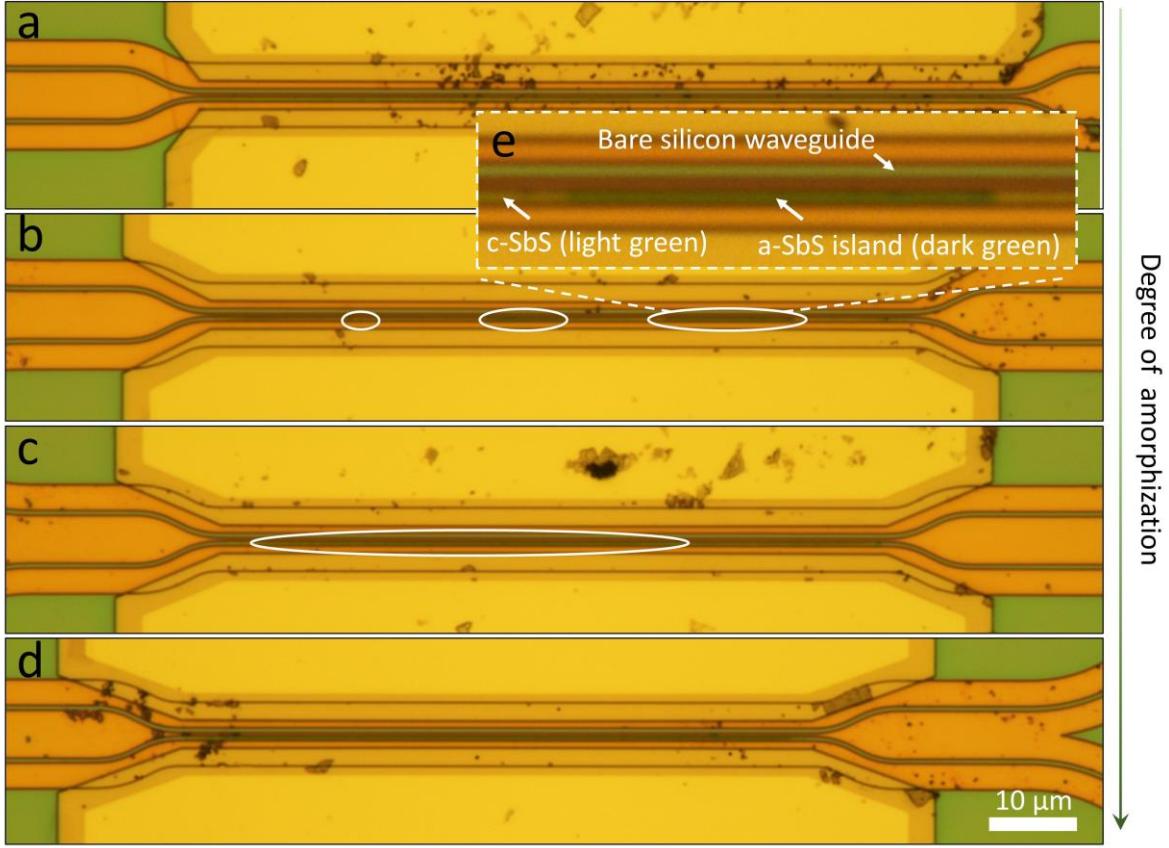


Figure 3.19: **Micrograph images for directional couplers in different intermediate levels.**

(a)-(d) The levels are set using identical pulses with one-second intervals. The degree of amorphization increases from. The dark (light) green regions on the lower waveguide are a(c)-Sb₂S₃. Islands of a-Sb₂S₃ (circled in red) are visible in (b) and (c) and continue to grow. (e) A zoom-in picture of the right-most circled region in (b). A clear boundary between a- and c-Sb₂S₃ is observed in the Sb₂S₃/Si hybrid waveguide (the lower waveguide).

3.5 Random phase error correction in balanced MZIs exploiting multilevel operation

Finally, exploiting the multilevel operation, we corrected random phase errors in a balanced MZI. A perfectly balanced MZI should initially be in an all-cross state. However, random phase errors due to fabrication imperfections can easily build up to a phase error of π , making the initial state unpredictable. Therefore, balanced MZIs usually require extra calibration¹⁵⁰. For example, Figure 3.20(a) shows the

transmission spectra of a phase error corrupted balanced MZI, indicating a high bar transmission. Both arms of the MZI are loaded with 40- μm -long Sb_2S_3 film to guarantee a phase tuning range of more than $\pm\pi$. The corrected MZI spectra by multilevel tuning of Sb_2S_3 are demonstrated in Figure 3.20(b), showing a pure “cross state” with a high extinction ratio of 24 dB. The trimming process is shown in Figure 3.20(c). We sent in a partial amorphization pulse (8.8 V, 150 ns, 232 nJ) every other second, which gradually increased the portion of amorphous Sb_2S_3 , resulting in quasi-continuous changes of the bar (blue) and cross (orange) transmission (at 1,340 nm). The correction finishes once a bar transmission minimum is reached, indicated by the red arrows in Figure 3.20(c), and the spectra in Figure 3.20(b) were then measured. Further pulses increase bar transmission because of the over-compensated phase. We performed the same experiment three times, indicated by different colored regions in Figure 3.20(c). Complete phase error correction was observed in all three instances, exhibiting excellent repeatability of our trimming process. Note that binary tuning cannot accomplish this task due to the random initial phase error. Even multilevel operations with limited discrete-level resolution can cause over- or under-corrected phase error, ultimately determining the trimming resolution. We highlight that this method requires zero static energy supply once the phase error is corrected, as the phase transition in Sb_2S_3 is non-volatile. Thanks to the relatively fine operation levels, slight over-tuning does not significantly affect the performance. The trimming resolution can be further improved using dynamically changed, near-identical electrical pulses, as shown in the previous Section. Moreover, if the phase error is over compensated, the device could be tuned back with partial crystallization pulses. In the future, our trimming process can potentially be fully automated by real-time adjusting the pulse numbers according to the measured transmission.

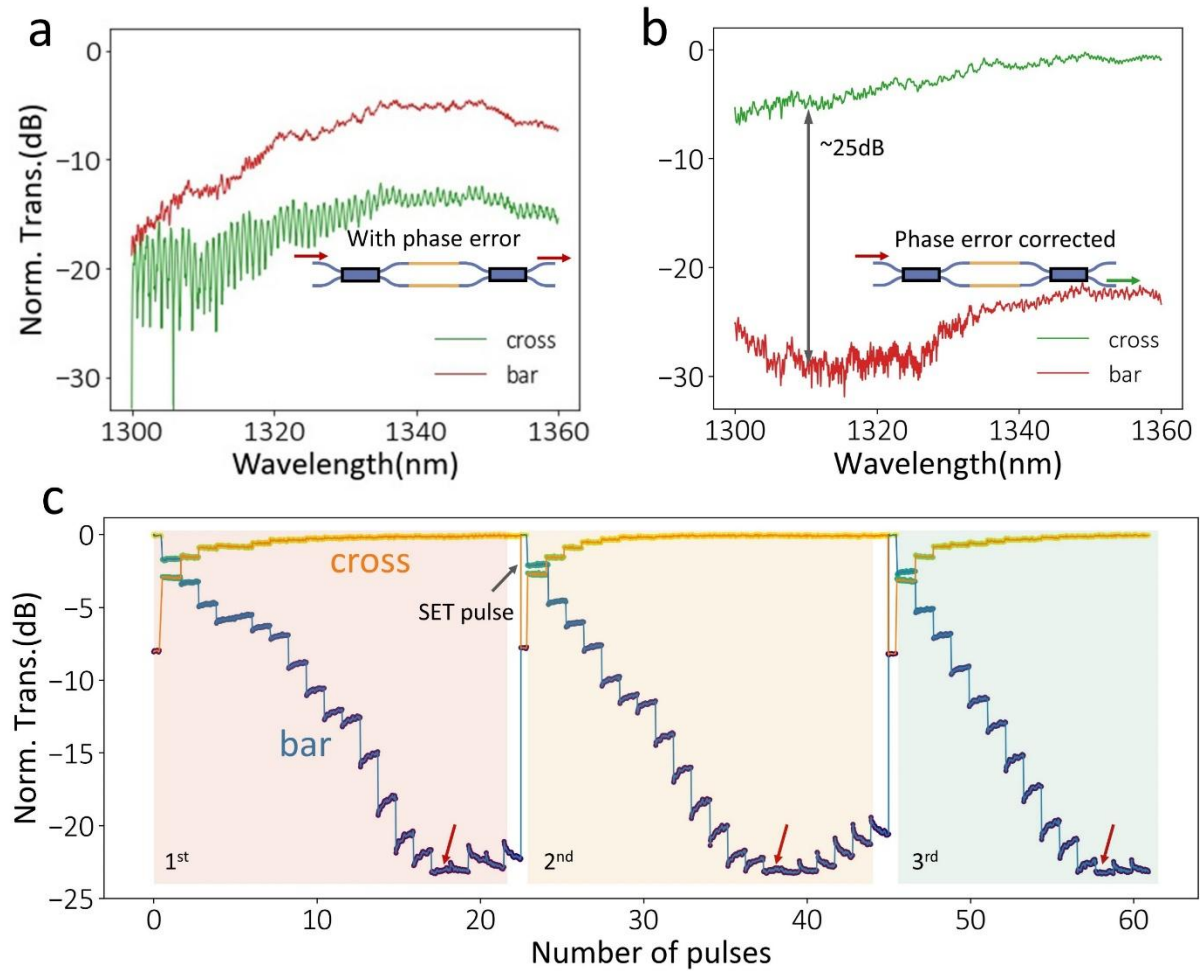


Figure 3.20: Random phase error correction in a balanced MZI based on the multilevel operation.

(a) Transmission spectrum of a balanced MZI with phase error due to fabrication imperfections. The red (green) line represents bar (cross) transmission. Light transmits mostly from the bar port instead of the ideal cross port.

(b) Transmission spectrum after the correction with 8.8 V, 150 ns, 232 nJ pulses. The device is in a “cross state” with a high extinction ratio of ~ 24 dB, indicating a phase-error-free device.

(c) Time trace measurement for three experiments shows the phase error correction step. The RESET pulses are sent at a one-second interval. As more pulses were sent in, the bar transmission continuously decreased until it reached a minimum of ~ -24 dB (red arrow), and then it went up. In all the experiments, the optimal error correction was obtained. The slight volatile increase (only visible when transmission is smaller than -12 dB) after each amorphization pulse happens over a much longer timescale than 10 μ s thermal relaxation time and could be attributed to a weak persistent photocurrent effect and requires more study. However, the transmission stabilizes before the next pulse. The blue (orange) represents bar- (cross-) transmission.

3.6 Discussion

Among the first few cycles (~ 50 cycles), sub-millisecond pulses failed to trigger the crystallization for Sb_2S_3 . We increased the voltage of a 500- μs pulse up to the material ablation voltage level without observing any crystallization. This suggests that the thermally induced Sb_2S_3 crystallization process is relatively slow, different from laser-induced crystallization¹⁰⁵, where a crystallization speed of tens of nano-second was demonstrated. We attribute this behavior to the difficulty in the initial nucleation. This hypothesis is supported by the fact that after the first few crystallization processes (conditioning), consecutive crystallization process could happen only at 100 μs , increasing the speed and lowering the energy by three orders of magnitudes. Hence, crystallization becomes easier after the initial nuclei/ defects are formed by the first few long thermal processes. We used 200-ms pulses in the reported experiments because the post-conditioning, shorter 100- μs pulse condition was identified later in our experiments.

However, this limited crystallization speed ($\sim \text{kHz}$) should not be considered as a problem, because of PCMs' main advantage of nonvolatility, and thus zero-static power consumption. This nonvolatile reconfiguration technology is complementary to the traditional high-speed modulators, and will find wide applications with infrequent programming needs, where high speed is not essential and the zero-static power is more important^{1,163}. Moreover, the slow crystallization speed could prevent unintentional recrystallization during long-pulse amorphization, which has a slower cooling rate. Since long-pulse amorphization means a smaller vertical thermal gradient, a thicker layer of Sb_2S_3 can potentially be switched completely. We verified that a pulse with 10 μs duration was able to trigger a large degree of amorphization, which is not possible in fast PCMs, such as GST. This capability of actuating phase transition in thicker films is useful in photonics, since switching a larger volume of PCMs is generally required to provide stronger modulation. In addition, such long amorphization pulse reduces the voltage from $>10 \text{ V}$ (for 500 ns pulses) to $\sim 5 \text{ V}$, showing a critical step toward CMOS-compatible operation levels (1~2 V). The voltage could be further reduced by designing the heater geometry to improve the thermal delivery efficiency¹⁶⁴, such as etching the

oxide beneath the silicon¹⁶⁵, adding thermal insulation¹⁶⁶ layers or using atomically thin 2D material heaters¹⁰⁷.

Chapter 4. PCM integration in high-volume silicon photonics¹⁶⁷

In the previous Chapters, we have shown the usage of low-loss PCMs can significantly improve the performance of optical components, such as lower insertion loss, higher extinction ratio, and capability of achieving multi-level operation. However, both GST and Sb_2S_3 components were fabricated through an in-house fabrication process, which involves e-beam lithography and is not suitable for high-volume fabrication. In this Chapter, we demonstrate a scalable platform harnessing the mature and reliable 300-mm silicon photonic fab, assisted by an in-house wide-bandgap PCM (Sb_2S_3) integration process. We show various non-volatile programmable devices, including micro-ring resonators, MZIs and asymmetric directional couplers, with low loss ($\sim 0.0044 \text{ dB}/\mu\text{m}$), large phase shift ($\sim 0.012\pi/\mu\text{m}$) and high endurance ($> 5,000$ switching events). Moreover, we showcase this platform's capability to handle relatively complex structures with multiple PIN diode heaters, each independently controlling an Sb_2S_3 segment. By reliably setting the Sb_2S_3 segments to fully amorphous or crystalline state, we achieved deterministic multilevel operation. An asymmetric directional coupler with two unequal-length Sb_2S_3 segments showed the capability of four-level switching, beyond cross-and-bar binary states. We further showed unbalanced MZIs with equal-length and unequal-length Sb_2S_3 segments, exhibiting reversible switching and a maximum of 5 ($N + 1, N = 4$) and 8 ($2^N, N = 3$) equally spaced operation levels, respectively. This work lays the foundation for future programmable very-large-scale PICs with deterministic programmability.

4.1 Reproducible zero-change integration of PCMs on silicon photonics from a 300-mm fab

The in-house fabrication process flow for integrating PCMs onto reticles from 300 mm Intel fab is shown in Figure 4.1. The initial pure silicon photonic chips were fabricated in a 300-mm semiconductor fab in Intel Corp., with silicon etch, doping, top oxide layer growth and metal vias growth included. We note that metallization was not available from the commercial manufacturing process at the time of tape-

out, but it is now possible with a thicker SiO₂ top cladding layer. We can include the metallization in the future once we develop and test the window opening process for thicker SiO₂ cladding.

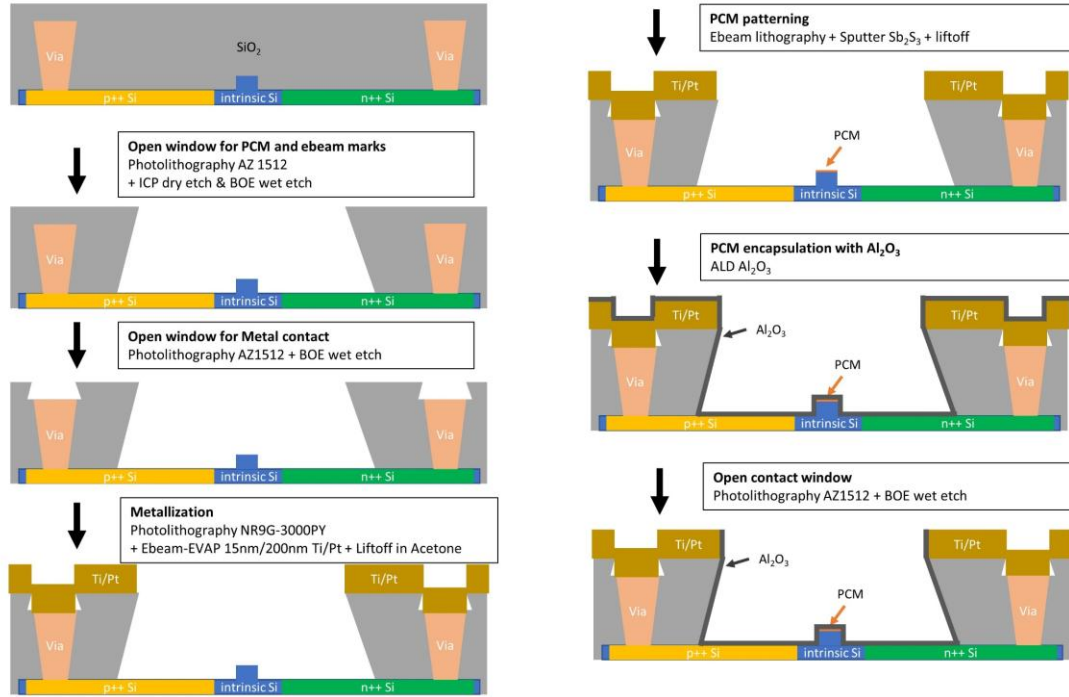


Figure 4.1: In-house fabrication workflow diagram.

Following is the detailed fabrication process as shown in Figure 4.1. The 300-mm wafer was then diced to 2.5 cm × 3.3 cm reticles for in-house Sb₂S₃ integration. The oxide window for Sb₂S₃ deposition on the intrinsic silicon waveguide was defined by an overlay using a direct write laser lithography tool (DWL, Heidelberg DWL66+) with adhesion-promoting primer HMDS (Yeild Engineering Systems, LP 3 A) and a positive tone resist AZ-1512 (~1 μm), followed by a partial dry etch of ~ 600 nm SiO₂ in a fluorine-based inductively coupled plasma etcher (ICP, Oxford PlasmaLab 100 ICP-18). The reticle was then immersed in 10:1 buffered oxide etcher (BOE) for 3~4 mins for complete SiO₂ removal. To form an ideal Ohmic contact, removal of the surface oxide (~100 nm) on the metal vias was done by a second DWL overlay and immersing the chips in 10:1 BOE for 75 seconds. The metal contacts were then immediately patterned by a third DWL overlay using a negative tone resist NR9G-3000PY. Metallization of Ti/Pt (15 nm/200 nm)

was done by electron-beam evaporation (CHA SEC-600) and lift-off. The Sb_2S_3 window was defined by JEOLJBX-6300FS 100 kV electron-beam lithography (EBL) using positive-tone resist double layer P(MMA-MAA) Copolymer and PMMA for high-quality liftoff process. A layer of 40-nm-thick Sb_2S_3 thin film was deposited using an Sb_2S_3 target (Plasmaterial Ltd.) in a magnetron sputtering system (Lesker Lab 18), followed by a lift-off process. We note the actual Sb_2S_3 thickness after the liftoff was reduced to ~ 20 nm due to the trench effect, that the narrow resist trench lowered the deposition rate. We then encapsulated the Sb_2S_3 with 40-nm-thick Al_2O_3 through thermal ALD (Oxford Plasmalab 80PLUS OpAL ALD) at 150 °C. To ensure good contact between the electric probe and metal pads while applying electrical pulses, the Al_2O_3 on the metal contacts was removed by defining a window using a fourth DWL overlay with positive tone resist AZ1512, then etching in a chlorine-based inductively coupled plasma etcher (ICP-RIE, Oxford PlasmaLab 100 ICP-18).

To highlight the simplicity of this fabrication process, we compare it with the in-house approach in Section 2.6. E-beam lithography (EBL) is one of the limiting factors for scalability and costs much money and time. The PCM integration process for Intel reticles only takes one EBL to precisely place the PCM thin films on the silicon waveguides for asymmetric DCs, which could be eliminated for micro-ring resonators and MZIs by using Heidelberg to define a PCM stripe much wider than the alignment error of Heidelberg ($\pm 0.5 \mu\text{m}$). We note the Heidelberg can be replaced with a deep-UV stepper for photolithography, which usually has higher alignment accuracy, smaller critical feature size, as well as better scalability. In contrast, our previous fully in-house fabrication process used six EBL steps: (1) define the photonic structures such as waveguides, micro-rings, grating couplers *etc.*; (2) and (3) define n^{++} and p^{++} doped region; (4) define metal pads; (5) define the PCM pattern; (6) define the Al_2O_3 etch window. In addition, additional fabrication steps were required, such as silicon etching, ion implantation, and annealing for dopant activation. Therefore, we conclude that the process of integrating PCMs onto Intel reticles takes significant less time than the fully in-house fabrication approach.

Figure 4.2(a) shows a schematic of the PCM-silicon hybrid photonics platform, on which different functional optical components are fabricated, including MRRs, MZIs and asymmetric DCs. All the components are armed with p⁺⁺-intrinsic-n⁺⁺ (PIN) doped silicon heaters for *in situ* electrical tuning of the PCMs. Electrical signals are applied on the platinum pads, which are well separated from the optical waveguides and are connected to the doped silicon regions by vertical metal vias. We emphasize that such multi-layer fabrication is crucial for low-loss routing of metal wires in VLS programmable PICs and is not available in our in-house fabrication. Figure 4.2(b) shows the photograph of a 300-mm wafer fabricated by Intel, which is diced into 2.5 cm × 3.3 cm reticles.

We developed an in-house process to open 4-μm-wide oxide windows followed by Sb₂S₃ deposition and patterning. We performed optical mode simulations to quantify the scattering loss due to the oxide window, suggesting less than -0.01 dB scattering loss (99.8% power coupling) per window. Such a small scattering loss comes from our 300-nm-thick waveguide, which confines 90.6% of optical mode in the silicon core. The in-house fabrication process can potentially be extended to whole-wafer level. An optical micrograph of the reticle after Sb₂S₃ integration is shown in Figure 4.2(c).

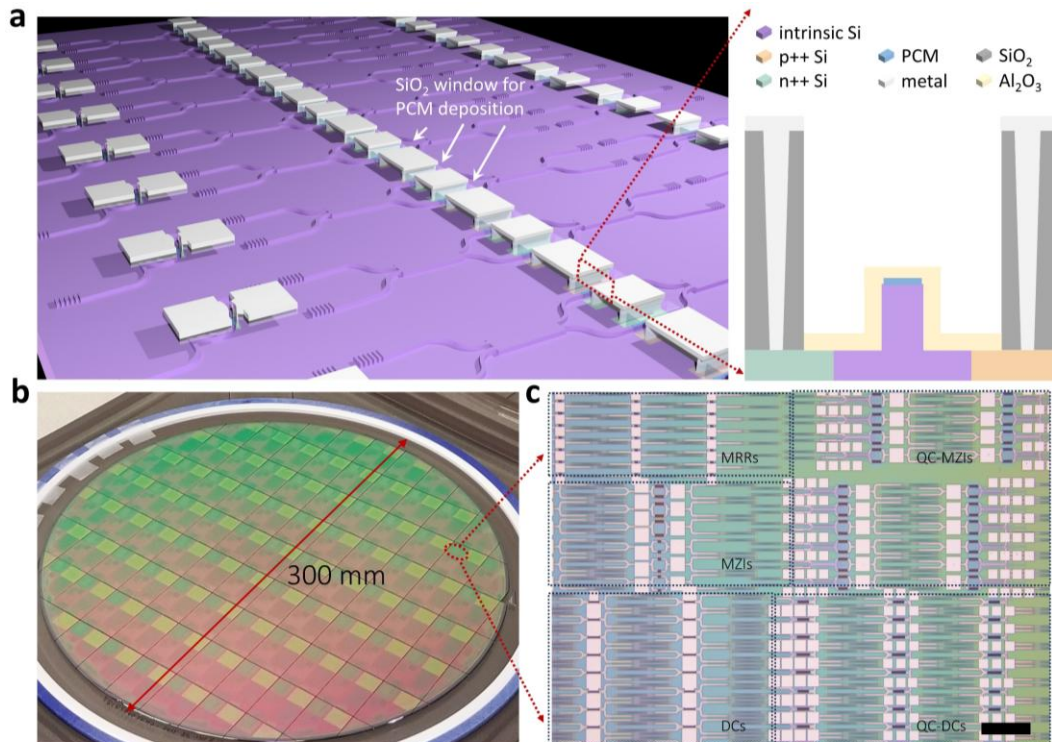


Figure 4.2: **Schematic and photograph of the fabricated wafers and reticles.**

(a) Schematic of the silicon-PCM hybrid platform. The 300-mm semiconductor fab promises high-volume manufacturing, and many reticles can be fabricated simultaneously for fast prototyping. The PCMs are integrated in-house by opening an oxide window on the optical waveguides followed by deposition and patterning processes. A schematic showing the cross-sectional view of the PCM-silicon hybrid platform is on the right. **(b)** Photograph of the 300-mm pure silicon photonic wafer, which is diced into multiple $2.5\text{ cm} \times 3.3\text{ cm}$ reticles. **(c)** Optical micrograph of a reticle after integrating the low-loss PCM Sb_2S_3 , showing various optical components such as micro-ring resonators (MRRs), Mach-Zehnder interferometers (MZIs), asymmetric directional couplers (DCs), quasi-continuously (QC) tunable MZIs and DCs. (Scale bar: $500\text{ }\mu\text{m}$)

We note that the excess optical loss arising from such in-house fabrication is negligible as optical mode perturbation caused by the oxide etching and Sb_2S_3 deposition is minor. This was verified by similar quality factors (Q-factor) of the MRRs, which only slightly reduced from $\sim 1.27 \times 10^5$ to $\sim 1.01 \times 10^5$ as fitted by Lorentz model in Figure 3.6. This implies an excess loss of only 0.02 dB for 20- μm -long Sb_2S_3 . We highlight that such a highly scalable platform can immediately enable screening and fast testing of different PCMs by simply changing the sputtering targets or using other deposition methods such as evaporation. We also emphasize that the PCM integration process is at the back end of a 300-mm fab line, and zero change is required on the 300-mm fab process, crucial to reliable and massive production.

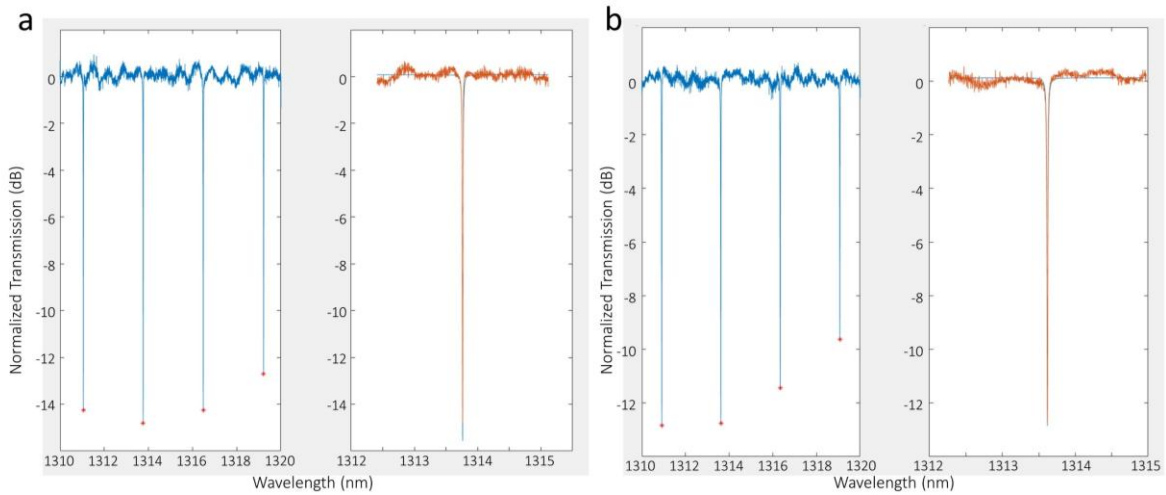


Figure 4.3: **Measured optical transmission spectra for a micro-ring resonator with 20- μm -long oxide window.**

(a) The response of a micro-ring resonator before any in-house process. Fitting to a Lorentz shape gives a Q-factor of 127k in the zoomed in plot. **(b)** The response of a micro-ring resonator after opening oxide windows, metallization and 20-nm-thick Sb_2S_3 deposition. Fitting to a Lorentz shape gives a Q-factor of 101k in the zoomed in plot, indicating very small extra loss due to the in-house fabrication process of ~ 0.02 dB, estimated using the formula in ref⁵².

4.2 Characterization results

4.2.1 Experimental measurement results

We first demonstrate reversibly switchable MRRs and MZIs on this platform using electrical control. We will further show asymmetric DCs with deterministic multi-level behavior in the next section. Although the devices were designed and tested at telecom O-band (1,260 $\sim$ 1,360 nm), we do not foresee any fundamental problem with extending the operation to the telecom C-band ($\sim 1,550$ nm) as Sb_2S_3 has even lower absorption loss in the longer wavelength regime (see the optical refractive index in Figure 3.1)^{104,113,146}.

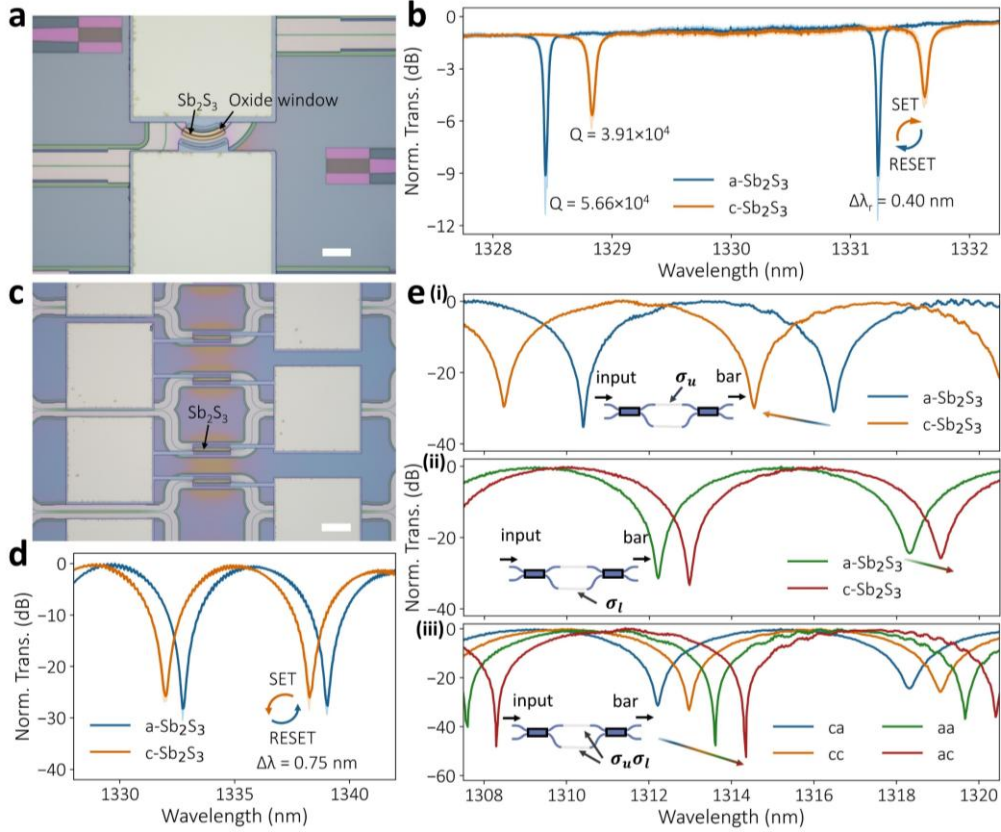


Figure 4.4: **Reversible reconfiguration of micro-ring resonators and Mach-Zehnder interferometers through electrically controlled 20-nm-thick Sb_2S_3 thin films.**

(a) Optical micrograph image of an MRR. An MRR is coupled with waveguide, and only a small portion of the MRR is viewable due to the metal pads. (Scale bar: 20 μm) (b) Reversibly tuning an MRR for 5 cycles by electrically switching 20-nm-thick, 25- μm -long Sb_2S_3 thin film on the intrinsic waveguide. A resonance red shift $\Delta\lambda_r$ of 0.40 nm and Q-factor reduction from 5.66×10^4 to 3.91×10^4 were observed after Sb_2S_3 crystallization. The shaded region indicates the standard deviation. Pulse conditions: 6.9 V, 500 ns for amorphization and 2.9 V, 200 ms for crystallization. (c) Optical micrograph image of an MZI. (Scale bar: 50 μm) (d) Reversibly tuning of an unbalanced MZI for 5 cycles by electrically switching 20-nm-thick, 60- μm -long Sb_2S_3 thin film on the intrinsic waveguide. A spectral blue shift of 0.75 nm was observed. Pulse conditions: 14.7 V, 500 ns for amorphization and 5.5 V, 200 ms for crystallization. (e) Push-and-pull operation of the dual-arm reconfigurable MZI by independently controlling the upper and lower MZI arms, showcasing a larger phase shift and deterministic four-level operation. The structural phases of the Sb_2S_3 on the upper σ_u and lower arm σ_l are denoted in the label as $\sigma_u\sigma_l$.

Figure 4.4(a) shows an optical microscope image of a fabricated non-volatile tunable MRR loaded with 25- μm -long, 20-nm-thick Sb_2S_3 thin film. The PIN diode had a resistance of $\sim 62.5 \Omega$ and a turn-on voltage

of ~ 0.8 V (see Figure 4.12 in a later section). Figure 4.4(b) shows 5 reversible switching cycles with a resonance shift of ~ 0.40 nm by applying three electrical pulses with amplitude of 6.9 V (2.9 V) and duration of 500 ns (200 ms) to switch the Sb_2S_3 into its a- (c-) phase. The free spectral range (FSR) of this MRR was measured as ~ 2.7 nm, suggesting a round-trip phase shift of $\sim 0.3\pi$ or $0.012\pi/\mu\text{m}$. This matches very well with the simulated phase shift $\sim 0.0125\pi/\mu\text{m}$ in Figure 4.5(a), indicating a complete phase change of Sb_2S_3 . By fitting the ring's spectrum to a Lorentzian line shape, we extracted a Q-factor of 5.66×10^4 (3.91×10^4) for a- (c-) Sb_2S_3 . Therefore, the excess loss of c- Sb_2S_3 was estimated as 0.11 dB according to the Q-factor reduction⁵², *i.e.*, loss per π was around 0.4 dB, which is slightly higher than the simulated loss per π of ~ 0.26 dB in Figure 4.5(b), and can be attributed to extra scattering at c- Sb_2S_3 grain boundaries¹¹³. We note that the Q-factor reported here reduces compared to the initial Q-factor ($\sim 1.27 \times 10^5$) due to extra optical loss caused by carrier migration from the doping region to the intrinsic region after high voltage pulses were applied. This excess loss was estimated as ~ 0.2 dB and can be eliminated in the future by enlarging the intrinsic region width.

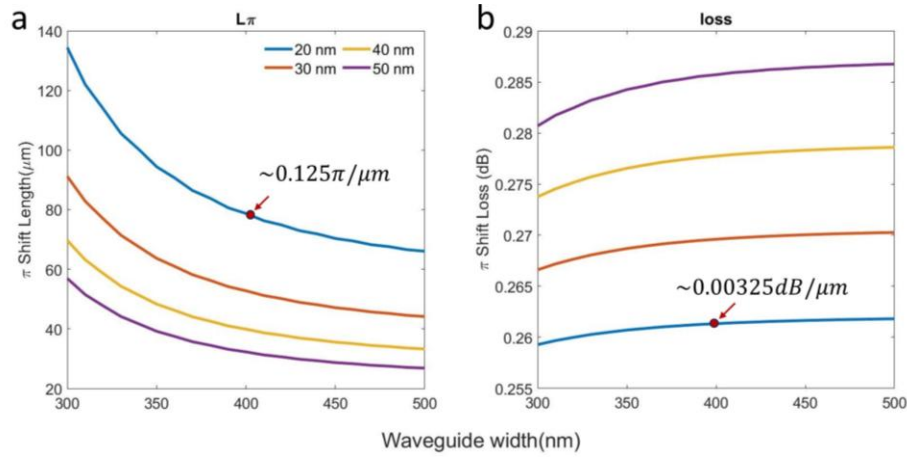


Figure 4.5: Numerical simulation results for π phase shift length L_π and loss per π when varying waveguide width and Sb_2S_3 thickness.

(a) Simulation results for L_π , where different curves represent different Sb_2S_3 thickness. A larger waveguide width and Sb_2S_3 thickness lead to a smaller L_π . For our Sb_2S_3 -based phase shifters, 400 nm waveguide width and 20 nm Sb_2S_3 thickness are used, leading to $L_\pi \approx 80\mu\text{m}$ and unit length phase shift of $\sim 0.125\pi/\mu\text{m}$. (b) Simulation results for the loss per π . A larger waveguide width and PCM thickness lead to a larger loss. The loss per π is ~ 0.26 dB and unit length loss is $\sim 0.00325\text{dB}/\mu\text{m}$ for our design.

We emphasize that the smaller resonance shift compared to recently reported results¹¹³ is due to differences in the waveguide geometry as the waveguides here are thicker (300 nm compared to 220 nm) and narrower (400 nm compared to 500 nm), which significantly reduces the optical mode interaction with Sb_2S_3 (Figure 4.6). To further increase the optical phase shift, we can design thinner and wider waveguides to enhance the light-matter interaction or use low-loss PCMs with a larger optical refractive index contrast such as Sb_2Se_3 ¹⁰⁶. Another approach is to increase the PCM thickness, which, however, incurs additional optical scattering¹⁰⁶ and difficulty in reversible switching¹⁶⁸.

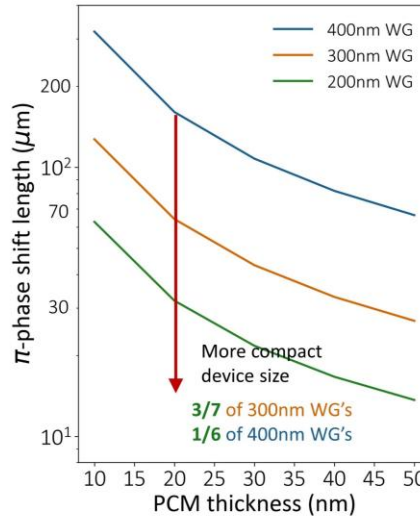


Figure 4.6: Numerical simulation results for π phase shift length L_π when varying Sb_2S_3 thickness and waveguide height.

Different curves represents the simulation results for waveguide height of 200, 300, and 400 nm. An increase of Sb_2S_3 thickness or decrease of the waveguide height lead to a decrease of L_π . The impact of waveguide height is significant as it determines the confinement of the optical mode, hence the interaction strength between light and Sb_2S_3 .

Similar to the MRR, the low-loss phase shifter functionality was also demonstrated in an unbalanced MZI in Figure 4.8(c), where 60- μm -long, 20-nm-thick Sb_2S_3 was deposited on both arms. Figure 4.8(d)

presents the reversible switching result of single arm for 5 cycles. Applying the amorphization (14.7 V, 500 ns) and crystallization (5.5 V, 200 ms) electrical pulses led to a resonance shift of ~ 0.75 nm for an FSR of ~ 6.3 nm, *i.e.*, a phase shift of $\sim 0.24\pi$. The electrical voltage is higher than MRRs due to impedance mismatch with the function generator during measurement. Moreover, the longer metal wire also led to a lower unit length conductivity in this MZI (Figure 4.7). We also note the MZI presents a smaller unit length phase shift ($0.004\pi/\mu\text{m}$) than the MRR ($0.012\pi/\mu\text{m}$). We attribute it to the relatively thick oxide residue on the MZI waveguides, which physically separated the optical modes from the Sb_2S_3 thin film and weakened the effective index contrast. This issue could be resolved by another wet-etch process to ensure complete removal of the oxide on waveguides.

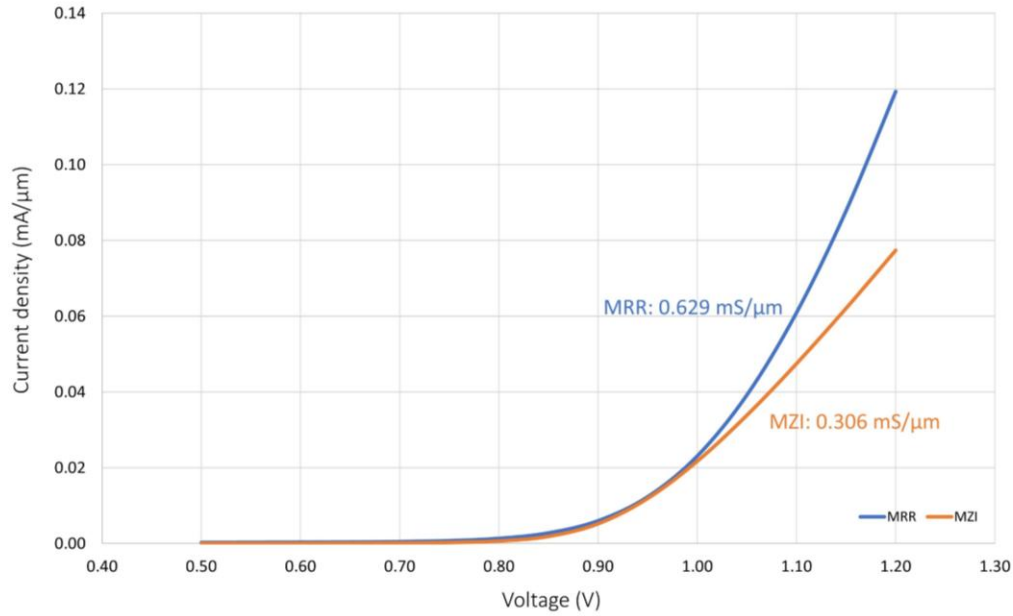


Figure 4.7: **Measured I-V curve of the micro-ring resonator and Mach-Zehnder interferometer.**

The current is normalized with respect to the PIN junction length. The unit length conductivity for the MRR and the MZI is $0.629 \text{ mS}/\mu\text{m}$ and $0.306 \text{ mS}/\mu\text{m}$, respectively. The MRR shows a higher unit length conductivity, which leads to the lower phase-transition voltages. This is attributed to the longer metal wire in the MZI and could be improved in the future fabrication by making the metal wire wider.

Dual-arm controlled MZIs support push-and-pull type operation, as shown in Figure 4.4(e). With input light injected from the upper input port, switching the Sb_2S_3 to the c-phase on the upper (lower) arm led to

a blue (red) spectral shift at the bar output port. We denote the structural phases σ of Sb_2S_3 on the upper and lower arms as a sequence $\sigma_u\sigma_l$. Figure 4.4(e-iii) shows a large relative phase shift of $\sim 0.7\pi$ between ca and ac phase and four distinct levels. We attribute the difference in spectral shift on two arms to incomplete phase transition or material ablation, which can be improved by further optimizing the pulse conditions. Previous simulation suggested an ablation-free voltage range of $0.6 \sim 1.0$ V, which highly depends on the PIN heater design¹⁶⁴. For our PIN design and experiment, we typically observed Sb_2S_3 ablation when the voltage was increased by $1 \sim 1.2$ V ($0.5 \sim 0.7$ V) above the minimum amorphization (crystallization) voltage. The tighter crystallization parameter window is attributed to the much longer crystallization pulse duration (200 ms). We note that both the incomplete phase transition and the material ablation could be a result of non-uniform heating produced by sub-optimal heater design in Figure 4.13. If the center temperature is significantly higher than the surrounding temperature, the middle portion of PCMs may be amorphized (ablated) while materials at the edge remain unswitched¹⁶⁸. In the future, a curved heater design¹⁶⁹ can be adopted to improve the heating uniformity hence a complete phase transition without material ablation. This MZI device maintained good optical contrast after more than 500 switching events in Figure 4.8.

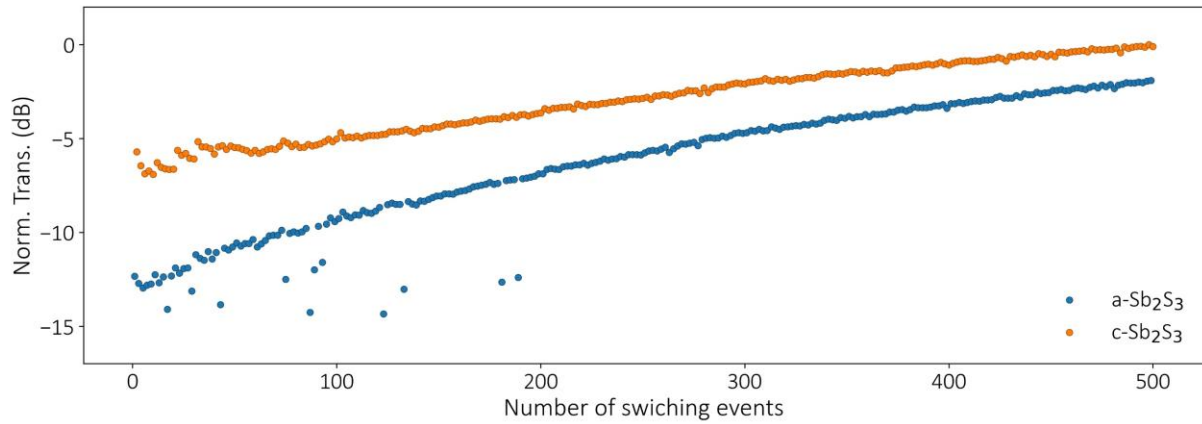


Figure 4.8: Endurance test of an unbalanced MZI.

We sent in amorphization and crystallization pulses for 500 switching events and the contrast still remains. There is a DC shift in the transmission level, which could be attributed to partial material damage and could be resolved later by optimizing the electrical pulse condition.

4.3 Asymmetric directional couplers with multiple Sb_2S_3 segments

On this scalable platform, we show a novel method to achieve deterministic multilevel or quasi-continuous tuning, which is generally a challenging task due to the inherent stochastic nature of electrically controlled PCMs¹⁶⁰.

4.3.1 Improved design procedure

The design of the Sb_2S_3 -loaded asymmetric DCs follows the procedure described in the previous chapter^{113,144}, but here we further improve the design flow and allow a straightforward design without calculating the loss manually as in Equations (2.3) and (2.4). Two waveguides of different widths are closely positioned to facilitate evanescent coupling, which allows optical power to transfer from one waveguide to the other. According to the coupled mode theory³³, the power transfer efficiency η is expressed by $\eta = \frac{1}{\sqrt{1+(\delta/\kappa_c)^2}}$, where $\delta = \frac{\pi}{\lambda_0}(n_2 - n_1)$ is the waveguide detuning, $\kappa_c = \frac{\pi}{\lambda_0}(n_e - n_o)$ is the coupling strength, $n_{1,2}$ is the effective refractive index for two waveguides assuming no coupling, $n_{e,o}$ is the effective index of the even (odd) super-modes formed by the coupled waveguide system, λ_0 is the vacuum wavelength of light. The maximum power transfer efficiency $\eta_{max} = 1$ is reached when $n_1 = n_2$, which is referred to as the phase-matching condition. In such phase-matched system, the coupling length L_c to achieve complete power transfer is expressed as $L_c = \frac{\pi}{2\kappa_c} = \frac{\lambda_0}{2(n_e - n_o)}$, where $n_{e,o}$ can be obtained from numerical simulators. In general, a larger gap between two waveguides leads to a smaller coupling strength κ_c and hence a longer L_c . To reconfigure the directional coupler, Sb_2S_3 is deposited and patterned on top of the narrower waveguide. The widths of the waveguides are carefully designed to achieve the phase matching condition in one state of Sb_2S_3 , in our case, the a-state. When switching Sb_2S_3 to the c-state, both the coupling strength κ_c and the waveguide detuning δ are changed due to effective index difference of the PCM loaded waveguide, thus a change in the output power. By judicious design of the gap, a complete switching from cross-state to bar-state can be achieved¹⁴⁴. As such, selectively switching part of the Sb_2S_3

can provide intermediate output states^{113,114,170}. It is important to highlight that while such intermediate levels naturally emerges with low-loss PCM Sb_2S_3 , achieving them using absorptive PCMs like GST requires additional device design¹.

We describe the steps to design the asymmetric directional coupler based on Sb_2S_3 in detail here.

1. Fix the width w_1 of the bare silicon waveguide WG1 and the height of Sb_2S_3 h_{SbS} to a reasonable number. We used $w_1 = 500 \text{ nm}$ and $h_{\text{SbS}} = 20 \text{ nm}$ in this design.
2. Design the width w_2 of the Sb_2S_3 -loaded waveguide WG2 to phase match with WG1. We should separately simulate WG1 and WG2. We can set the Sb_2S_3 to a-phase (c-phase also works¹¹³), sweep w_2 , and calculate WG2's effective index difference Δn from WG1. The phase matching condition is obtained when $\Delta n = 0$, see Figure 4.9(b).
3. Design the gap between WG1 and WG2. First, we need to calculate the effective index $n_{e,o}$ of the super-mode of the coupled waveguide system by a Lumerical FDE simulation. The coupling length L_c can be calculated as $L_c = \frac{\lambda_0}{2(n_e - n_o)}$, where λ_0 is the vacuum wavelength, see Figure 4.9(c). Second, we can use the optical mode in isolated WG1 as the input field and propagate through the coupled waveguide system with a length of L_c using the *propagate* command in Lumerical. A high cross transmission should always present for a- Sb_2S_3 , see Figure 4.9(d-i). The key requirement for gap optimization is to ensure high bar-state transmission for c- Sb_2S_3 , see Figure 4.9(d-ii). We should pick the smallest gap to make the device more compact.
4. All the key parameters are obtained. The last step is to verify the design by running an FDTD simulation, see Figure 4.10.

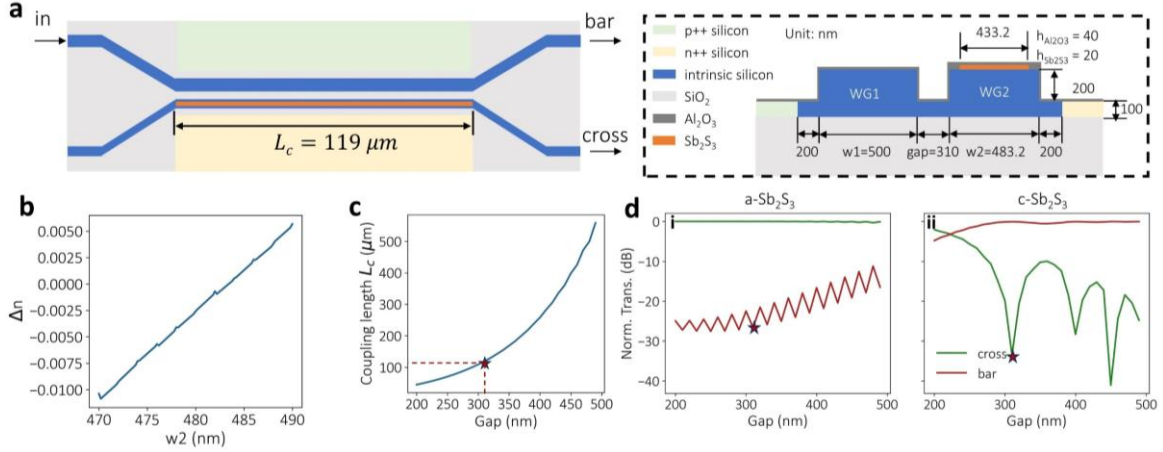


Figure 4.9: **Schematic of the Sb_2S_3 -based asymmetric directional coupler and main results during simulation.**

(a) Schematic. Left: top view. Right: cross-sectional view. All the design dimensions are included. (b) Difference between the effective index of waveguide WG1 and WG2 when they are fully decoupled, i.e., $\Delta n = n_2 - n_1$. The phase matching condition is achieved at $w_2 = 473.2$ nm, where $\Delta n = 0$. (c) Numerical simulated coupling length with respect to gap. (d) The calculated optical transmission at cross and bar port for both phases of Sb_2S_3 . A consistent cross state for a-Sb₂S₃ verifies the coupling length is calculated correctly. The smallest gap that fulfills this requirement is ~ 310 nm, which renders the smallest L_c . The design, highlighted by a red star, shows a high extinction ratio between cross and bar output port of ~ 25 dB (35 dB) for a-Sb₂S₃ (c-Sb₂S₃).

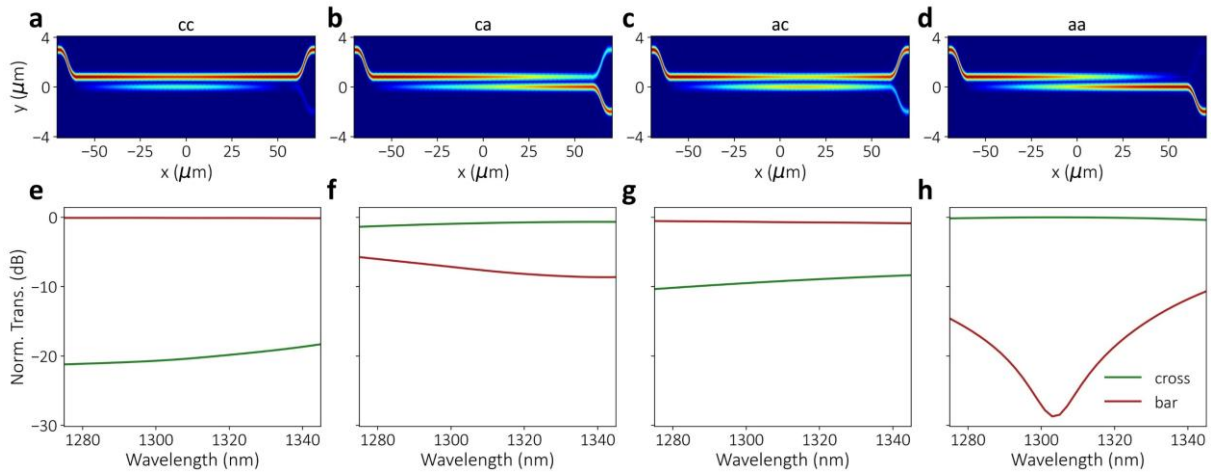


Figure 4.10: **Simulated electric field distribution and transmission spectra for quasi-continuously tunable beam splitters with 2 Sb_2S_3 segments.**

(a)-(d) The field distribution and (e)-(h) the transmission spectra. The optical characteristics are programmable depending on the phases of two Sb_2S_3 segments indicated in the titles of the sub-figures. We note here the

optical splitting ratios are different from the experimental results and it can be attributed to fabrication imperfections such as variations of Sb_2S_3 deposition thickness, waveguide width and waveguide gap.

Figure 4.11(a) shows our scheme to achieve deterministic multilevel operation, where multiple segments of Sb_2S_3 thin films are individually controlled using interleaved PIN doped silicon heaters. Each Sb_2S_3 segment is switched electrically and independently to fully-a- or fully-c-phase in a repeatable fashion. By encoding the state of each Sb_2S_3 segment, multiple deterministic operation levels were obtained. To avoid potential thermal crosstalk, the segments are separated by 1 μm . One potential pitfall of this scheme is the relatively complex structure, incurring a higher device failure rate due to fabricated dimension inconsistencies. In that regard, mature wafer-scale silicon photonic fab/foundries provide a reliable solution.

As a proof-of-concept demonstration, we designed a two-segment asymmetric DC, which functions at bar(cross)-state when both Sb_2S_3 segments are in c(a)-phase, and other configurations function as intermediate levels as shown in Figure 4.10(e)-(h). Two segments were designed deliberately with different lengths to achieve four operation levels. Such multilevel asymmetric DC was fabricated, and Figure 4.11(b) shows the microscope image, where the longer, 70- μm -long Sb_2S_3 segment (labeled 2) is twice as long as the shorter, 35- μm -long one (labeled 1). The orientation of the PIN diode heaters was designed to have opposite polarity to reduce unwanted crosstalk due to potential doping region mixing. The measured transmission spectrum is shown in Figure 4.11(c), where the insets indicate the structural phase of each Sb_2S_3 segment. As shown in Figure 4.11(c-i), initially two Sb_2S_3 segments were in the cc-state, and the asymmetric DC guided the light to the bar-port with an insertion loss of ~ 0.7 dB and extinction ratio of ~ 12.1 dB at 1,343 nm. When switching Sb_2S_3 Segment 2 with short electrical pulses with amplitude of 7.8 V and duration of 500 ns, a complete spectrum flip was observed as in Figure 4.11(c-ii), exhibiting high cross-port transmission with an insertion loss of ~ 1.0 dB and an extinction ratio of ~ 8.6 dB at 1,343 nm. We further amorphized Segment 1 using 7-Volt, 500-ns electrical pulses and measured spectra in Figure 4.11(c-iii) and (c-iv). An intermediate operation level with a splitting ratio of $\sim 32:68$ between the bar- and cross-port was realized in Figure 4.11(c-iii). The extinction ratio increased from 12.1 dB in the cc-

configuration to 15.7 dB in the ac-configuration. Segments 1 and 2 were switched back to c-phase with 3-Volt, 200-ms electrical pulses. We repeated the switching experiment 5 times and plot the standard deviation as the shaded region in Figure 4.11(c). The only slight standard deviation showcases the deterministic nature of this multi-segment approach. The discrepancy of the experimental performance from the simulation can be attributed to the fabrication imperfection and can be overcome by finer device parameter sweep during tape-out and better process control.

Figure 4.11(d) shows the cross-port transmission at 1,330 nm for 52,600 switching events by alternatively sending in amorphization and crystallization pulses to Segment 2. We note that one switching event is accomplished by applying three pulses, crucial for repeatable Sb_2S_3 phase transition¹¹³. To facilitate the cyclability test, we used three faster pulses for crystallization with amplitude 3.3 V and duration 2 ms and the amorphization pulses remained the same. The thermal stabilization time between pulses was set to ~ 40 ms, allowing us a rate of around $\frac{1}{3 \times (40 + 2 + 0.5) \text{ ms}} \approx 8 \text{ Hz}$ and to finish all 52,600 switching events within ~ 2 hours. The optical contrast remained high $\sim 8.5 \pm 1.0$ dB after 5,000 switching events, showcasing excellent cyclability. After that, we observed a gradual drift in the c- Sb_2S_3 level and a decrease in the contrast, which could be attributed to partial Sb_2S_3 damage. The latter may also be a result of PIN heater degradation indicated by the IV characteristics change after 52,600 events (Figure 4.12). As such, we had to increase the amorphization (crystallization) pulse amplitude to 8.3 V (3.3 V) at event 17,000. An optical misalignment occurred at $\sim 17,000$ switching events, indicated by a low optical transmission level and is highlighted in Figure 4.11(d) by a gray box region. After we realigned the optical setup and increased the pulse amplitude, the optical contrast recovered to $\sim 4.5 \pm 0.7$ dB until $\sim$ event 30,000 and gradually decreased again. The Sb_2S_3 stopped responding to any electrical pulses after 50,000 switching events. Scanning electron microscope images in Figure 4.13 show some black areas at the edge of waveguides after the cyclability test, which could be a result of Sb_2S_3 ablation or thermal reflowing. Several strategies can be used to further improve the cyclability, such as developing more durable PCMs¹⁷¹, engineering the thickness and material of the encapsulation layer¹⁷², patterning the PCMs into subwavelength

nanostructures⁹², and engineering the microheaters and pulse conditions to provide a uniform temperature distribution¹⁶⁹.

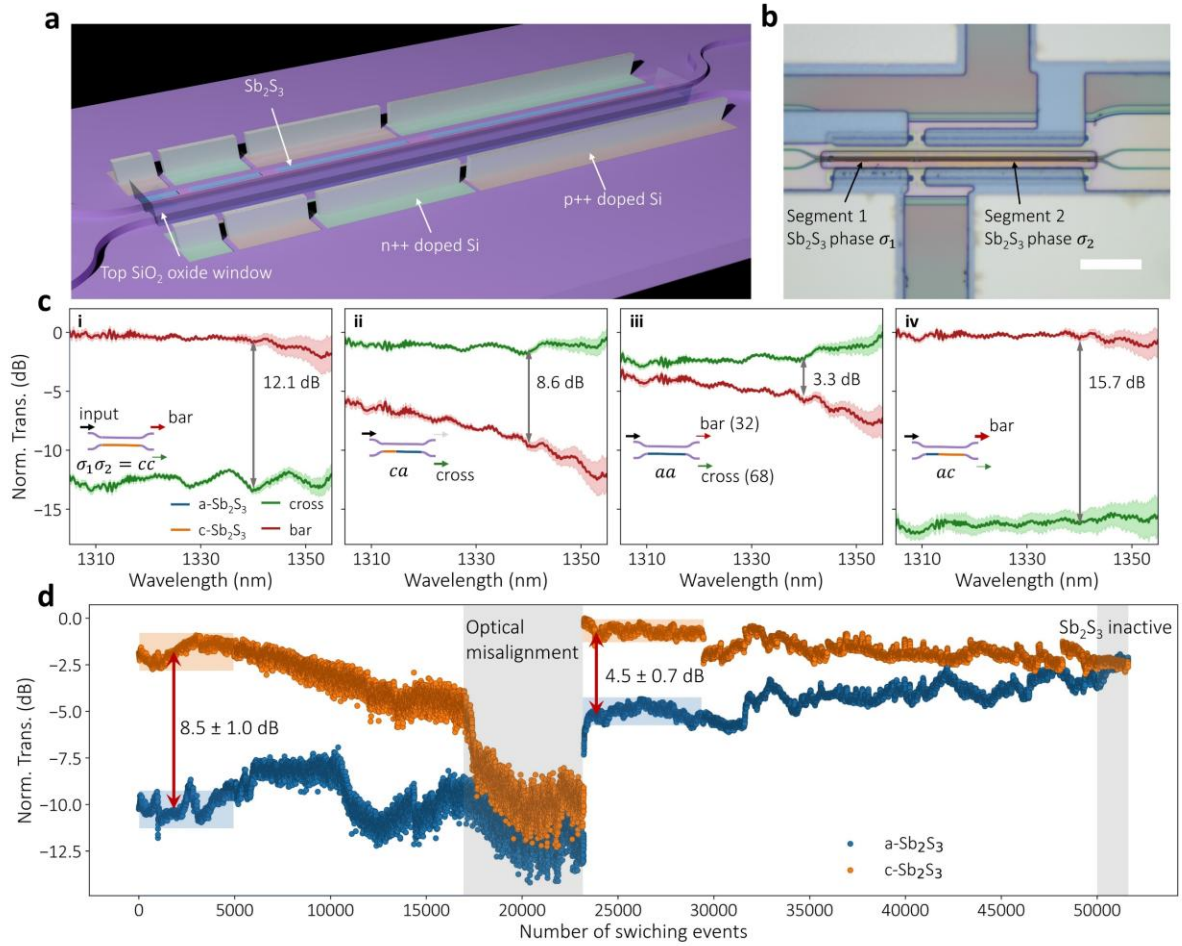


Figure 4.11: Quasi-continuously tunable asymmetric directional coupler with two individually controlled Sb₂S₃ segments.

(a) Schematic with metal pads omitted for visualization, (b) Optical micrograph of an QC-DC with two Sb₂S₃ segments. (Scale bar: 20 μ m) (c) Transmission measurement results at both bar and cross port for different phase sequences of the material, demonstrating 4 operation levels: (i) cc (ii) ca (iii) aa (iv) ac, where we have denoted the phases of segments 1 and 2 as $\sigma_1\sigma_2$. The transmission spectra were normalized to a reference waveguide on chip. The device was reconfigured with electrical pulses five times and the shaded region indicates the standard deviation, showing excellent deterministic quasi-continuous tuning beyond binary levels. The switching condition was three 7.8V, 500ns pulses for amorphization and three 3V, 200ms pulses for crystallization. (d) Endurance test recording cross-port optical transmission while switching Sb₂S₃ Segment 2 at 1,330 nm for 52,600 times (26,300 cycles). The switching condition was three 7.8V, 500ns pulses for amorphization and three 3.3V, 2ms pulses for crystallization. Little performance degradation was observed

before 5,000 switching events, exhibiting a large optical contrast of 8.5 ± 1.0 dB. The contrast decreases after then and an optical misalignment happens at around event 17,000, highlighted by the gray box labeled “optical misalignment”. After realigning the setup, a contrast of 4.5 ± 0.7 dB was preserved. The Sb2S3 became inactive after around 50,000 switching events as indicated by the gray box labelled “Sb2S3 inactive”.

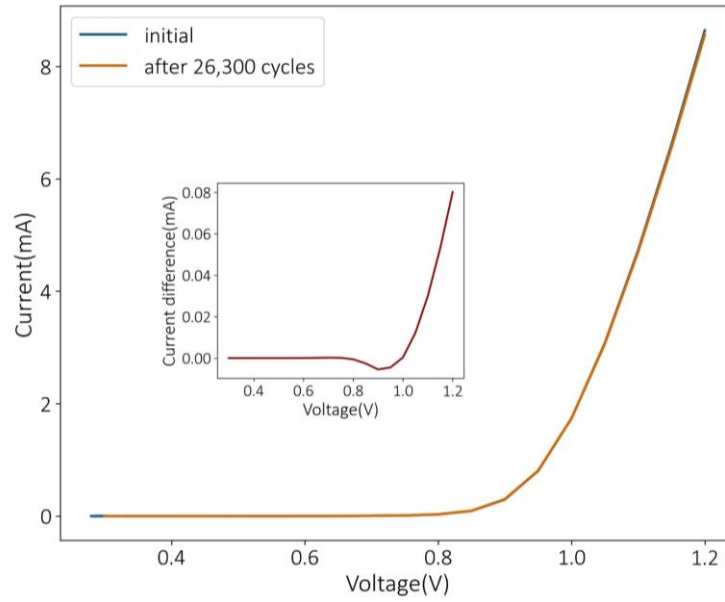


Figure 4.12: The I-V curve before and after the PIN diode heater was switched for 26,300 cycles.

Although a small decrease in the current is observed, the PIN diode heater still functions well.

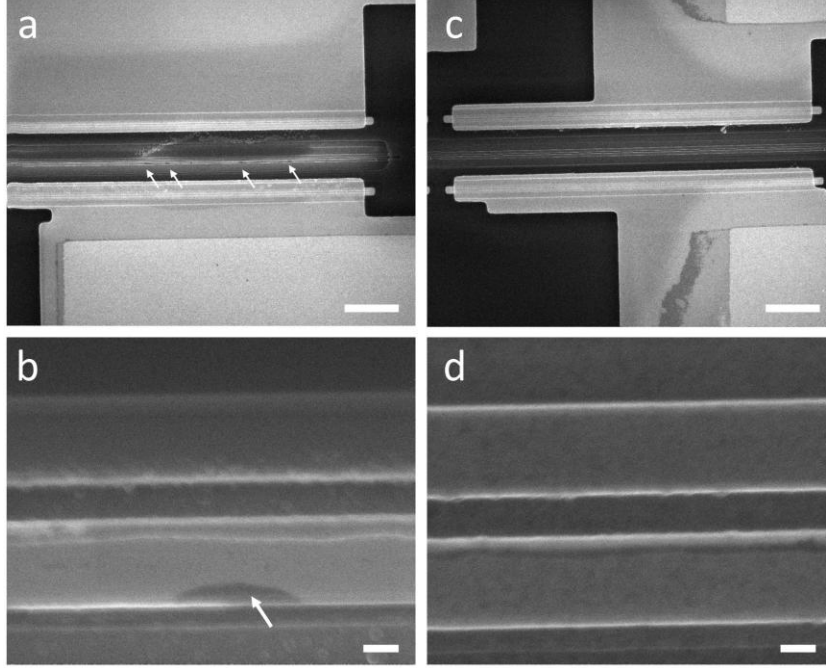


Figure 4.13: **The scanning electron microscope images after switching 50,000 switching events.**

(a) The SEM image for the device after 50,000 switching events. (b) The zoom-in image of a. Black areas after switching many cycles, indicate Sb_2S_3 ablation and thermal reflow, pointed by white arrows. (c) The SEM image for another device which was not switched. (d) The zoom-in image of (c). Scalebar: 10 μm for (a, c) and 200 nm for (b, d).

4.4 Quasi-continuously tunable MZIs with equal and unequal-length multi-segments schemes

The idea was further extended to more Sb_2S_3 segments for a larger number of operation levels in unbalanced MZIs under single-arm operation in Figure 4.14. We designed, fabricated, and characterized two types of devices, with N Sb_2S_3 segments having the same or different lengths. Since the phase shift $\Delta\phi$ induced by each Sb_2S_3 segment is proportional to its length, the equal length scheme loses some encoding capability by the redundant Sb_2S_3 configurations, leading to $(N + 1)$ level. In the unequal-length scheme, we design the lengths of segments as a geometric sequence with a common ratio of 2. For example, we denote the length of Sb_2S_3 segment i as L_i , then $L_1:L_2:L_3 = 1:2:4$ for a three-segment device.

Redundancies in this configuration were avoided, and the system implemented at most 8 ($2^N, N = 3$) distinct levels with equal channel spacing.

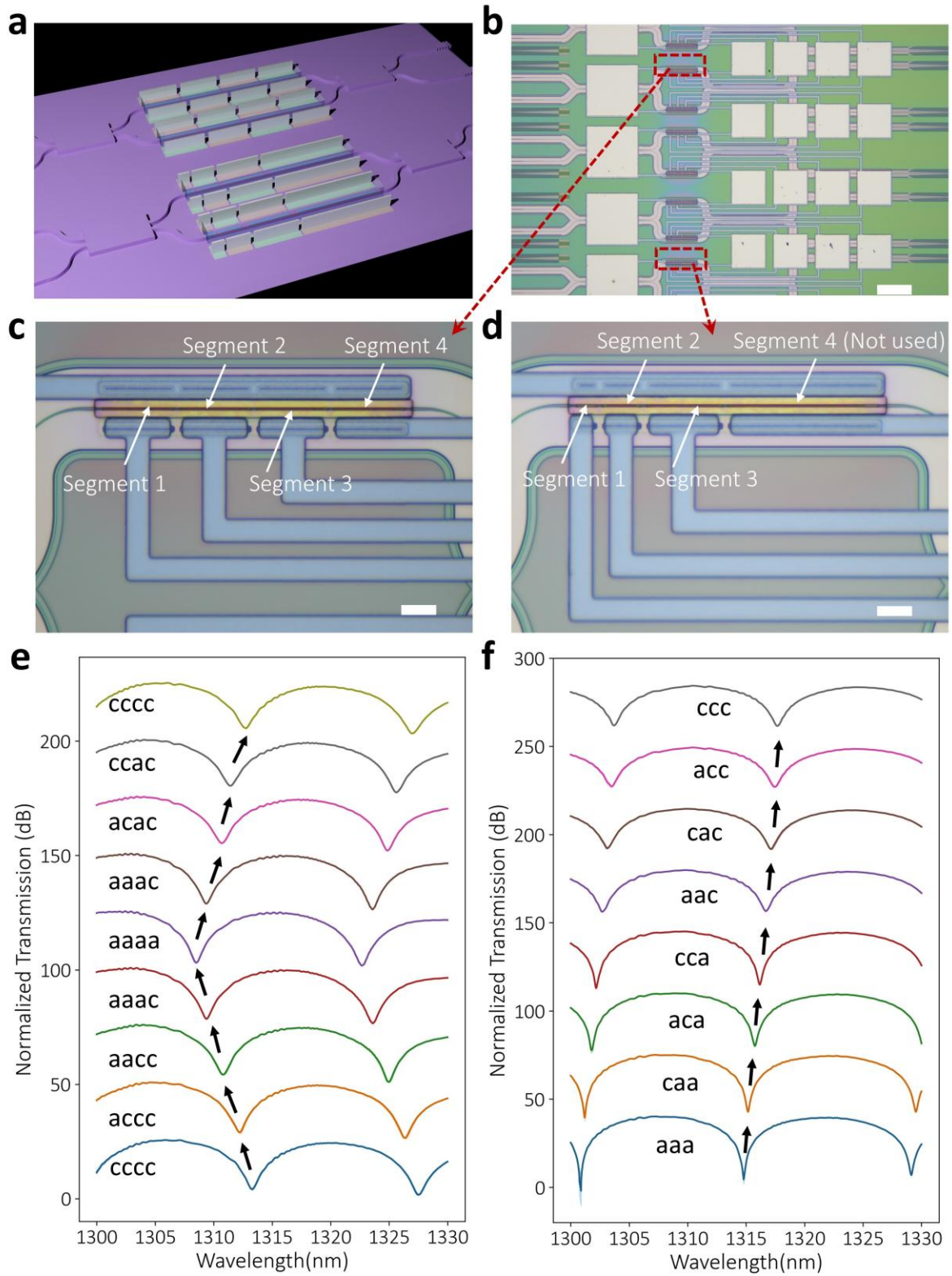


Figure 4.14: Quasi-continuously tunable Mach-Zehnder interferometers with four equal and unequal Sb_2S_3 segments.

(a) Schematic, (b) Optical micrograph of the quasi-continuously tunable MZIs with equal and unequal Sb_2S_3 segments. (Scale bar: 100 μm) (c, d) Zoomed-in optical micrograph of (c) equal (d) unequal Sb_2S_3 segment lengths. (Scale bar: 10 μm) (e) Measured optical transmission spectra after gradual amorphization of equal-length Sb_2S_3 segments. Five operation levels were achieved with spectral shift of 1.125 ± 0.26 nm per step. Reversible switching was demonstrated by bringing the system level back through one-by-one crystallization in a different order. The structural phase of Sb_2S_3 segments is indicated near each curve with the same convention in Figure 4.11. (f) Experimental demonstration of 8 ($2^N, N = 3$) operation levels enabled by unequal segment lengths in a geometric series with common ratio of 2. The spectrum is continuously shifted with uniform step resonance shift of 0.41 ± 0.12 nm or 0.059π . We highlight that measurement for both (e) and (f) were repeated five times and the shaded regions indicate the standard deviation. The barely visible shaded region indicates a highly deterministic quasi-continuous operation. (Note: metal pads were omitted in the schematic for visualization.)

Figure 4.14(b) shows the optical microscope image of the fabricated quasi-continuously tunable MZIs with four equal (see zoomed-in picture in Figure 4.14(c)) and unequal (see zoomed-in picture in Figure 4.14(d)) Sb_2S_3 segments. In both cases, the total length of four Sb_2S_3 segments was ~ 80 μm to provide a large phase shift. Figure 4.14(e) shows the measured results for the equal length scheme, where we achieved 5 ($N + 1, N = 4$) operation levels and demonstrated reversible switching between different levels. We first tested the pulse conditions of each segment with measured impedance of $\sim 106, 130, 156, 185$ Ω . This variation could be attributed to the difference in the metal wires' length and could be resolved by engineering the geometry of these wires. However, we note the switching voltage levels were similar after matching the load impedance of the function generator, showing less than ± 0.5 V variation for amorphization. We used three ~ 8.8 V, 500 ns (~ 3.6 V, 200 ms) pulses for amorphization (crystallization). The waterfall plot of Figure 4.14(e) shows the measured bar-port spectrum labeled with Sb_2S_3 segments' phases when light was injected from the upper input port and tuning the lower MZI arm. All Sb_2S_3 segments were first set to the c-state, then amorphized one-by-one from Segment 1 to Segment 4. A gradual blue shift is observed, agreed with the smaller refractive index of a- Sb_2S_3 compared to c- Sb_2S_3 . The Sb_2S_3 segments were then crystallized one-by-one in a different order until all were switched to the c-phase. Figure 4.14(e)

shows that the final transmission spectrum (the top curve) aligning well with the initial one (the bottom curve), indicating a reversible switching behavior. The spectral shift was estimated as 1.125 ± 0.26 nm per step. The slight non-uniformity of the spectral shift could be attributed to incomplete phase change in the Sb_2S_3 segments and non-uniformity of Sb_2S_3 films, which could be resolved by further optimizing the electrical pulse condition and the fabrication process. We emphasize that no thermal crosstalk was observed, showcasing the thermal-crosstalk-free advantage of PCM tuning.

Compared to the equal length scheme, which only achieves $N + 1$ distinct optical levels, the unequal length scheme can achieve a maximum of 2^N levels with N Sb_2S_3 segments due to the strict non-redundant configurations. Figure 4.14(f) shows our measurement results with three unequal Sb_2S_3 segments with a total length of 40 μm . The longest Segment 4 was not used in this proof-of-concept experiment. Like the previous experiment for the equal length scheme, we first set all the Sb_2S_3 segments to the a-phase, and then programmed the binary phases of three Sb_2S_3 segments to demonstrate 3 bits or 8 ($2^N, N = 3$) distinct levels by different combination of the segments' phases, labeled in Figure 4.14(f). We report a uniform step resonance shift of $\sim 0.41 \pm 0.12$ nm and a step phase shift of $\sim 0.059\pi$. We note that we observed a red shift when amorphizing the upper arm in another MZI and achieved a larger spectral shift after pulse condition optimization. Such an exponential increase in the number of levels is critical to reducing the complexity of the control circuits for large-scale integration. We emphasize that the measurements for both equal-length and unequal-length devices were conducted for five reversible switching cycles. The standard variation was shown by a barely visible shaded region in Figure 4.14(e) and (f), implying a highly deterministic quasi-continuous tuning behavior.

4.5 Discussion

We note that this idea of using multiple segments of PCMs has been shown recently in another work with a different PCM GSSe and tungsten heaters¹⁷⁰. We emphasize that it was limited to pure-amplitude modulation in a 1×1 waveguide switch, but we show phase-only modulation with the low-loss PCM Sb_2S_3 in 2×2 asymmetric directional couplers and MZIs, which are crucial building blocks for large-scale PICs.

We note although we only demonstrated integrating Sb_2S_3 , any other PCMs can be easily tested on this versatile platform by simply changing the sputtering targets or using different deposition methods such as evaporation. Such a platform can open new opportunities in fast-prototyping and examination of PCMs. Lastly, we compare our scalable platform with other existing PCM-PIC works in Table 6, showing similar performance. The energy efficiency for switching can be further improved by reducing the distance from the waveguides to metal vias.

In summary, we demonstrated a scalable programmable PIC platform by combining the mature and reliable 300-mm silicon photonic fab with in-house backend-of-line integration of the low-loss PCM Sb_2S_3 . Non-volatile electrically programmable MRRs, MZIs, and asymmetric directional couplers were shown with low loss, large phase shift, and high endurance. Moreover, thanks to the platform's capability of handling complex structures, we showed a novel scheme to achieve deterministic multi-level operation by independently controlling multiple Sb_2S_3 segments. We experimentally demonstrated such deterministic quasi-continuous tuning behavior in both asymmetric directional couplers and MZIs, showcasing at most N bits or 2^N optical levels with N Sb_2S_3 segments by careful geometry engineering. Overall, our work lays the foundation for very-large-scale programmable PICs with zero-static power consumption and deterministic multi-level operations.

The table below compares our PCM-based asymmetric directional coupler with other PCM-based devices. We would like to point out that the higher energy consumption of our directional coupler can be attributed to the relatively large distance between the metal via and the intrinsic region, which leads to voltage drop in the doping region and hence large power waste. It could be improved in future tape-outs by reducing this distance. The relatively larger footprint of our devices is caused by the thick silicon waveguide used and Sb_2S_3 's smaller refractive index change (~ 0.6) compared to other PCMs such as GST (~ 3) and Sb_2Se_3 (~ 0.8). We can further improve this by utilizing Sb_2Se_3 , trying to switch to a thicker PCM film, as well as using wider and thinner waveguides. We emphasize although PCMs are inherently immune to thermal crosstalk, the highest temperature different PCMs can tolerate highly depends on the material property. Here we quantify thermal immunity of each PCM by the glass transition temperature, which is

the lowest temperature the device's optical characteristics may be changed. Lastly, scalability is measured by whether the photonic structures were fabricated by e-beam lithography (low scalability) or photolithography (high scalability).

Table 5: PCM integrated photonic device performance comparison

Ref	Year	PCM	Structure	IL (dB)	Energy per switch (nJ)	PCM length (μm)	Number of cycles	Crosstalk immune temperature ($^{\circ}\text{C}$)	Scalability
173	2015	GST	MRR 1×1	N.R.	0.533 (3.1) ^c	1.0	50	150	Low
174	2017	GST	MRR 1×1	5.1 / 4.3 ^a	0.19 (17.1) ^c	60.0	1,000	150	Low
162	2018	GST	WG 1×1	N.R.	0.68	2	10	150	Low
52	2018	GST	MRR 1×1	0.54	0.62 (0.2) ^c	2	> 2	150	Low
92	2019	GST	MRR 1×2	0.75 / 0.46 ^a	0.25 (11) ^c	25.0	> 2	150	Low
175	2019	GST	WG 1×1	1.5	0.7	3.6	N.R.	150	Low
53	2019	GSST	MRR 1×1	< 0.5	N.R.	5 ^b	> 3	200	Low
176	2021	GST	MZI 2×2	0.5	14 (9.5 $\times 10^5$) ^c	43.0	600	150	Low
158,159	2021	GST	WG 1×1	0.9	0.38	10.0	1,000	140	Low
177	2021	GST	Crossing	0.4	0.8	2	N.R.	150	Low
178	2023	Sb ₂ Se ₃	SF 3×3	N.R.	N.R.	> 500	N.R.	200	High
179	2017	GST	WG 1×1	4.8	20 (7.2 $\times 10^6$) ^c	1	~10	150	Low
112	2019	GST	MMI 1×1	1	10 (9) ^c	1	> 1500	150	Low
111	2020	GST	MRR ^f 1×1	0.06	8 (78) ^c	3	> 500	150	Low
106	2021	Sb ₂ Se ₃	MZI ^f 2×2	> 0.3	176 (3.8 $\times 10^3$) ^c	> 100 ^b	> 125	200	Low
180	2022	GST	MMI 1×1	3.7	4.5 (4.08) ^c	1	N.R.	150	Low
59	2022	GST	DC ^f 2×2	2.0	380 (6.8 $\times 10^3$) ^c	50	> 2,800	150	Low
107	2022	Sb ₂ Se ₃	MRR ^f 1×1	0.33	9.25 (1.4 $\times 10^3$) ^c	6	> 1,100	200	Low
170	2022	GSSe	WG 1×1	0.12	400	80	5 $\times 10^5$	325	Low
114	2023	GST	MZI ^f 2×2	1	81 (1.9 $\times 10^3$) ^c	10	> 3	150	Low
113	2023	Sb ₂ S ₃	DC ^f	< 1	56 (3.4 $\times 10^6$ 1.7 $\times 10^3$) ^{c, e}	79	> 800	275	Low
181	2023	Sb ₂ Se ₃	DC ^f	< 0.36	N.R.	33	> 1000	200	Low

This work	2023	Sb ₂ S ₃	DC ^f	~1	1216.8 (7.2 × 10 ⁷) ^e	105	> 2500	275	High
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(ER: extinction ratio, IL: insertion loss, BW: bandwidth, MMI: Multi-mode interferometer, MZI: Mach-Zehnder Interferometer, MR(D)R: Micro-ring(disk) resonator, WG: waveguide, DC: directional coupler, N.R.: not reported)

Note: here, only devices with reversible switching are compared. ^aFor drop and through ports, respectively. ^bEstimated from figures. ^cEnergy per switching event for amorphization (crystallization). ^dThe study did not perform multiple runs to verify the multilevel reliability. ^eFor ring resonators. A smaller crystallization energy was achieved with shorter 100-μs crystallization pulses. ^fThis work contains multiple devices; only one device is picked for easy comparison.

Chapter 5. Nonvolatile transmissive spatial light modulator with PCMs¹⁸²

Different from the previous Chapters mainly focusing on PICs, we switch our interest to metasurface applications in this Chapter. Free-space modulation of light is a key enabling technology behind optical communications, holography, ranging, and virtual/ augmented reality. Traditional spatial light modulators (SLMs) based on liquid crystal (LC) on silicon¹⁸³ or micro-electro-mechanical systems (MEMS)¹⁸⁴ employ large pixels ($\sim 10\mu\text{m} \times 10\mu\text{m}$), resulting in bulky devices and generally require large driving voltage. To address these limitations, recent years have seen tremendous effort to realize free-space light control based on subwavelength diffractive optical metasurfaces integrated with active materials.^{116–118,120–123,185–187} Metasurfaces can support resonances that enable substantial phase or amplitude modulation with small pixel-size. Since a smaller active volume is modulated, lower energy and faster modulation speed can be achieved. For example, metasurface resonators ($Q \sim 550$) based on organic electro-optic (EO) polymers have enabled GHz modulation speed;¹¹⁹ LCs combined with a Huygen's metasurface significantly reduced the pixel size ($\sim 1\mu\text{m}$) and LC thickness ($\sim 1.5\mu\text{m}$) required to attain a full 2π phase shift range;¹¹⁶ metasurfaces based on plasmonic resonances coupled to epsilon-near-zero materials have enabled a full 2π modulation with independent control of amplitude and phase;¹¹⁷ a large phase-modulation of $\sim 1.3\pi$ was reported by tuning a plasmonic metasurface using graphene.¹²³ Nevertheless, these approaches are all based on volatile changes such as the Pockels effect or free carrier dispersion, necessitating a constant power supply to hold the static state. To ensure time-multiplexed pixel control, most of these volatile SLMs require an active memory matrix with transistors to hold the written state. In addition, the most prevalent LC-based phase-only SLMs suffer from detrimental pixel crosstalk¹⁸⁸ and temporal phase fluctuations or jitter.¹²⁴ To overcome some of these limitations, a promising solution is to modulate light using non-volatile materials, which can drastically improve energy efficiency and avoid phase flickering. Moreover, the control complexity can be significantly reduced due to the built-in memory of the non-volatile reconfiguration. Chalcogenide-based PCMs are ideal candidates to realize such functionality,¹²⁶ thanks to their non-volatile microstructural phase transition,⁴⁹ large contrast in complex refractive index (typically $\Delta n \geq 1$),⁵⁰ and

CMOS compatibility.⁴⁷ Since PCMs hold their state once configured, a truly ‘set-and-forget’ switching element can be realized. In fact, PCMs have already attracted considerable attention to create tunable metasurfaces for applications such as varifocal lensing,^{122,127} beam steering,^{128,129} intensity switching,^{120,121,130,131} and spectral filtering.¹³² Despite the progress, non-volatile optical phase-only modulation in transmission - a highly desirable feature for SLMs - remains elusive. This is because previous works on nonvolatile tunable metasurfaces have used lossy PCMs such as GST^{120,131} or GSST¹²¹ which concomitantly induce large absorption upon phase transition, prohibiting optical phase-only modulation. The use of metallic heaters further leads to ohmic losses and makes transmissive operation difficult. In fact, to date, all electrically tunable PCM meta-optics have been demonstrated in reflection mode. Although non-volatile phase-only control has been demonstrated in mid infrared where GST is transparent,¹³³ the PCM was switched optically, which prevents a fully integrated and scalable platform. A similar work has shown near 2π phase shift via optical switching of low-loss PCM Sb_2S_3 in the visible spectrum,¹⁸⁹ but phase modulation is accompanied by a large amplitude change due to non-negligible loss of crystalline Sb_2S_3 .

By leveraging a thin layer of low-loss PCM Sb_2Se_3 ,¹⁹⁰ we demonstrate a non-volatile, electrically programmable metasurface for phase-only modulation of free-space NIR light in transmission. The ultra-low loss of Sb_2Se_3 enables decoupling of the phase modulation from amplitude modulation in NIR. A phase-only modulation of $\sim 0.25\pi$ in simulation and $\sim 0.2\pi$ in experiment is achieved by coupling the PCM to a high- Q diatomic metasurface ($Q \sim 409$). The tunable metasurface also demonstrates large endurance with over $\sim 1,000$ transitions. We further exploited a guided-mode resonance, albeit with a lower Q -factor, to facilitate a larger electric field overlap with the Sb_2Se_3 layer, which enables a full 2π phase shift. Beyond global control of the entire metasurface, we further show independent electrical control of 17 pixels, verified by optical microscope images and the spectral response, which shows discrete and reversible resonance levels as function of the respective configuration. A deterministic multi-level resonance tuning of the metasurface is achieved by switching the meta-molecules one-by-one with a total resonance shift of ~ 8 nm at a center wavelength of ~ 1230 nm. By imparting different phase profiles through independently controlling individual pixels, we demonstrate dynamic beam focusing with three distinct focal distances.

This work constitutes a crucial step towards a truly non-volatile “set-and-forget” transmissive phase-only SLM.

5.1 High-Q silicon diatomic metasurfaces

Sb_2Se_3 undergoes a refractive index contrast of ~ 0.7 and exhibits zero loss¹⁹⁰ near 1550nm upon phase transition, which stipulates a $\sim 1.1\mu\text{m}$ PCM thickness to obtain π phase shift. Although this is significantly thinner than LC used in commercial SLMs, it still poses a severe challenge in reversible switching the PCMs as PCMs need to be melt-quenched to be amorphized and such a large thickness prevents the critical cooling rate to be reached¹⁹¹. Motivated by the use of micro-ring resonators to increase the modulation in integrated photonics¹⁹², a high-Q planar resonator can also be used to enhance the phase-modulation of free-space light by thin film PCMs, while allowing thinner device layer compared to Fabry-Perot cavities. Earlier works on high-Q planar resonator focused on high contrast gratings (HCGs)¹⁹³, while the more recent works studied guided mode resonances^{194,195} and quasi-bound-state-in-continuum (q-BIC) in periodic nanostructures with in-plane asymmetry^{196,197}. Here we combine the idea of HCGs and q-BIC by introducing an asymmetry into the periodicity of traditional HCGs, realizing a diatomic metasurface (Figure 5.1a). Such diatomic gratings have also been proposed theoretically in several previous works^{198–200} but have not yet been demonstrated experimentally. Figure 5.1(a) shows that the symmetry of the HCG is broken by slightly displacing one of the gratings relative to the other so that the grating spacing becomes dissimilar i.e., $a_1 \neq a_2$. We denote such displacement or perturbation by $\delta = \frac{a_2 - a_1}{\Lambda}$ where Λ is the period of the diatomic gratings. The duty cycle Γ is defined as $\frac{w}{\Lambda_{HCG}}$ for HCGs and $\frac{2w}{\Lambda}$ for diatomic gratings, where w is the grating width. It can be seen that Γ is essentially identical for the two types of gratings because the period of diatomic gratings becomes doubled. The periodicity doubling causes the folding of the first Brillouin zone such that the dark modes that were originally at the edge of the Brillouin zone, which is outside the free space light cones, get folded into the interior of the light cones, allowing for free-space excitation^{198,199}. Figure 5.1(b) shows the simulated spectral response of HCGs ($\delta=0$) and diatomic gratings

($\delta=0.05$) upon excitation of normal incident transverse-magnetic (TM) polarized light near 1550nm wavelength ($\Lambda=900\text{nm}$ and $\Gamma=0.7$). When $\delta=0$, the dark modes are not accessible to the free-space excitation and hence no resonance is observed. While a small perturbation of $\delta=0.05$ is enough to introduce a sharp q-BIC resonance with its signature Fano line shape. The pronounced resonance is also clearly visible where the q-BIC resonance represents a ~ 40 times electric field enhancement compared to when $\delta=0$. By fitting the experimentally measured resonance we extract a large Q factor of 409 for heavily N-doped 220nm silicon-on-insulator (SOI) at doping concentration $\sim 10^{20}\text{cm}^{-3}$, as shown in inset of Figure 5.1(b). Such a high experimental Q factor is attributed to the ultra-smooth etching side wall as revealed by Figure 5.1(c), despite the additional loss from the doping. Figure 5.1(d) shows the experimentally measured resonances as the period increases from 900nm to 1000nm (silicon thickness=220nm, $\delta=0.05$ and $\Gamma=0.7$). The resonance shifts almost linearly across the telecommunication wavelength range without significant change in the Q factor – a highly-desirable characteristic of diatomic gratings¹⁹⁸. In contrast, changing the period of HCGs will lead to dramatic change in the Q factor as reported previously¹⁹³. Now it becomes clear why diatomic grating makes an ideal platform for demonstrating nonvolatile phase-only modulation with low-loss PCMs. First, the high Q resonance is very sensitive to loss. Cladding the metasurface with lossy materials will lead to a drastic reduction in the Q factor and hence obscuring the phase response, which is shown in the simulation where 20nm GST is cladded on the diatomic gratings. Secondly, 1D gratings with equal width w allow identical microheater resistance, which is essential for uniform heating of PCMs cladded on top. Using dissimilar gratings width¹⁹⁹ or introducing notches¹⁹⁴ in the gratings will also lead to high Q resonances, but each grating will have different resistance and distinct Joule heating from current injection. Lastly, the resonance can be fine-tuned to arbitrary wavelength by changing the period without degrading the Q factor, enabling operation over a large wavelength range limited only by the material bandgap. Figure 5.2(a) and (b) show the electric field distribution near the diatomic grating when $\delta = 0$ and $\delta = 0.05$. It is observed clearly that the a resonance mode localized in the air emerges when $\delta \neq 0$.

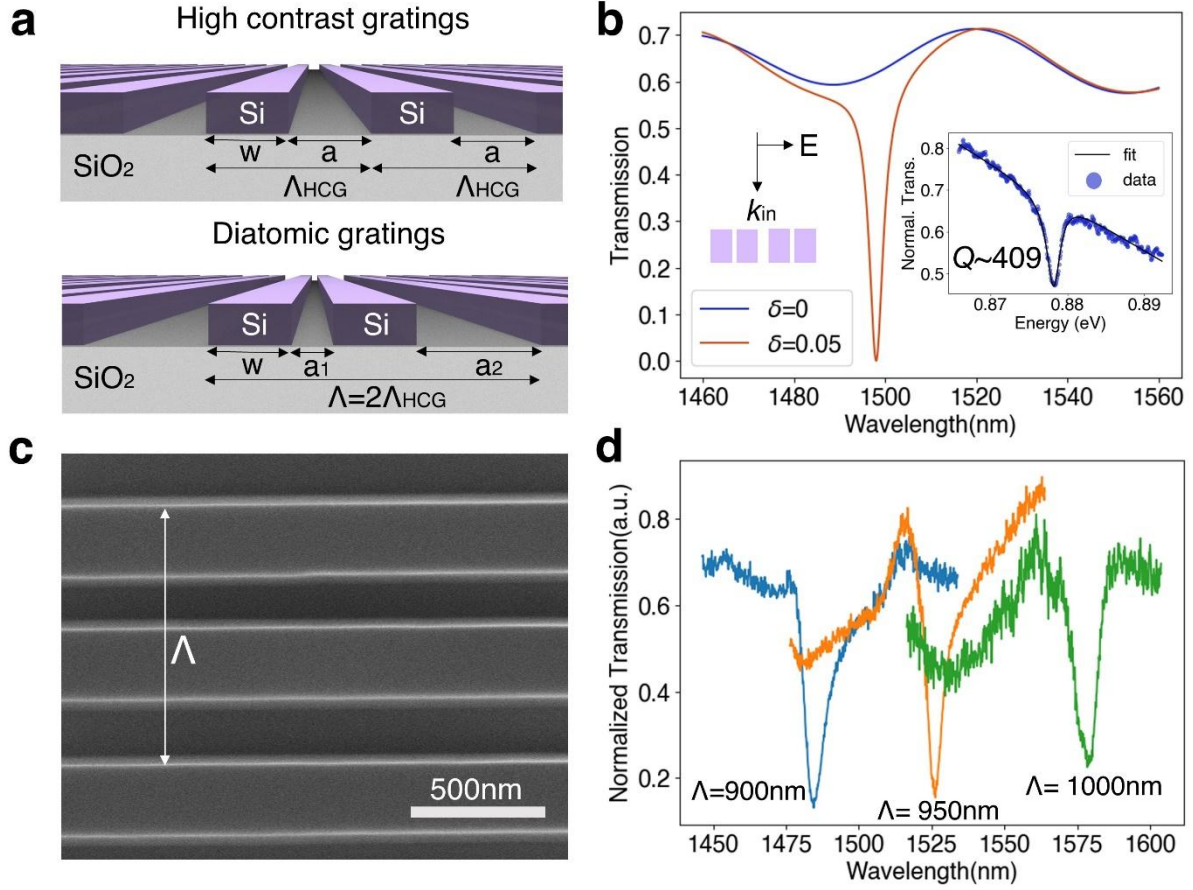


Figure 5.1: **High-Q silicon diatomic metasurfaces.**

(a) Schematics of the high contrast gratings (top) and diatomic gratings (bottom). Λ_{HCG} and Λ are the periods of the high contrast gratings and diatomic gratings respectively. The spacing between the gratings are denoted as a , a_1 , and a_2 . w is the grating width. **(b)** Simulated transmission spectrum of the high contrast gratings (blue) and diatomic gratings (orange) under normal incident TM polarized light. Silicon thickness is 220nm, $\Lambda=900\text{nm}$ and $\Gamma=0.7$. Inset: Experimental spectrum of a resonance fitted by Fano equation, $\Lambda=950\text{nm}$ and $\Gamma=0.7$. **(c)** SEM of fabricated silicon diatomic gratings. **(d)** Experimental spectrum of diatomic gratings with different periods from 900nm to 1000nm, where $\delta=0.05$ and $\Gamma=0.7$.

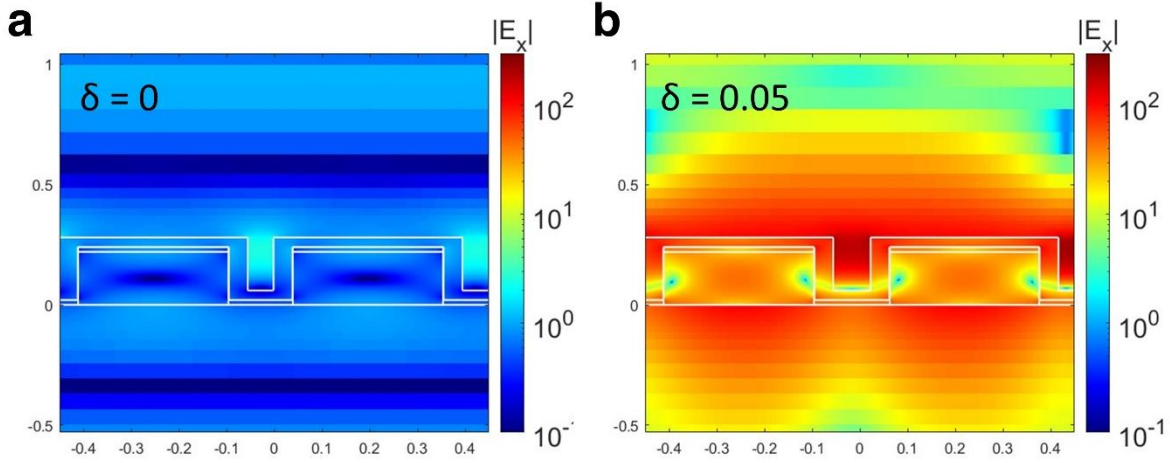


Figure 5.2: **Electrical field amplitude of the diatomic resonance.**

(a) The electric field profile when $\delta=0$, corresponding to the high contrast gratings. (b) The field profile of diatomic metasurfaces on resonance. The unit for the scale bar is micrometer. $\Lambda=900\text{nm}$ and $\Gamma=0.7$.

5.2 A nonvolatile electrically reconfigurable metasurface for phase-only control

In order to dynamically control the diatomic metasurface, we heavily dope the SOI into microheaters^{201,202} that is used to switch the Sb_2Se_3 cladded on top in Figure 5.3(a). The Phosphorus doped (doping concentration $\sim 10^{20}\text{cm}^{-3}$) SOI is then etched into diatomic gratings before uniformly cladded with 20nm Sb_2Se_3 , followed by 40nm atomic-layer-deposited (ALD) Al_2O_3 encapsulation to prevent oxidation and PCM re-flowing during switching. Ohmic contacts are then formed by Ti/Au electrodes. The cross-section of the metasurface is shown in Figure 5.3(c). Current is injected into the highly doped silicon gratings via electrical pulses that causes joule heating, which in turn switches the PCMs. A two-objective transmission setup is built to probe the reversible switching of Sb_2Se_3 -loaded diatomic metasurface. The fabricated chip is wire bonded to a customized printed circuit board (PCB), labelled PCB1 in Figure 5.3(b), connected to a second customized PCB carrying a microcontroller, labelled PCB2 in Figure 5.3(b). PCB2 is then connected to an arbitrary function generator (AFG) that generates pulses. The microcontroller on PCB2 can be programmed by a computer to individually address metasurface pixels fabricated on the same

chip. Figure 5.3(d) shows the optical micrograph of a 30- μm aperture metasurface pixel on a chip that has been wire bonded to the PCB.

Below is the detailed fabrication process of this device. The reconfigurable diatomic metasurface is fabricated on a 220-nm-thick silicon layer on top of a 3- μm -thick buried oxide layer (SOITECH) with back-side-polished silicon. The blanket SOI wafer is first implanted by phosphorus ions with a dosage of $2 \times 10^{15} \text{ cm}^{-2}$ and ion energy of 40 keV at a tilt angle of 7° . Subsequently, the wafer is annealed at 950°C for 30 min to activate the dopants. The metasurface pattern is defined by a JEOLJBX-6300FS 100kV electron-beam lithography (EBL) system using positive tone ZEP-520A resist. 220 nm fully etched gratings are made by an inductively coupled plasma reactive ion etching (ICP-RIE) process in Fluorine-based gases. Before metallization, the surface native oxide was removed by immersing the chips in 10:1 buffered oxide etchant (BOE) for 15 seconds to ensure Ohmic contact. A second EBL exposure using positive tone poly(methyl methacrylate) (PMMA) resist is subsequently carried out to create windows for the Ti/Au deposition. After development, 5nm Ti followed by 150 nm Au was electron beam evaporated onto the chip. The lift-off of Ti/Au was completed again by immersing the chip in methylene chloride. Note that for the individual control of meta-molecules we replaced Au with Pt for electrodes to avoid the melting of the traces at high voltages. The third EBL step is used to expose the PMMA resist before depositing Sb_2Se_3 via magnetron sputtering. The Sb_2Se_3 is sputtered using a magnetron sputtering system at 30 W RF power under a deposition pressure of 4 mTorr and Ar flow of 30 sccm. The deposition rate for Sb_2Se_3 is $\sim 1 \text{ nm/min}$. Additionally, the samples are capped with 10 nm of SiO_2 sputtered in situ (150 W RF power, 4 mTorr pressure, and Ar flow of 30 sccm), to prevent oxidation during sample shipping. The atomic ratio of Sb_2Se_3 after deposition is confirmed using XPS to be Sb:Se $\approx 44:56$ which is close to the sputtering target stoichiometry of Sb:Se $\approx 40:60$. Immediately after lifting off the PCM in methylene chloride, a 40nm ALD Al_2O_3 is grown on the chip to protect the PCM from oxidation and reflowing during switching. To allow good adhesion between the wedge bonds and the metal pads, the 5th EBL step is used to open windows in PMMA resist at the wire bonding regions for Al_2O_3 etching. The Al_2O_3 on top of the contacts is etched away using ICP-RIE etching in Chlorine-based gases. Then the PCMs are initialized into the fully

crystalline state by rapid thermal annealing (RTA) at 200° C for 10 min under N₂ atmosphere before measurements. Finally, the chip is wire bonded onto the custom-made PCBs using a wire bonder (Westbond) via gold ball-wedge bonds.

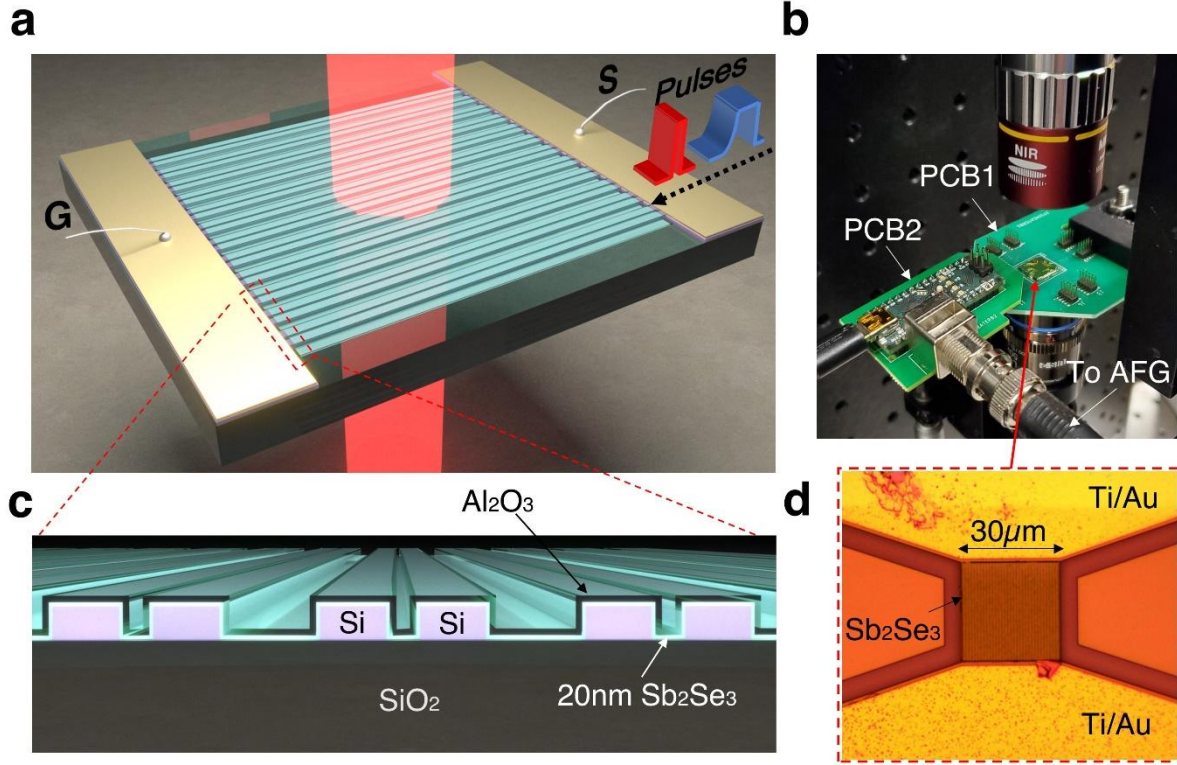


Figure 5.3: **A nonvolatile electrically reconfigurable metasurface based on Sb₂Se₃.**

(a) Schematic of the transmissive tunable diatomic metasurface based on Sb₂Se₃. S (G), signal (ground) electrode. (b) The optical setup for probing the metasurface in transmission along with the devices under test wire bonded to a customized PCB. AFG is the arbitrary function generator. (c) The schematic of the tunable metasurface cross section. (d) Optical micrograph of a single metasurface pixel on the chip under test.

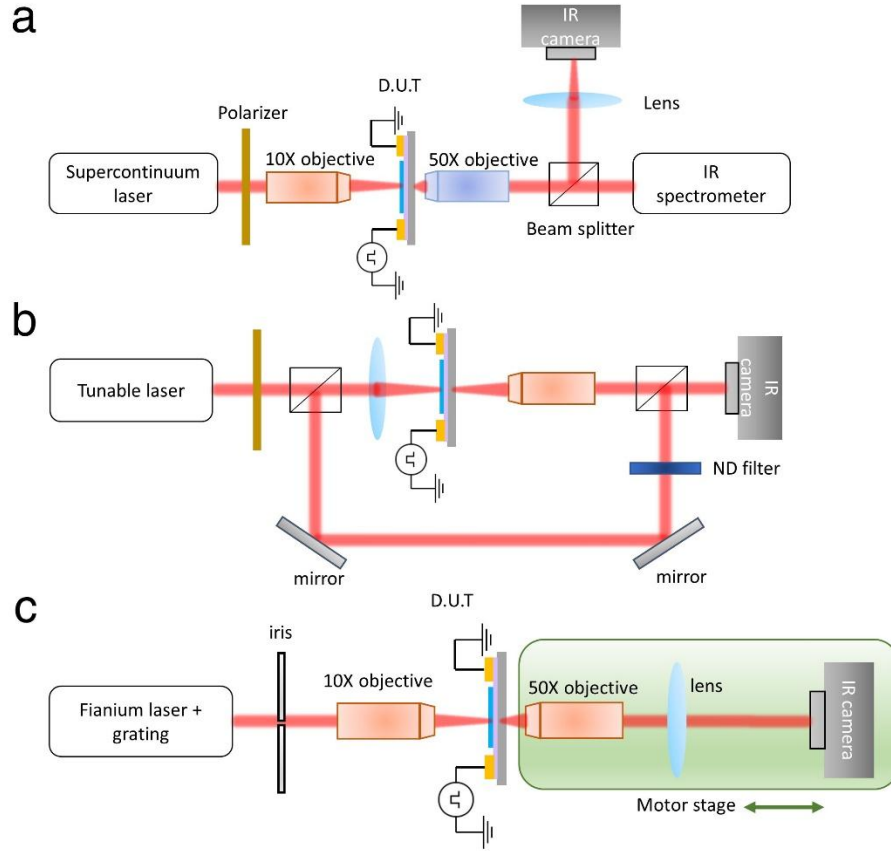


Figure 5.4: **Optical measurement setup for *in situ* electrical control of metasurface.**

(a) Transmissive spectral measurement setup. **(b)** Optical phase measurement based on a Mach-Zehnder Interferometer. **(c)** Motorized stage setup for far-field beam profile imaging.

The experimental setup we built for reversible switching experiment is shown in Figure 5.4(a) and described as following. Each metasurface pixel on the chip is connected to a metal pad that is wire bonded to a pin on the carrier PCB or PCB1. A hole (0.8cm in diameter) is opened at the center of PCB1 to allow direct light transmission through PCB. To individually control the pixels, a second customized PCB (PCB2) carrying a microcontroller (Arduino Nano) is inserted into the predefined pins on PCB1. Most commercial microcontrollers normally supply low voltage (≤ 5 V) and slow speed (tens of megahertz), whereas high amplitude (> 10 V) and short (nanosecond falling edge) pulses are required to amorphized the PCMs. Hence the microcontroller cannot be directly used to switch PCMs, instead an external function generator is connected to the PCB2 as a source of excitation. The microcontroller can be programmed to turn on/off 17

MOSFETs connected in series with the on chip microheaters. By switching the MOSFET, the voltage drop across the microheater can be controlled independently when an electrical pulse is applied. The resistance of the microheaters is measured using a source meter (Keithley 2450). A $30\ \mu\text{m} \times 30\ \mu\text{m}$ large metasurface pixel typically has resistance of $\sim 115\ \Omega$ at 1 mV DC bias, with $\sim 45\ \Omega$ due to the relatively long Pt wires. The resistance of a single channel is $\sim 1.45\ \text{k}\Omega$. The SET and RESET pulses were generated from an arbitrary function generator (Keysight 81150A). To reconfigure the metasurface, we used a voltage pulse of 15 V ($\sim 10\ \text{mA/channel}$), 1.25 μs pulse width, and 8 ns rising/trailing edge to induce the amorphization. For crystallization, multiple voltage pulses of 6 V ($\sim 4.1\ \text{mA/channel}$), 50 μs pulse width, and 30 μs trailing edge is used. Our current device size is limited by the maximum voltage (20 V at $50\ \Omega$ load impedance) of our function generator. A larger aperture size will require function generator that can source higher voltage to amorphize the PCMs.

Reversible tuning of the diatomic resonance is shown in Figure 5.5(a) (simulation) and 4.3(b) (experiment). The spectra of three consecutive switching cycles are plotted in Figure 5.5(b) and the shaded regions indicate standard deviations between the cycles. The small standard deviation reveals excellent cycle to cycle reproducibility. The experimentally extracted spectral shift ($\Delta\lambda \sim 1.2\ \text{nm}$) matches very well with the simulated shift ($\Delta\lambda \sim 1.3\ \text{nm}$). Reversible tuning of the diatomic resonance is shown in Figure 5.5(a) for simulation and Figure 5.5(b) for experiment, respectively. The spectra of three consecutive switching cycles are plotted in Figure 5.5(b) and the shaded regions indicate standard deviations between the cycles. The small standard deviation reveals excellent cycle to cycle reproducibility. The experimentally extracted spectral shift ($\Delta\lambda \sim 1.2\ \text{nm}$) matches very well with the simulated shift ($\Delta\lambda \sim 1.3\ \text{nm}$). Figure 5.5(c) shows the phase shift ($\Delta\phi$) and transmission contrast ($\Delta T\%$) between the two optical states near the 1518 nm resonance. A good agreement between the simulation and the experiment can be clearly observed. We extract a maximum phase shift of $\sim 0.2\pi$ ($\sim 0.25\pi$) near the resonance wavelength via digital holography experiment (simulation) with less than 10% measured change in transmission. To measure the phase shift caused by the switching, we built a free-space MZI in Figure 5.4(b) and switched the pixel in-situ. The

interference fringes between the signal beam through the metasurface and the reference beam are taken by the IR camera. The images are captured at 11 different wavelengths from 1513 nm to 1523 nm for the two optical states, averaged over 20 frames. The phase of each optical state is calculated by first applying a high pass filter on the image in the Fourier domain, and then take the argument of the filtered image in the real space. The phase shift is the difference between the extracted phase in crystalline state and amorphous state. We note that, this phase shift is ~ 10 times larger than what can be achieved by switching a 20-nm-thick blanket film of Sb_2Se_3 without a metasurface. The extracted Q factor only decreases from 312 to 271 upon crystallization, representing only 13% reduction, which shows that minimal loss is introduced by the phase transition. In contrast, the high Q resonance is completely suppressed by the same thickness of GST cladded on the metasurface due to its high optical loss in Figure 5.6(d). This is done by fitting the spectrum to a Fano resonance via $T = |a + jb + \frac{c}{E - E_0 + j\gamma}|^2$, where a , b , and c are constant real numbers. E is the photon energy and E_0 is the central resonance energy. 2γ is the line width of the resonance. So, the Q factor is calculated to be $\frac{E_0}{2\gamma}$.

Finally, we show that the tunable metasurface is robust against switching over 1,000 times without degradation in contrast, as shown in Figure 5.5(d). The tunable laser is parked near the resonance to detect a measurable change in the transmission. Optical micrographs taken before and after the cyclability test indicate no ablation is caused by the switching across the entire $30 \times 30 \mu\text{m}^2$ metasurface. Apart from switching Sb_2Se_3 , we also show that the doped silicon microheater is a versatile platform for switching other PCMs, for example we have also reversibly switched GST using doped silicon on sapphire microheaters to realize a broadband tunable notch filter in transmission (Figure 5.6).

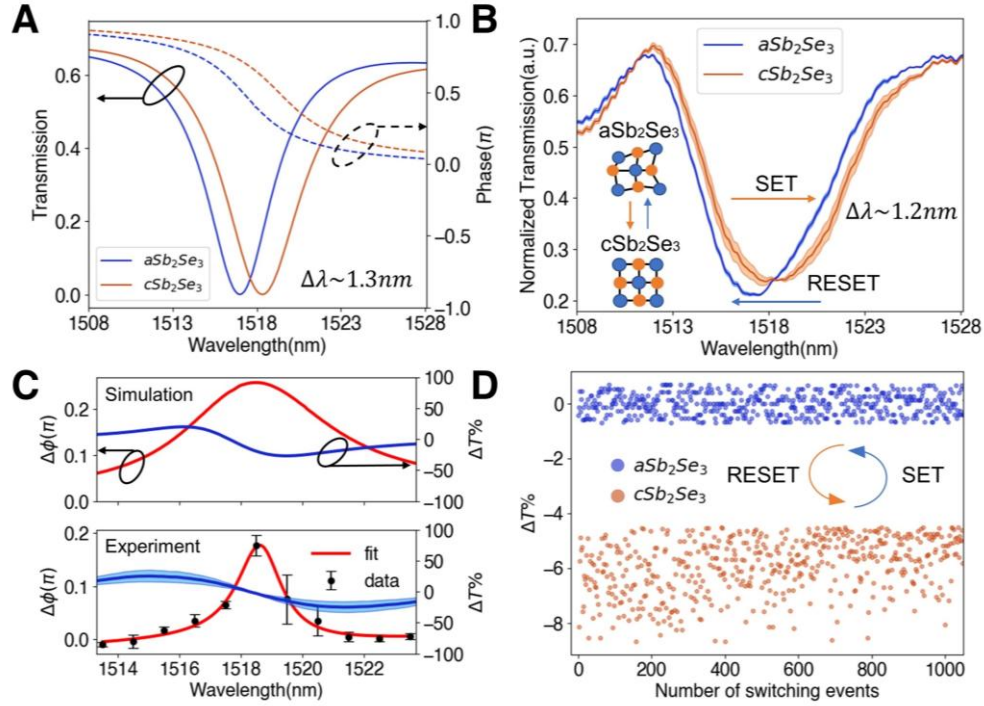


Figure 5.5: **Reversible switching of the diatomic metasurface and nonvolatile phase-only modulation.**

(a) Simulated spectral and phase shift caused by the phase transition of 20-nm-thick Sb_2Se_3 . $\Delta\lambda$ is the wavelength shift of the resonance dip. The diatomic metasurface is designed to have $\Lambda=900\text{ nm}$, $\Gamma=0.7$, and $\delta=0.05$. a(c) Sb_2Se_3 : amorphous(crystalline) Sb_2Se_3 . (b) Measured reversible switching of the diatomic resonance. The switching conditions are 3.6 V, 50 μs pulse width, 30 μs trailing edge for SET and 11.6 V, 1 μs pulse width, 8 ns trailing edge for RESET. Three consecutive cycles are plotted where the shaded area indicates the standard deviation between the cycles and the solid line indicates the average. The spectrum is normalized with that of bare SiO_2 on silicon. (c) Phase shift ($\Delta\phi$, red) and transmission contrast ($\Delta T\%$, blue) between two optical states extracted from simulation (top) and experiment (bottom). The phase is measured at 11 different wavelengths with 1nm spacing and averaged over three switching cycles. The standard deviation over the cycles is shown by the error bars. (d) Cyclability of the tunable metasurface for 1,000 switching events. The switching conditions are 3.6 V, 50 μs pulse width, 30 μs trailing edge for SET and 11.6 V, 600 ns pulse width, 8 ns trailing edge for RESET. Each pulse is temporally separated for 2 seconds to ensure long thermal relaxation. The data is filtered by a two-point moving average to reduce fluctuation caused by thermal and mechanical noises.

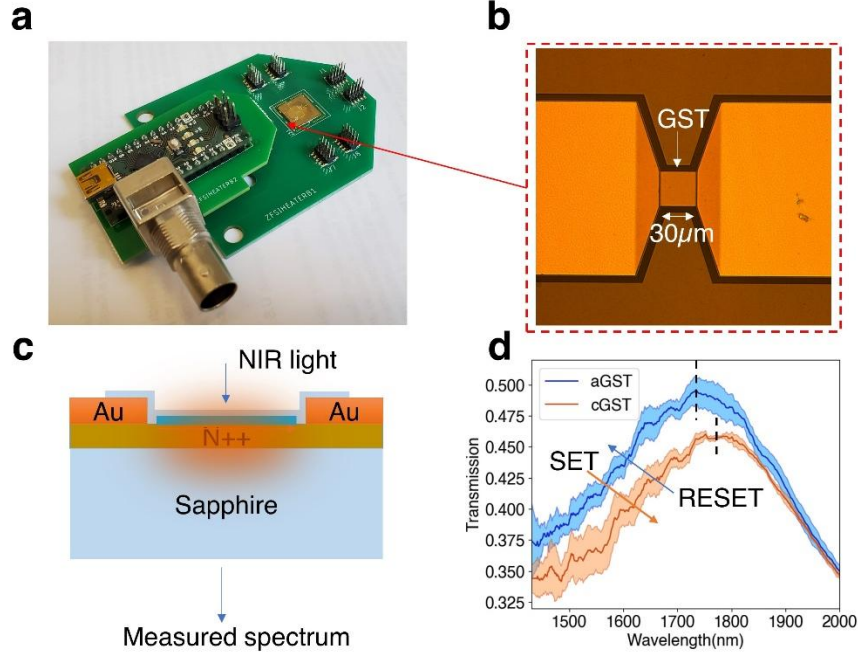


Figure 5.6: **Reversible switching of GST blanket film using doped Si heater.**

(a) A silicon-on-sapphire chip wire bonded to a customized PCB. (b) A switchable GST pixel on the chip. (c) Schematic of the device structure. The Si is 500nm thick and the GST is 20nm thick. (d) Reversible switching of the transmission spectrum of a 10 μ m large GST pixel measured by a FTIR. The spectrum is averaged across five cycles. 2.5V, 50 μ s wide, 50 μ s trailing edge pulses are used for crystallization, 7V, 200ns wide, 8ns trailing edge pulses are used for amorphization.

5.3 Individually addressing meta-gratings

In this section, we demonstrate the manipulation of light in spatial domain by individually programming the meta-gratings. To demonstrate the spatial light modulation, we found a TE-polarized guided mode resonance with much stronger electric field interaction with Sb₂Se₃ in Figure 5.7(b), which is utilized in the following experiment to achieve a larger resonance shift (~ 10 nm measured in experiment) and phase shift ($\sim 2\pi$ near the resonance extracted from the simulation), albeit at the expense of a lower Q-factor (~ 100) than the q-BIC designs. We note that such phase shift could in principle be measured with the same digital holography setup in Figure 5.4(b), but we do not have a laser source with fine enough linewidth near this new resonance wavelength in Figure 5.8. The linewidth of the laser source can influence the phase

measurement result significantly by smearing out the interference effects at different wavelengths. Figure 5.4(c) and (d) show that near the resonance, a wavelength dependent phase shift is presented, and at certain wavelengths the amplitude contrast is low. Figure 5.4(e) and (f) show the experimentally measured spectrum for a(c) Sb_2Se_3 , as well as the transmission contrast in %, showing a similar phase-only behavior near 1225 – 1228 nm.

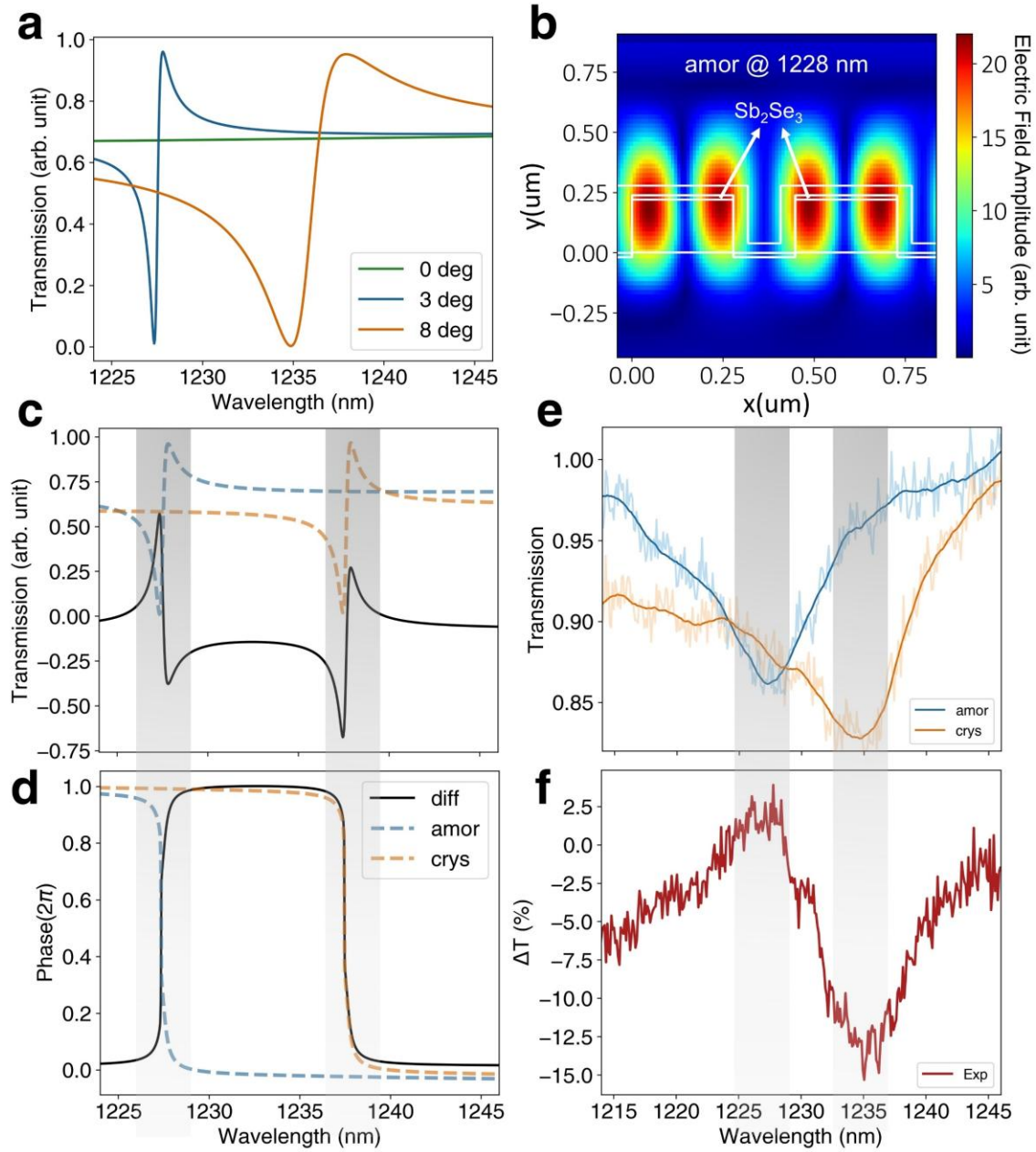


Figure 5.7: Transverse-electric polarized guided-mode resonance mode with strong field overlap with Sb_2Se_3 , achieving larger resonance shift and a full 2π phase modulation.

(a) The transmission spectra for light with normal incident (green) and with a 3° (blue) and 8° (orange) angle. The resonance is only found with a non-zero incident angle. It is shown that the resonance is not clearly visible below 3° and a further increase of the angle leads to a decrease in Q-factor. Therefore, we chose 3° because it supports a resonance mode with a relatively high Q-factor. The following results are simulated with an incident angle of 3° . **(b)** Electric field distribution for amorphous-Sb₂Se₃ at resonance wavelengths 1228 nm. The white contour represents the metasurface structure. The field on Sb₂Se₃ is much stronger compared to the quasi-BIC mode in Figure 5.2. Using crystalline-Sb₂Se₃ gives a similar field profile at 1238 nm due to the relatively thin Sb₂Se₃. **(c)** Calculated transmission spectra at amorphous (denoted "amor", blue dashed line) and crystalline (denoted "crys", orange dashed line) state. The transmission change is plotted in black. A large spectral shift of ~ 10 nm is observed. The transmission change is highly wavelength dependent and is close to 0 % (25%) when π (2π) phase shift is achieved. **(d)** Wavelength-dependent phase difference (denoted "diff", black line) between the amorphous (blue dashed line) and crystalline (orange dashed line) state with a maximum phase modulation of full 2π . One can achieve an arbitrary phase shift ($0 \sim 2\pi$) near the resonances (near 1228 or 1238 nm, denoted by the gray boxes) by precisely controlling the laser wavelength. **(e)** Measured optical transmission spectrum when all Sb₂Se₃ was set to amorphous (blue line) and crystalline (orange line) phases. The data is smoothened by a 72-data moving average filter and the raw data is indicated by light colors. We note that the raw data is only normalized for the transmission to a reference background (a box area with silicon etched away). The absolute transmission is around 86% (83%) at minimum for amorphous (crystalline) phase. This transmission is much higher compared to the simulation, which can be attributed to finite metasurface area and the 0-th order transmission. **(f)** Relative transmission change ΔT when changing the entire metasurface from amorphous to crystalline phase. A maximum change of $\sim 15\%$ (2.5%) is observed near the crystalline (amorphous) phase resonance, indicating a very small amplitude change.

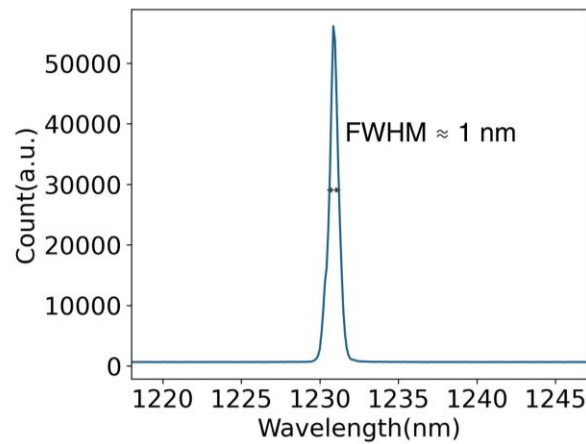


Figure 5.8: Spectrum of the Fianium broadband source combined with a grating.

To ensure the uniformity of resistance across the channels, we derive an analytical model for the metal wires from the metasurface to the metal pads, depicted in Figure 5.9(a). The model was then used to design the metal wire geometry to obtain uniform resistance, which is essential for the simultaneous control of multiple channels.

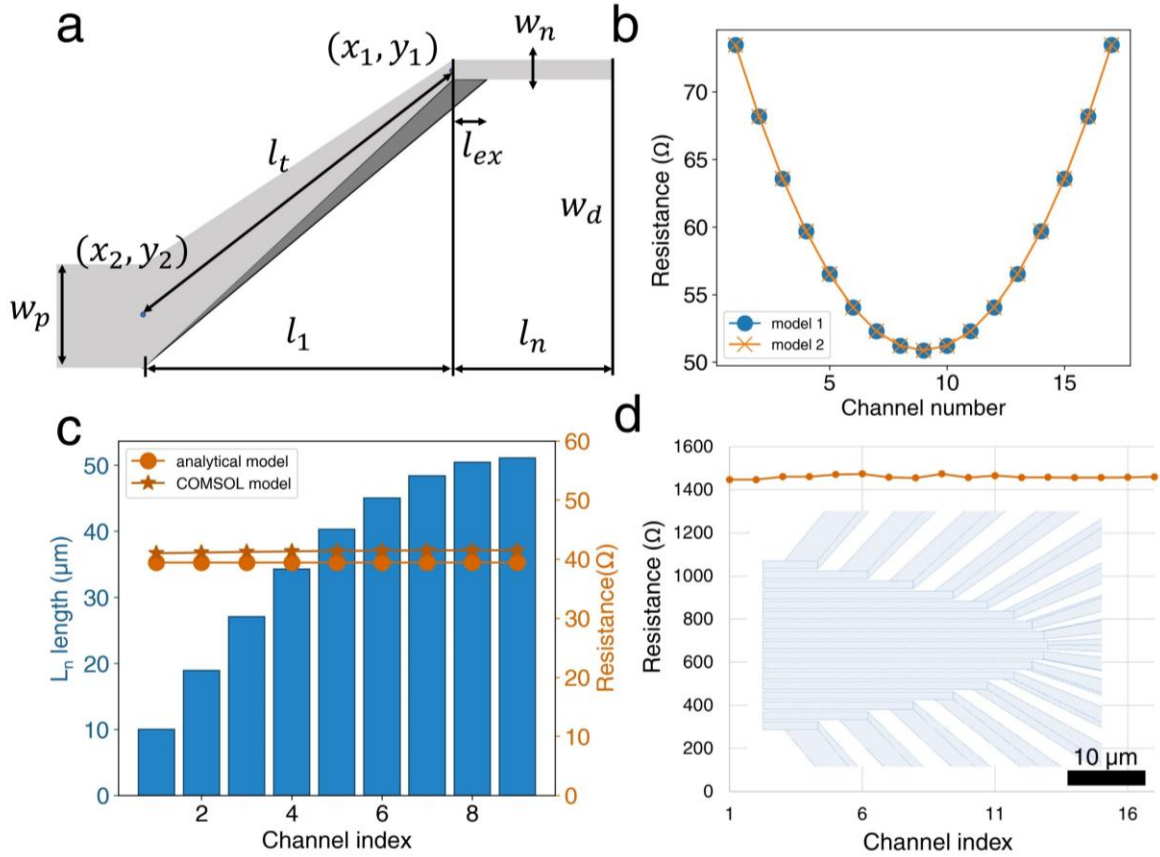


Figure 5.9: **Metal wire engineering to achieve equal resistance across 17 channels.**

(a) Schematic for a single metal wire with parameters denoted. 17 channels have different w_d , hence geometry engineering is necessary to achieve uniform resistance. For the first model, only the light gray region is used. In the second model, the dark gray region is added to avoid narrow width at the turn, enhancing the wire's robustness against high current. **(b)** Calculated resistance using model 1 (blue) and model 2 (orange), showing matching results of a large resistance variation of around 25Ω across the channels if L_n is constant. **(c)** Optimized design for uniform resistances by varying L_n across the channels (blue). The orange line with circle (star) markers is the resistance calculated from the analytical model (COMSOL simulation). **(d)** Experimentally measured resistance across 17 channels.

We denote the resistance of the rightmost straight wire as R_1 and that of the tilted part from points (x_1, y_1) to (x_2, y_2) as R_2 . The pad resistance is usually small and is ignored. Therefore, the total resistance is calculated as $R = R_1 + R_2$.

In our first model, where the dark gray part is not considered, R_1 is given by:

$$R_1 = \frac{\rho l_n}{h w_n} \quad (5.1)$$

Where $\rho = 10.8 \times 10^{-8} \Omega/m$ is the resistivity of Pt, $h = 250 \text{ nm}$ is the metal wire thickness, l_n and w_n are denoted in the schematic. The tilted wire can be approximated by a trapezoid, the resistance of which could be obtained by segmenting the wire into small rectangular pieces and integrating them over the entire length. Although this method ignores the boundary effects of electric currents, it works very well for a slowly varying shape. Considering an isosceles trapezoid with a top width of w_t , bottom width of w_b and height of l_t , the resistance is calculated as $R = \frac{\rho}{h a_0} \ln \left(\frac{a_0 l_t}{w_t} + 1 \right)$, where $a_0 = (w_b - w_t)/l_t$. Here, w_t and w_b could be approximated as:

$$\begin{cases} w_t = w_n \cdot \cos(\theta) \\ w_b = w_p \cdot \cos(\theta) \end{cases} \quad (5.2)$$

Where w_n and w_p are constants as denoted in the schematic, and θ is the tilting angle ($0 \sim \pi/2$) of the wire, given by

$$\theta = \left| \arctan \left(\frac{y_2 - y_1}{x_2 - x_1} \right) \right| \quad (5.3)$$

Where $|a|$ means taking the absolute value of a . The length of the tilted wire can be obtained by $l_t = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. Therefore, the total resistance is given by the following equations:

$$\left\{ \begin{array}{l} R = \frac{\rho l_n}{h w_n} + \frac{\rho}{h a_0} \ln \left(\frac{a_0 l_t}{w_t} + 1 \right) \\ a_0 = (w_b - w_t)/l_t \\ w_t = w_n \cdot \cos(\theta) \\ w_b = w_p \cdot \cos(\theta) \\ \theta = \left| \arctan \left(\frac{y_2 - y_1}{x_2 - x_1} \right) \right| \\ l_t = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \end{array} \right. \quad (5.4)$$

In the experiment, we observed that the corners were the most prone to damage. This is attributed to a narrow wire at the corner, especially for edge channels with large tilting angles. We add extra metal wires drawn in dark gray to improve the robustness. The second model for this revised structure is given by:

$$\left\{ \begin{array}{l} R = \frac{\rho(l_n - l_{ex}/2)}{h w_n} + \frac{\rho}{h a_0} \ln \left(\frac{a_0 l_t}{w_t} + 1 \right) \\ a_0 = (w_b - w_t)/l_t \\ w_t = w_n \cdot \cos(\theta) + l_{ex} \cdot \sin(\theta) \\ w_b = w_p \cdot \cos(\theta) \\ \theta = \left| \arctan \left(\frac{y_2 - y_1}{x_2 - x_1} \right) \right| \\ l_t = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \end{array} \right. \quad (5.5)$$

As a sanity check, Eq. (5.5) reduces to Eq. (5.4) if $l_{ex} = 0$. The accuracy of our model is also verified by Figure 5.9(b), where two models match well. It can also be seen that there is a large resistance variation of $\sim 25\Omega$ across the 17 channels if we use the same L_n . By varying the L_n spatially, it is possible to obtain uniform resistance (variation $\sim \pm 0.5\Omega$, $< 1\%$) across the channels as shown in Figure 5.9(c). The analytic model also agrees with the COMSOL simulation with less than 2Ω difference. The optimized metal wire shape is shown in the inset of Figure 5.9(d). In experiments, the doped-silicon gratings contribute to a much higher resistance than the simulation with an average resistance of $\sim 1460\Omega$ across 17 channels, see Figure 5.9(d). However, the variation in the resistance is only around $\pm 10\Omega$ ($\sim 1\%$ of the resistance) which will not lead to significant variation in Joule heating.

Besides optical resonance engineering, we also designed electrical signal routing and improved the uniformity of the electrical response. Each pixel of the metasurface must be individually addressed to fully control the optical wavefront. As shown in Figure 5.10(a)-(c), such controllability of individual pixel is

realized using a source metal wire and 17 separate ground wires for each channel (two periods). The wires are electrically isolated with each other by over-etching silicon and wire-bonded to the PCB 1 in Figure 5.3(b). Each ground wire is switched ON/OFF by PCB2 through a CMOS transistor. The source wire delivers the voltage pulses to all the ON channels with equal current.

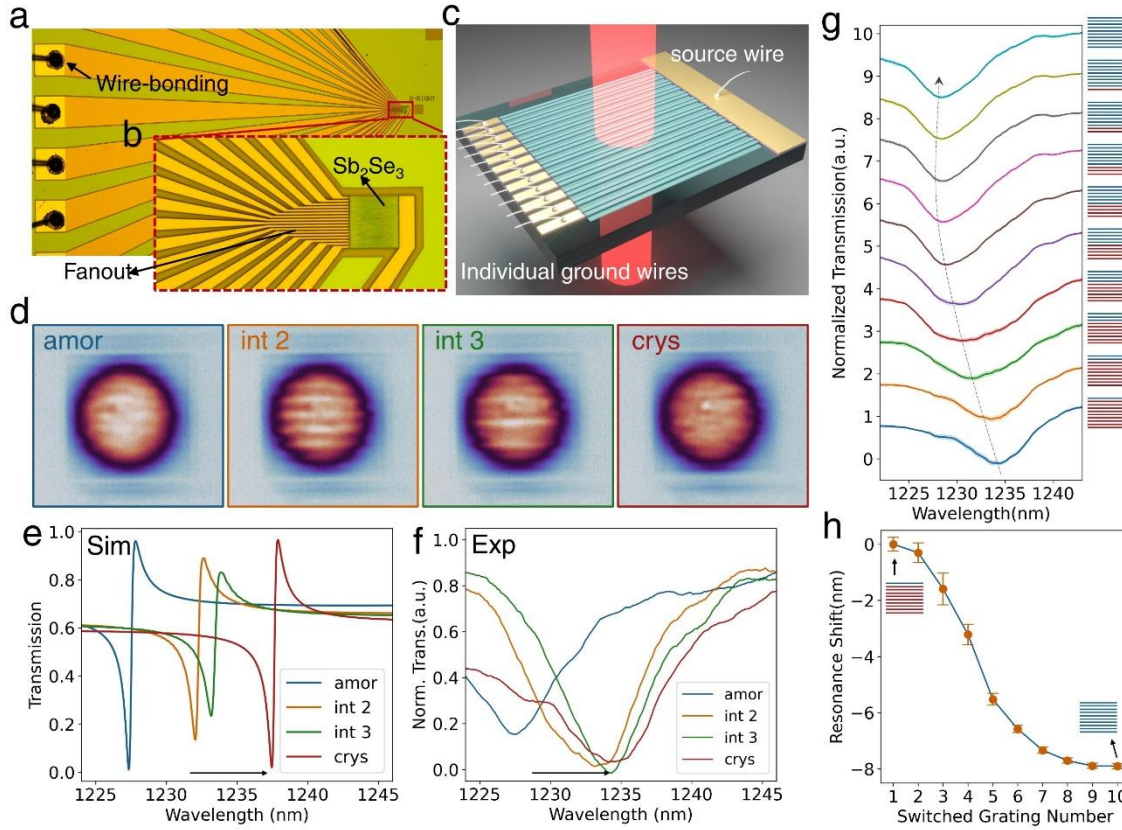


Figure 5.10: Electrically addressing individual meta-atoms.

(a) Micrograph image of the metasurface with individual meta-atom controllability, where each channel is wire-bonded to a PCB. (b) Zoomed-in micrograph image that shows 17 electrical wire fan-outs. (c) Schematic plot. (d) IR images showing four different metasurface configurations. The brighter (dark) color shows an amorphous (crystalline) Sb_2Se_3 due to the slight absorption difference. (e) Simulated spectra corresponding to each configuration in d. (f) Measured spectra. The spectral shifts agree well with the simulation. (g) Waterfall plot for the normalized transmission spectra as switching meta-atoms one-by-one. The result is averaged over 9 repeated experiments, and the barely visible shaded region indicates the standard deviation. The resonance dip shifts gradually from ~ 1235 nm to ~ 1228 nm with little variation. (h) Fitted Fano-resonance spectral shift with respect to the number of channels switched. The resonance wavelength gradually blue shifts as more gratings are switched. The minimal error bar indicates a near-deterministic multilevel operation.

We implement arbitrary phase masks via the following two-step sequence: (1) first, all meta-molecules are electrically switched to the crystalline phase; (2) a single amorphization pulse is then applied to switch the selected meta-molecules. Amorphization, instead of crystallization, is used for independent control to avoid channel crosstalk. We observed large crosstalk if crystallization is used to switch the individual channel, as the longer crystallization pulses lead to a more severe thermal dispersion (Figure 5.11). This can be easily verified in COMSOL simulator Figure 5.12. Additionally, the lower temperature threshold for crystallization compared to amorphization (200 °C for crystallization vs. 620 °C for amorphization) can also contribute to crosstalk. Using this two-step switching method, four different configurations of the metasurface were obtained, shown in the IR camera images in Figure 5.10(e) and (f): (i) all amorphous metasurface; (ii), (iii) hybrid metasurface with an amorphous period two and three times the original channel pitch respectively, and (iv) all crystalline metasurface. Movie S1 shows the reversible switch between these configurations. The insets at the bottom left corner of each subplot show a schematic for the respective metasurface configurations for clarity. The bright (dark) lines correspond to amorphous- (crystalline-) Sb_2Se_3 from the slight absorption difference. The patterns are implemented by the same phase transition condition (15 V, 1.25 μs for amorphization and 6 V, 50 μs for crystallization), showcasing a universal method to set arbitrary patterns. Besides the IR camera images, we also measured the spectra of the configurations in, which qualitatively matches with simulations.

The individually addressable metasurface was first globally switched to crystalline phase; then arbitrarily phase pattern was imparted by selecting the channels via Arduino and applying the same voltage pulse for amorphization. Starting from crystalline phase is preferred because unintentional switching of the neighbor pixels could be avoided by the more stringent amorphization transition condition. This is also verified by heat transfer simulation. Figure 5.10(d) shows four example images taken by an IR camera, where the brighter (darker) parts are amorphous- (crystalline-) Sb_2Se_3 due to the slight absorption difference. The patterns are implemented by the same phase transition condition (15 V, 1.25 μs for amorphization and 6 V, 50 μs for crystallization).

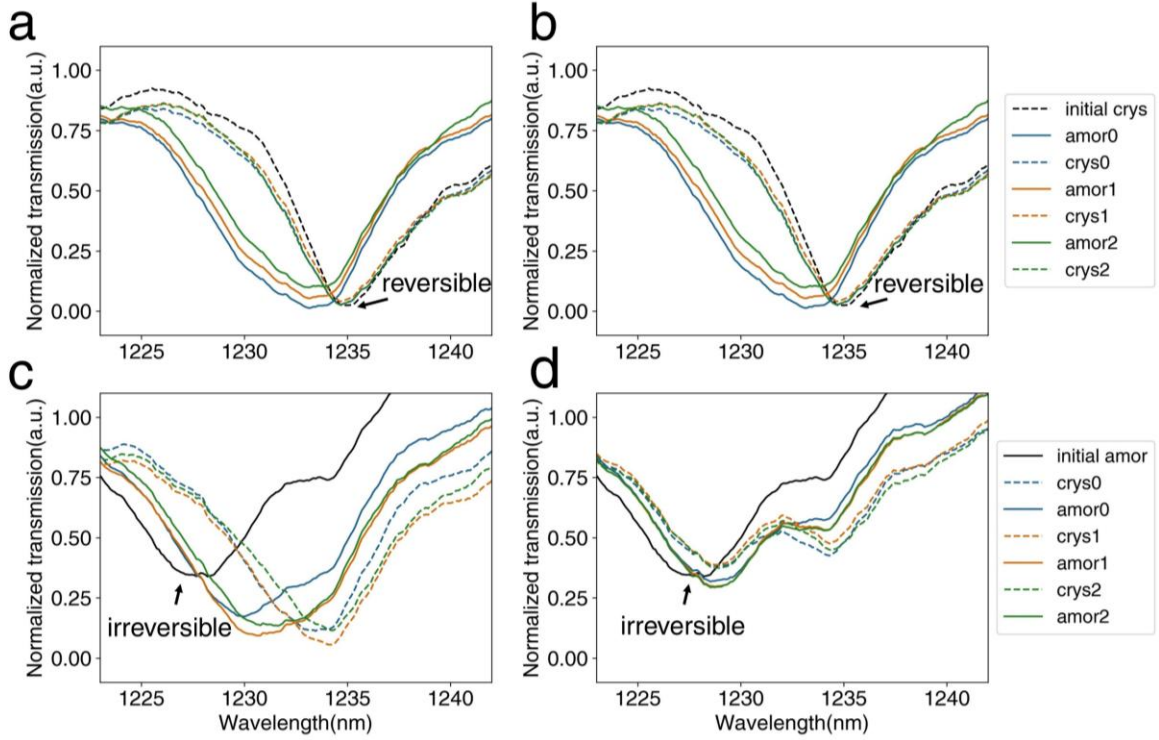


Figure 5.11: Normalized transmission spectra showing evidence of thermal crosstalk-free performance during amorphization process.

Normalized transmission spectra for hybrid gratings with an amorphous period two and three times the original channel pitch. **(a, b)** We start from an all-crystalline state and reversibly switch the selected channels via amorphization. Different colors show multiple switching cycles. After applying the amorphization pulse, we can return the spectrum to the initial state every time using a crystallization pulse, as indicated by the overlapping between the dashed and black lines. **(c, d)** We start from an all-amorphous state and reversibly switch the selected channels via crystallization. The crystallization pulse leads to unintentional crystallization of the adjacent meta-atoms due to thermal crosstalk. As a result, the subsequent amorphization pulses cannot return the systems to the initial all-amorphous state and the switching is irreversible. In contrast, the amorphization pulses we used in **a, b** will not switch the adjacent channels due to a much smaller thermal mass and higher temperature threshold. We note a global amorphization pulse could bring the metasurface back to the initial all-amorphous state, ruling out the possibility of device damage.

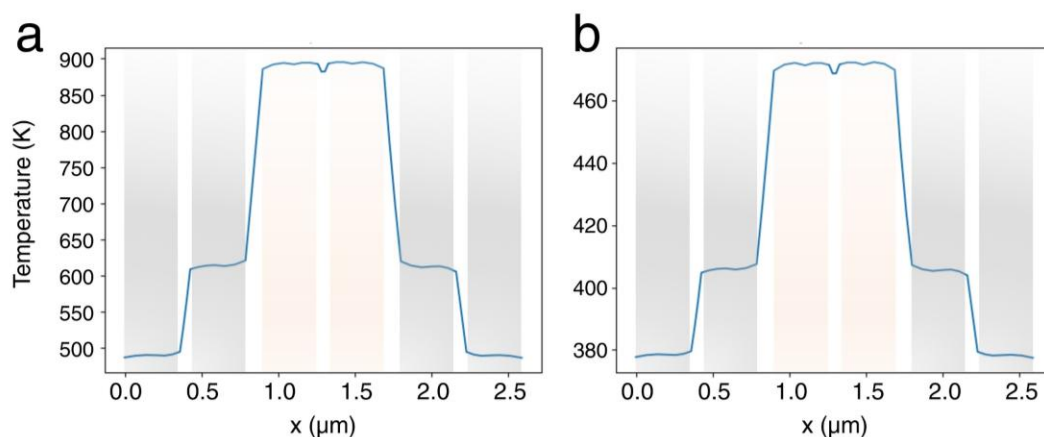


Figure 5.12: **Joule heating simulation in COMSOL for understanding of the thermal crosstalk-free performance during amorphization.**

(a) Simulated temperature distribution for amorphization using a 10.8V, 1μs pulse. **(b)** Simulated temperature distribution for crystallization using a 4.5V, 50μs pulse. The grating structure is overlaid on the plot. The electric current is only injected in the center diatomic grating (light orange), while the adjacent gratings (gray) are heated up due to thermal crosstalk. The temperature drops quickly away from the center. The amorphization temperature drop by ~280 K on the nearest gratings due to the shorter pulse width. Since the adjacent gratings do not reach the melting point, the thermal crosstalk will not lead to inadvertent switching of the nearby cells. In contrast, the temperature only drops by ~60K for the nearest gratings after the crystallization pulse, which is not enough to suppress accidental crystallization.

Apart from collectively switching multiple channels, we further showed that the pixels can be independently addressed one by one. Increasing the number of amorphized channels causes a gradual spectral shift of the resonance from 1235 nm to 1228 nm, as shown in Figure 5.10(g). We fitted the resonance to a Fano line shape and extracted the resonance shift versus the number of meta-molecules switched in Figure 5.10(h). The small error bars averaging over nine repeated cycles suggest a highly deterministic multilevel operation. Compared to the partial amorphization of a single pixel via pulse amplitude or width modulation, individual tuning of the meta-molecules is much more reliable since each meta-molecule undergoes a full amorphization process. The resonance shift is not observed when more than ten meta-molecules were switched because the focused probe beam with a natural Gaussian shape has low intensity at the edge.

Additionally, this decrease in the resonance shift from the center to the edge could be attributed to the non-local nature of the diatomic grating metasurface. Since the meta-atoms at the center have the most neighbors, the resonance effect is the strongest. The meta-atom at the edge has the least neighbor and coupling, hence weaker resonance shift. This behavior is verified through another rigorous coupled wave analysis (RCWA) simulation, where a super cell with 17 meta-molecules is simulated with only one crystalline meta-molecule while keeping all other meta-molecules amorphous. Figure 5.13 shows the resonance shift when placing the crystalline meta-molecule at different positions from 1 (edge) to 9 (center). Due to the symmetry, here we only show half of the total meta-molecules. Switching a center meta-molecule into the crystalline phase clearly causes a larger resonance red shift compared to an edge one.

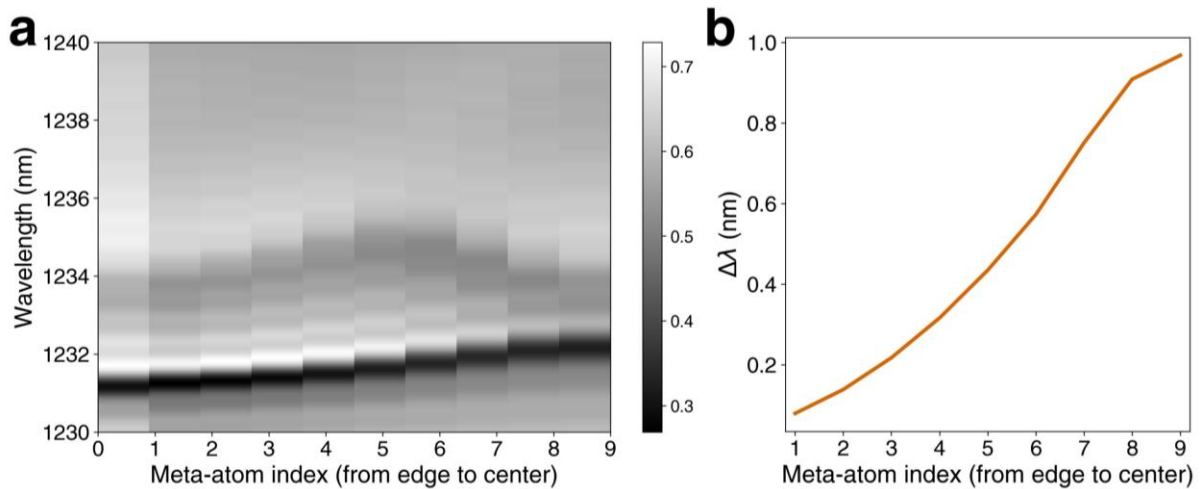


Figure 5.13: **Simulated resonance shift of the metasurface when different meta-atoms are switched.**

(a) Simulated transmission spectrum. The resonance is first simulated (indexed 0 in the x-axis) when Sb_2Se_3 on all the meta-atoms are set to amorphous phase. Then we separately simulated when only one meta-atom is switched to the crystalline phase from edge (indexed 1) to center (indexed 9). A larger resonance shift is observed when the meta-atom closer to the center is crystallized. **(b)** Plot of resonance shift versus the index of meta-atoms switched. A much larger shift (> 12 times) in the center (0.968 nm) is observed compared to the edge (0.078 nm). This simulation validates our observation in experiments that outer meta-atoms could not produce an observable resonance shift.

The fitted Q factor (Figure 5.14) first decreases from ~ 120 to ~ 90 until 4 meta-molecules are switched and then increases to ~ 120 . We attribute the lower Q-factor to inhomogeneous broadening, resulting from the coexistence of the amorphous and crystalline resonance mode. As more meta-molecules are switched, the amorphous resonance gradually dominates, leading to an increase in the Q-factor.

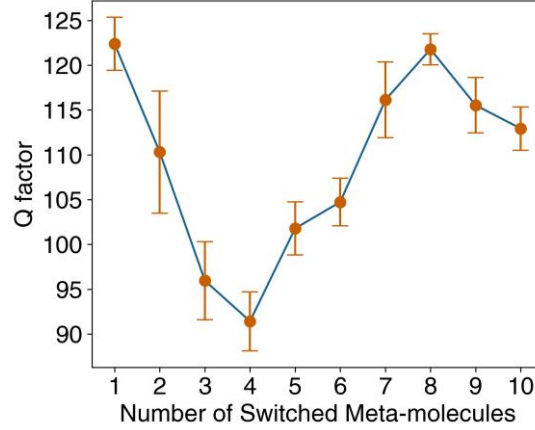


Figure 5.14: **Fitted Q-factor of the metasurface versus the number of switched meta-molecules.**

The Q-factor first decreases because of the inhomogeneous broadening of the amorphous-crystalline hybrid resonance mode and then increases as the amorphous resonance mode dominates. The Q reduction at the fully amorphous state near the end is not physical and could be attributed to a Fano resonance fitting error.

Resonances are in general angle dependent since the effective index of systems changes as the angle changes. This could also be observed in our TM-polarized quasi-BIC mode and TE-polarized guided-mode resonance, as shown in the energy-momentum spectrum (E-k spectrum) in Figure 5.15(a) and (b) below. Due to the angle dependence, the input FOV is highly limited to < 0.5 degrees. Fortunately, it is possible to overcome this angle-dependence by flatband resonances, which have been demonstrated^{203,204} by breaking the vertical symmetry of the metasurface and therefore hybridizing multiple resonant modes. One example design for the TE-polarized guided mode resonance in Figure 5.15(c) and the simulated E-k spectrum is presented in Figure 5.15(d), where a resonance shift below 1 nm is observed across a half angle $\sim 10^\circ$. Such exotic resonance modes can create new opportunities for metasurface-based SLMs with a large input FOV.

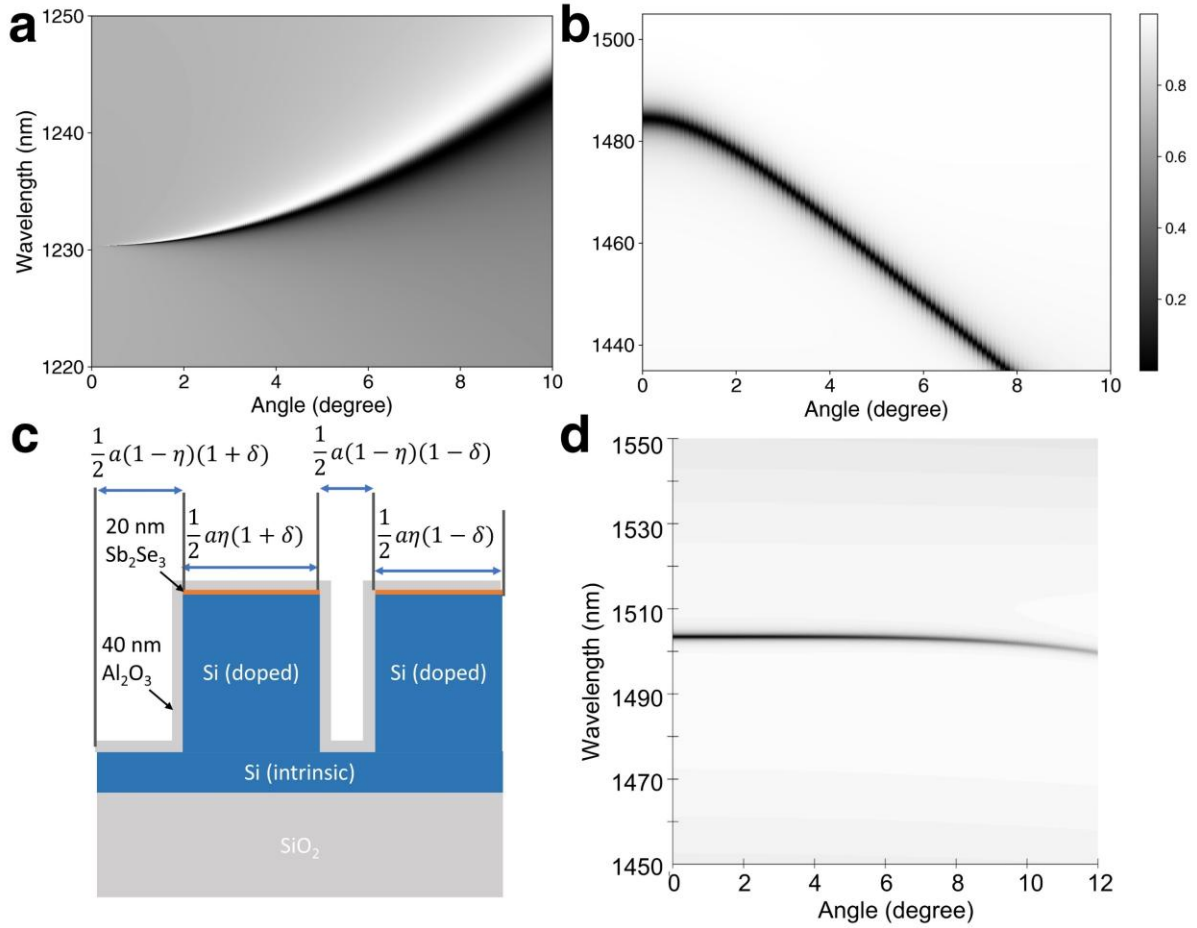


Figure 5.15: **Simulated energy-momentum spectrum for both resonance modes and a flatband metasurface design for wide input FOV.**

(a) TE-polarized guided-mode resonance. The resonance red shifts and Q-factor reduce as the angle increases. (b) TM-polarized quasi-BIC mode. The resonance blue shifts as the angle increases. (c) Geometry of the designed flatband metasurface. Parameters are $a = 0.62$, $\eta = 0.37$, $\delta = 0.1$. The thickness of the intrinsic silicon slab (doped silicon gratings) is 140 (380) nm. (d) A TE-polarized guided-mode resonance with an angle-independent resonance within 10° half angle (resonance variation smaller than 1 nm).

Lastly, as a proof-of-concept demonstration, we show that such individually addressable metasurface could enable tunable wavefront control. Switching the meta-atom induces a local, arbitrary optical phase shift near the resonance wavelength ($0 \sim 2\pi$, controlled by the laser wavelength). Using the angular spectrum propagation method and assuming a phase shift of $\pi/2$, we simulated the simple situations, where

only the center 4, 8, or 12 meta-atoms were amorphized while all the other parts were crystalline. The simulation results in Figure 5.16(a) suggest weak focusing phenomena with different focal lengths (10, 30, 75 μm). We experimentally imparted the phase profile by collectively switching center pixels and measure the 3D intensity distribution using a moving stage setup. Figure 5.16(b) shows the measurement results in the yz plane and the focal distance changes for different phase profiles, showing good agreement with the simulated results. The measured beam focusing is weak and non-ideal, primarily due to the relatively wide linewidth of our laser source (~ 1 nm) in Figure 5.8, which smeared out the optical phase contrast. This experiment could be improved by optimizing the resonance to a wavelength range that is supported by commercial tunable continuous-wave lasers, such as 1260 $\sim$ 1360 nm or 1465 $\sim$ 1565 nm. The focus efficiency could be improved by engineering phase profile and by using more unit cells.

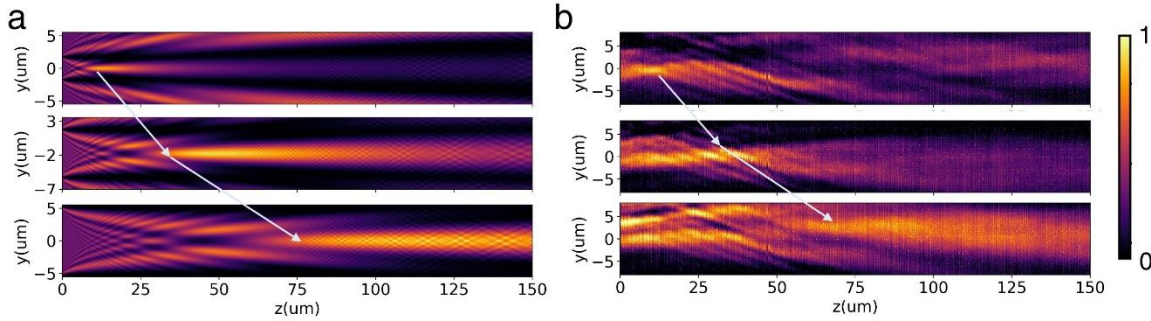


Figure 5.16: **Tunable free-space beam focusing.**

(a) Angular spectrum propagation simulation for the situation where only the center 4, 8, or 12 gratings are amorphized and other gratings are kept crystalline. A phase shift of $\pi/2$ is assumed. Weak focusing could be observed and the focal lengths are clearly different ($\sim 10, 30, 75$ μm) for three configurations. **(b)** Measured beam profile. The shift in focal lengths agrees well with the simulation. The plotted data is normalized to global crystalline configuration to avoid objective focusing and then averaged in the x-direction over the center 10 pixels of the metasurface.

Table 6 compares our Sb_2Se_3 -based SLM with other works, including some commercial products based on liquid crystals (LCs) and digital mirror devices (DMDs). First, most of the commercial products work in the reflection mode instead of transmission, despite the need for transmissive SLMs in many applications such as AR/VR. A typical transmissive SLM is in the second row of Table 6, which has a large pixel size

(36 μm compared to 1.8 μm in our work) and a large optical loss (transmittance $\sim 28\%$ compared to $\sim 90\%$ in our work). The limited pixel size further leads to a small output field of view (FOV) of ~ 1 degree⁸⁸, constrained by the first-order diffraction. Thanks to the smaller pixel size, our output FOV is ~ 56 degrees. We note the resolution of our work could be easily extended to 0.9 μm with a PCB supporting more channels to support a large enough area metasurface. Our work also shows excellent power consumption compared to other reported values. We note the number reported in the table assumes a switching frequency of 1Hz for our device. In practice, once one programmed the PCM-based SLM, it can self-hold the state for much longer than 1 second with no energy consumption. For example, if the state is held for one hour, the power consumption per pixel becomes 0.06 (0.42) nJ/s for RESET (SET), showcasing orders of magnitude higher performance than the state-of-the-art commercial products. The pixel speed is around 10 kHz, mainly limited by the long SET process. This could be potentially resolved in the future by exploring faster PCMs.

Table 6: Comparison of our Sb_2Se_3 -based transmissive SLMs with other SLMs

Ref	Model name	Tuning Method	Transmissive or reflective	Phase-only	Pixel size (μm)	Optical loss (dB) *	Pixel power consumption (nJ/s)	Pixel Speed (MHz)	Nonvolatile
205	TELCO-033	LC	Reflective	Yes	3.74	-1.4	N.R.	0.24 *	No
206	LC 2012	LC	Transmissive	Yes	36	-5.5	N.R.	0.05 *	No
207	DLP6500	DMD	Reflective	No	7.56	~ 0	~ 3100 *	11.88 *	No
88	Lab work	LC	Transmissive	Yes	~ 1	-4.4	N.R.	N.R.	No
208	Lab work	EO polymer	Reflective	No	390	-1	< 10000 *	50	No
209	Lab work	LC	Reflective	Yes	~ 1	-3	N.R.	0.0005	No
22	Lab work	FC	Reflective	Yes	5	-15.2	1.9×10^6 *	5.4	No
210	Lab work	FC	Reflective	Yes	5	-0.2	675 *	135	No
This work	Lab work	PCM	Transmissive	Yes	1.8 (0.9)	-0.65	200 (RESET) 1500 (SET)†	0.01	Yes

(LC: Liquid crystal; N.R.: not reported; DMD: digital mirror devices; EO: electro-optical; FC: free-carrier dispersion effect; PCM: phase-change materials; *estimated or calculated values from figures or related parameters; † Assume a programming frequency of 1 second. This number corresponds to the switching energy for each phase transition.)

Chapter 6. Challenges and opportunities

Despite impressive progress, several limitations and challenges exist in PCM-integrated photonics, including high optical loss of traditional PCMs, unreliable multi-level operation with electrical control, low endurance, and difficulty identifying accurate phase transition conditions. This section discusses these challenges and a few potential opportunities to mitigate them.

6.1 High loss of traditional PCMs

The high material loss of traditional PCMs, *e.g.*, GST^{52,63,95}, GeTe⁴⁵, GSST⁵³, and GSSe⁹⁷, can introduce extra device insertion loss. Deposited on top of Si₃N₄ or silicon waveguides, PCMs provide strong reconfigurability. However, close to the optical mode, they also induce significant optical absorption, especially in crystalline phases. Moreover, non-uniform PCM deposition, and mode mismatch at PCM interfaces can cause additional scattering loss⁵⁵. Physically separating the PCM further from the waveguide can reduce the loss at the price of switching contrast. Such optical loss limits applications to direct intensity modulation, although generally phase-only modulation is desired. For example, a well-known way to switch between different optical paths is to use an MZI^{21,39,211}. Using GST in one MZI arm to modulate the phase, its excess loss in the crystalline state drastically attenuates the signal in that arm, making the interference imperfect and reducing the extinction ratio.

To mitigate the high loss in the crystalline GST/GSST for low-loss applications, a three-waveguide device geometry (Figure 6.1) was conceptualized^{57–59}. In this scheme, only the middle waveguide is deposited with PCMs, and is purposefully phase matched with other two bare silicon waveguides when the PCM is in the amorphous state. Therefore, light can couple to the cross output port for a-PCM. Once the PCM is switched to the crystalline phase, a large effective index mismatch significantly reduces the coupling, so the light directly transmits through the bar port and barely interacts with the lossy c-PCM, hence bypassing the high loss. However, we note that this geometry only works for PCMs transparent in the amorphous state and requires a significant refractive index contrast. A more promising solution will be wide bandgap PCMs, which are transparent in both phases and introduce negligible excess losses after

deposited on waveguides (Figure 6.1). Specifically, two classes of PCMs, Sb_2Se_3 and Sb_2S_3 ^{104,105}, have very low material absorption loss ($\kappa_a \approx 0$, $\kappa_c < 0.005$) in the telecommunication wavelength range (near 1310nm and 1550nm) due to their wide bandgap. The extra scattering loss due to mode mismatch could be relaxed by patterning the PCM into a taper shape⁵⁵.

6.2 Reliable multi-level operation with electrical control

It is difficult to achieve reliable multi-level operation with electrical control, due to PCMs' stochastic nature¹⁶⁰, where only two states (complete amorphous or complete crystalline phase) can be reliably produced. While using a fs-pulsed laser, reliable multi-level operations^{52,62,65,66,69} have been reported, electrical control of intermediate states remains unreliable⁵⁹. Specifically, each time an amorphization event is triggered, the stochastic melt-quench process results in a slightly different amorphous state. It then leads to significant distinctions in the subsequent long-range nucleation and growth process, hence the PCM ends up with a stochastic partial crystalline phase¹⁶⁰.

Electrically controlled PCM waveguide switches with a reliable multi-level operation were demonstrated recently using segmented heaters for both phase-only⁵⁵ and amplitude modulation⁹⁷. Here we propose a similar scheme⁹⁷ using multiple PIN silicon heaters, as shown in Fig 3a and 3c. Each heater separately controls a short PCM patch in a binary but reliable manner. The device then performs reliable multi-level operation by programming the states of all PCM patches individually.

Furthermore, using this similar idea, beam splitters with quasi-continuously tunable splitting ratios, an essential component in many PICs, can be fabricated, as shown in Figure 6.1(b) and (d). Traditionally, such tunable beam splitters are realized in an MZI configuration, which may require active lengths exceeding 100 μm ^{21,39,143,211,212}. The length of the phase shifter in an MZI is given by $\sim \lambda / 2\Delta n_{eff}$, with λ being the wavelength and Δn_{eff} being the effective index change. As Δn_{eff} is generally small using traditional modulation methods, the phase shifter is long. Additionally, two fixed beam splitters add considerable footprint (*e.g.*, $\sim 36\mu\text{m}$ in Ref. [211]), but do not contribute to the active tuning. In contrast, the PCM device

footprint is significantly reduced to $\sim 30 \text{ } \mu\text{m}^{58}$, further improving the PIC's integration density. As conceptualized in Figure 6.1, quasi-continuously programmable beam splitters can be realized by placing low-loss PCM directly on one of two waveguides to form an asymmetric directional coupler¹⁴⁴, and controlling with segmented heaters. With lossy PCMs, however, additional design considerations are necessary to mitigate material loss, such as adapting a three-waveguide geometry in Figure 6.1(d), as explained earlier.

In all these devices, the central design principle is to change the coupling between waveguides using PCM phase transition. The typical design procedure^{57–59,144,213} starts with picking a PCM thickness and performing optical mode simulations of the directional couplers using an electromagnetic field solver. One can then obtain the coupling length as $L_{couple} = \lambda/2(n_e - n_o)$, with λ being wavelength and n_e and n_o being the effective index of the even and odd supermode of coupled waveguides, respectively. Then, by optimizing the waveguides gap and PCM thickness, a tunable beam splitter is designed¹⁴⁴.

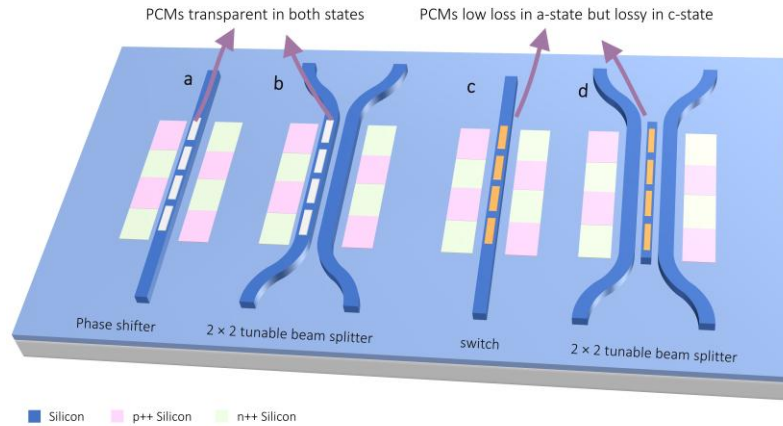


Figure 6.1: **Quasi-continuously programmable phase shifters, photonic switches, and beam splitters with PCMs and PIN diode-based doped silicon micro-heaters on a silicon-on-insulator (SOI) chip.**

(a, b) A phase shifter and a tunable beam splitter using transparent PCMs; **(c, d)** A photonic amplitude switch and a tunable beam splitter using PCMs absorptive in the crystalline phase but low loss in the amorphous phase. **(a)** The phase of light is changed due to the PCM refractive index difference between two states. **(b)** Upon PCM phase transition, the coupling strength between two waveguides is changed, and the splitting ratio changes. **(c)** Light is switched on and off, harnessing the PCM loss difference. **(d)** The middle waveguide is phase matched with the other two waveguides when the PCM is in the amorphous state. In the crystalline state,

the light will not be coupled to the lossy c-PCM due to the large refractive index change, and the high crystalline material loss is effectively mitigated.

6.3 Limited PCM endurance

Another important unsolved issue is the limited PCM endurance²¹⁴, i.e., how many times the PCM can be cycled through. Although recent years have witnessed orders of magnitude improvement in optical PCM devices' cyclability (10 cycles⁹⁶ to half 10^6 cycles⁹⁷ with different PCMs and heater designs, see Table 7), it is still lower than what has been achieved in electronic memories (10^{12} cycles²¹⁵, and potentially 10^{15} cycles²¹⁶ for GST). In electronic memories, PCMs are typically shaped into tiny units of volume ($10 \times 10 \times 10 \text{ nm}^3$)²¹⁷, whereas the size is much larger ($10 \mu\text{m} \times 1 \mu\text{m} \times 10 \text{ nm}$)^{54,59,95} for photonics. Generally, a smaller PCM volume suffers less degradation from thermal reflowing issues and is less prone to elemental segregation, which causes material failure⁹². Additionally, oxidization can occur if the material is not properly encapsulated, as phase transition involves high temperature. Assuming a linear scaling with volume, we expect to achieve around 10^{10} cycles in photonics. We note that even 10^{10} cycles are insufficient for high-speed modulation. For example, a GHz modulator with an endurance of 10^{10} would only last 10 seconds!! While this is a severe limitation, 10^{10} cycles are sufficiently high for reconfigurable applications. Assuming a PIC/meta-optic is changed, kept for 1 second, and changed again for another application, it takes more than 300 years to complete 10^{10} cycles! Besides, the kept time could be much longer for many applications, e.g., optical computing or optical programmable gate arrays (OPGAs). Therefore, temporal response or the switching times of PCM-based programmable units are of little significance¹⁶³.

Different capping materials²¹⁴ have been used to protect the PCM from thermal reflowing and oxidation, including ITO⁶², SiO_2 ²¹⁸, Si_3N_4 ²¹⁸, ZnS/SiO_2 ⁶⁴, Al_2O_3 ^{59,67,95}, and others²¹⁸. In particular, recent developments show that atomic-layer deposited Al_2O_3 can provide excellent protection^{59,67,95}, primarily due to its highly conformal nature. Further optimizing the material property may also help improve device endurance. For example, to avoid element segregation, single-element PCMs²¹⁹ may be explored. Finally,

since smaller volumes of PCM are more durable⁹², patterning the PCM on a subwavelength scale^{67,92} could improve device endurance. We refer readers to a recent review²¹⁴ on this topic.

Table 7: PCM integrated photonic device performance comparison

Ref	Year	PCM	Structure	ER (dB)	IL (dB)	Energy per switch (nJ)	Footprint (μm)	Optical BW (nm)	Tuning method, cycles
62	2015	GST	MRR 1×1	10	N.R.	0.533 (3.1) ^c	1	< 1	Optical, 50 cycles
174	2017	GST	MRR 1×1	> 5.0	5.1 / 4.3 ^a	0.19 (17.1) ^c	60	< 1	Optical, 1,000 cycles
92	2019	GST	MRR 1×2	14	0.75 / 0.46 ^a	0.25 (11) ^c	25	< 1	Optical, N. R.
93	2021	GST	MZI 2×2	8.0	0.5	14 (9.5×10^5) ^c	43	N. R.	Optical, 600
96	2017	GST	WG 1×1	1.2	4.8	20 (7.2×10^6) ^c	1	>100	Electrical, ~10 cycles
112	2019	GST	MMI 1×1	6.5	7.5	N. R.	1	>100	Electrical, >1500
95	2020	GST	WG 1×1	5	1.6	13 (715) ^c	5	>100	Electrical, >500
55	2021	Sb ₂ Se ₃	MZI 2×2	6.5/ 15.0 ^a	> 0.3	176 (3.8×10^3) ^c	> 100 ^b	> 15 ^b	Electrical, >125 cycles
59	2022	GST	DC 2×2	10.0	2.0	380 (6.8×10^3) ^c	50	> 30	Electrical, >2,800 cycles
97	2022	GSSe	WG 1×1	0.12	12	N. R.	80	N. R.	Electrical, 5×10^5

(ER: extinction ratio, IL: insertion loss, BW: bandwidth, MMI: Multi-mode interferometer, MZI: Mach-Zehnder Interferometer, MR(D)R: Micro-ring(disk) resonator, WG: waveguide, DC: directional coupler, N.R.: not reported)

Note: here, only devices with reversible switching are compared. Footprint refers to the total device length. ^aFor drop and through ports, respectively. ^bEstimated from figures. ^cEnergy per switching event for amorphization (crystallization)

6.4 Difficulty identifying phase change conditions

Identifying the phase transition condition is non-trivial because the amorphization condition can be close to the device damaging threshold. We consider the silicon PIN heater and GST as an example in the following. In comparison to silicon, GST has lower melting temperature T_m ($T_{m,Si} = 1450^\circ\text{C}$, $T_{m,GST} = 650^\circ\text{C}$), thermal conductivity k_{th} ($k_{th,Si} = 148\text{W/m}\cdot\text{K}$, $k_{th,GST} < 1\text{ W/m}\cdot\text{K}$) and specific heat capacity C_p ²²⁰ ($C_{p,Si} = 0.72\text{J/g}\cdot\text{K}$, $C_{p,GST} = 0.2\text{J/g}\cdot\text{K}$). A smaller thermal conductivity means that heat diffuses away slower and hence becomes more localized within the GST. A smaller specific heat capacity indicates GST requires less energy to heat up. Therefore, the low melting point T_m , thermal conductivity k_{th} , and heat capacity C_p all together imply that GST is much easier to melt than silicon with the same input energy. However, in our experiments, the silicon waveguide could be damaged when applying a slightly higher voltage ($\sim 0.3\text{V}$) than the amorphization voltage. Simulations^{164,221} suggest that such surprising device damage stems from local hotspots at the edge of the waveguide, due to current crowding, as the silicon thickness abruptly changes between the waveguide and partially etched slab. Another challenge is that the phase change condition is not universal. As the phase transition is thermally induced, any change in the substrate or the cladding requires re-optimizing the heating conditions.

Although identifying the accurate phase change conditions requires trials and errors, the conditions are reliable, once found. Therefore, the conditions must be identified on several separate testing devices before being applied on large-scale PICs. We can also further optimize the material systems to avoid device damages. Besides designing new PCMs with lower T_m , exploring other material systems for the photonic backbone with higher T_m than silicon, such as Si_3N_4 , can facilitate a larger amorphization window. Another important research direction is to optimize the heaters. For doped silicon heaters, the geometry of the doping

area and the silicon waveguides can be optimized to eliminate the local hotspots. Furthermore, new heaters, such as graphene heaters^{107,221}, should be explored to maximize heat delivery to the PCMs, easing the stringent phase change conditions and significantly improving their energy efficiency.

6.5 opportunities toward large-scale systems

The main advantage of using PCMs in large-scale systems comes from their zero-static power consumption. Here, we perform a simple calculation on energy consumption to stress the utility of small (or zero) static energy consumption for semi-static active photonics. Let us consider a thermo-optically tunable component, which usually consumes 10mW power^{21,211}. The energy consumption to hold the system configuration is thus estimated as $10\text{mW} \times 3600\text{s} = 36\text{J}/\text{hour}$ or $864\text{J}/\text{day}$. Compared with the typical energy of $1\mu\text{J}$ (or less) for switching a PCM device, the static energy consumption is seven orders of magnitude larger per hour per switch!!

In addition to the energy saving benefit, the weak thermo-optic effect usually leads to a very high temperature at the heater locations, resulting in thermal crosstalk. Such thermal crosstalk limits the optical component density and may cause unreliable operations. PCM devices need a relatively high thermal threshold to switch and are unaffected by such thermal crosstalk. Although researchers recently developed many algorithms^{212,222} to compensate for the thermal crosstalk, they require additional software and complex control circuits.

Overcoming the challenges outlined in the previous section will create opportunities to build large-scale electrically controlled PCM systems for various applications, including quasi-arbitrary unitary transformation²²³, non-blocking switching fabrics²²⁴, adding redundancy to optical systems, multi-purpose PICs^{39,41,143,212}, optical neural networks^{67,68,159,175,211}, and quantum simulations²¹. As an overview, Table 8 compares several state-of-the-art PICs at the device (insertion loss, extinction ratio, active region length, and power consumption) and system levels (number of devices, insertion loss, and footprint). We also refer the readers to a few review articles^{222,225,226} on programmable PICs.

Table 8: State-of-the-art PIC systems comparison

Ref	Applic ation	Year	Mechanis m, platform	Device IL (dB)	Device ER (dB)	Active length (μm)	Device power (mW) or (mJ/switch)	# of devices	System IL (dB)	System footprint ($\mu\text{m} \times \mu\text{m}$)
²²⁴	SF	2016	EO, SOI	0.44	30 (18) ^a	380	26	56	6.7 (14) ^c	10700 $\times$ 4400
¹⁴³	OPGA	2015	TO, Si ₃ N ₄	N.R.	N.R.	2100	250	9	1.0	8500 $\times$ 3500
^{39,212}	OPGA	2017 (2020)	TO, SOI	0.6	N.R.	800 ^b	110	60	0~30 ^c	1500 $\times$ 2000
⁴¹	OPGA	2020	TO, SOI	0.8 (9.0) ^a	5 (20) ^a	6	1.6	128	2.8(9.8) 4(18) ^c	300 $\times$ 300 ^b
^{67,159}	ONN	2021 (2022)	PCM, SOI	0.9 (6.5) ^a	16 (3.5) ^a	10.0	3.81 $\times 10^{-7}$	4	N.R.	N.R.
^{21,211}	ONN QS	2017	TO, SOI	-3 $\times 10^{-3}$	6.3	33 ^b	10	48(176)	8.0	1830 $\times$ 4100 ^b
⁶⁸	ONN	2021	PCM, Si ₃ N ₄	0.4	N.R.	2	8 $\times 10^{-7}$	16/64	12	1140 $\times$ 1416
¹⁷⁵	ONN	2019	PCM, Si ₃ N ₄	1.5	9	3	7 $\times 10^{-7}$	4	N.R.	2461 $\times$ 270 ^b
Envisioned PCM systems			PCM, SOI/Si ₃ N ₄	0.1	30	<50	10 ⁻⁷	>100	<10	500 $\times$ 500

(ER: extinction ratio, IL: insertion loss, N.R.: not reported, SF: switching fabric, OPGA: optical programmable gate array, ONN: optical neural networks, QS: quantum simulation)

Note: The device power for volatile (non-volatile) devices is in mW (mJ/switching event). ^aFor drop and through ports, respectively. ^bEstimated from figures. ^cPerformance for different configurations.

6.5.1 Quasi-arbitrary unitary transformation

Any arbitrary unitary transformation can be implemented using an array of programmable units consisting of a tunable beam splitter and a phase shifter²²³. Combining these unitary transformations, we can implement arbitrary matrix-vector multiplication at the heart of optical signal processing^{212,227,228}, neural

networks²¹¹, and even quantum simulation²¹. Although these systems have been demonstrated using the thermo-optic effect in the past^{21,39,211,212}, the number of programmable units remains limited due to thermal crosstalk, massive energy consumption, and complex control circuit. While a non-volatile programmable unit, as shown in Figure 6.2(a), can circumvent these problems. However, no demonstrations using PCMs currently exist, due to the challenges in the previous section. While the loss in PCMs can be acceptable for a single unit, these losses add up for massive arrays of devices and incur a considerable signal reduction. Additionally, the loss can be non-uniform along different paths and further limit the system performance⁵⁷. Therefore, we must ensure an excess insertion loss of $<0.1\text{dB}$ and an extinction ratio of $> 30\text{dB}$ per programmable unit for a large system, with at least ~ 10 units in the critical path. This is beyond the capabilities of traditional PCMs such as GST because 20nm thick c-GST on a standard silicon waveguide introduces an insertion loss of around $7\text{dB}/\mu\text{m}$ ^{52,95}. Wide bandgap PCMs, *e.g.*, Sb_2S_3 and Sb_2Se_3 ^{104,105}, exhibit a low insertion loss of less than $0.02\text{dB}/\mu\text{m}$ in the same setting, reducing the loss by more than 300 fold. The Sb_2Se_3 -based PCM phase shifters⁵⁵ demonstrate a promising approach to this application, but more work is required to further reduce the loss from 0.33dB ⁵⁵ to less than 0.1dB and to achieve more operation levels reliably.

6.5.2 Adding optical redundancy with non-blocking switching fabric

A large PIC may contain some critical components that are more prone to failure, and such single-device failure can render the whole circuit unusable. A straightforward approach to overcome this is to add several backup devices and a switching fabric, bypassing the broken device and rewiring another functional device. Figure 6.2(b) shows a proposed schematic of a fully integrated transceiver with multiple on-chip lasers and a PCM non-volatile switching fabric. This type of switching fabric demands zero-static energy but has no switching speed requirement, rendering PCMs ideal candidates. Other switching fabrics may also be established with PCMs, such as the 16×16 Benes type non-blocking switch fabric⁵⁷ in Figure 6.2(c), which can route all input signals to corresponding output ports simultaneously. We again stress that

the successful creation of such a fabric requires optimized insertion loss ($< 0.1 \text{ dB}$) and extinction ratio ($> 30 \text{ dB}$). Although this is possible in theoretical designs^{57,213}, currently reported PCM programmable units (listed in Table 8) do not yet meet such stringent demands, primarily due to fabrication imperfections and residual material losses. Therefore, further research and engineering on loss reduction techniques are needed.

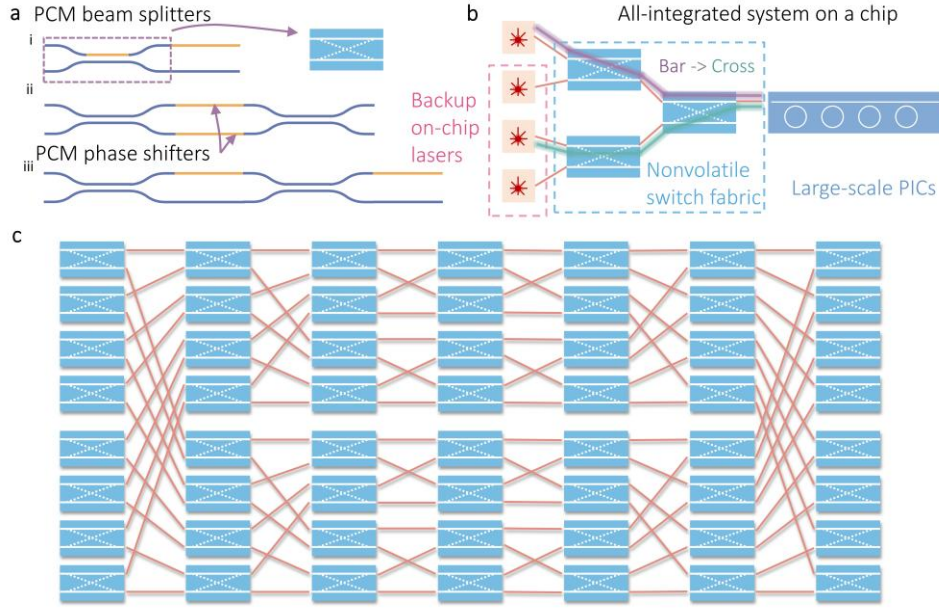


Figure 6.2: **Schematic of non-volatile arbitrary unitary transformation and switching fabrics.**

(a) Three schematics of programmable units for arbitrary unitary transformation based on PCMs (orange). The tunable beam splitter is boxed in purple dotted lines. (b) Proposed switching fabrics for adding optical redundancy to all-integrated systems on a chip. Because on-chip lasers are prone to failure, one can fabricate several backup lasers together. The PCM-based switching fabric in the dotted light blue box can be placed between the laser and the large-scale PICs (such as an array of ring modulators in optical transceivers). The switching fabric routes a functioning laser to the PIC using zero-static energy, akin to a free-space optomechanical setup. (c) Proposed 16×16 Benes type non-blocking switching fabrics for non-volatile signal routing. We envision all the tunable beam splitters will be programmed electrically.

6.5.3 Optical neural networks

Deep neural networks have been an immensely promising platform for many problems, such as image recognition and classification^{229–231}, natural language processing^{232–234}, image-to-image translation^{235,236},

artwork generation²³⁷, and mathematical problem solving^{238–240}. With the enlarging problem space, increasingly larger neural networks are implemented, which, unfortunately, requires prohibitive amount of computational resources.

Photonics has the potential advantage of being lower loss and faster than electronics, providing power-efficient and high-speed computation. Therefore, implementing part of the artificial neural networks, especially the linear operations, using optics is a promising alternative. Recently, rudimentary deep neural networks²¹¹, convolutional neural networks^{67,68}, reservoir networks²⁴¹, and generative adversarial networks⁷¹ have all been implemented using photonics.

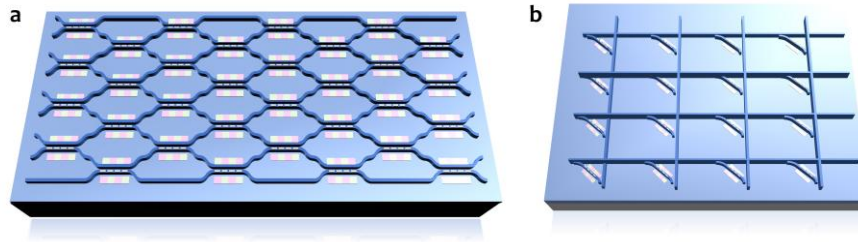


Figure 6.3: Schematic of PCM-based non-volatile platform to perform linear operations in an optical neural network.

(a) A forward matrix-vector multiplier for deep neural network based on PCM tunable beam splitters; **(b)** A convolutional block using a tunable attenuator.

In optical neural networks (ONNs), the input vector is encoded in the phase and amplitude of the input light. The weights (matrices) are implemented by PICs using tunable devices, such as MZI or crossing meshes, as shown in Figure 6.3(a) and (b), respectively. Therefore, a matrix-vector multiplication is performed by propagating the light through the PIC. Notably, once the neural networks are trained, the weights are fixed, hence a fixed PIC configuration. In other words, holding the PIC for a long time is necessary, making PCM photonics an encouraging solution. Indeed, spiking neurosynaptic networks with self-learning capability¹⁷⁵ and convolutional neural networks^{67,68} have already been demonstrated with GST. Nevertheless, all the ONNs mentioned above relied on optical control, complicating the laser

alignment, and potentially hindering the scalability. On the contrary, electrically controlled PCM devices and electronic integrated circuits (EIC) could be packaged together^{242,243}, even monolithically integrated on the same chip^{244,245}, offering a higher degree of integration and flexibility. Therefore, electrically controlled PCM photonics is a promising path toward energy efficient and large-scale optical neural networks.

6.5.4 Non-volatile electro-optical programmable gate array

PICs primarily work in application-specific ways, where they are carefully designed and optimized for a particular task. However, there is an increasing interest in creating a general-purpose PIC, i.e., developing optical programmable gate arrays (OPGAs)^{39,41,143,212}, an idea inspired by the electronic field-programmable gate array (FPGA). These OPGAs can be reconfigured to implement different functionalities. Each gate consists of the programmable unit described earlier (Fig. 4a) and is connected in meshes^{39,41,143,212}, such as the rectangular meshes shown in Figure 6.4(a).

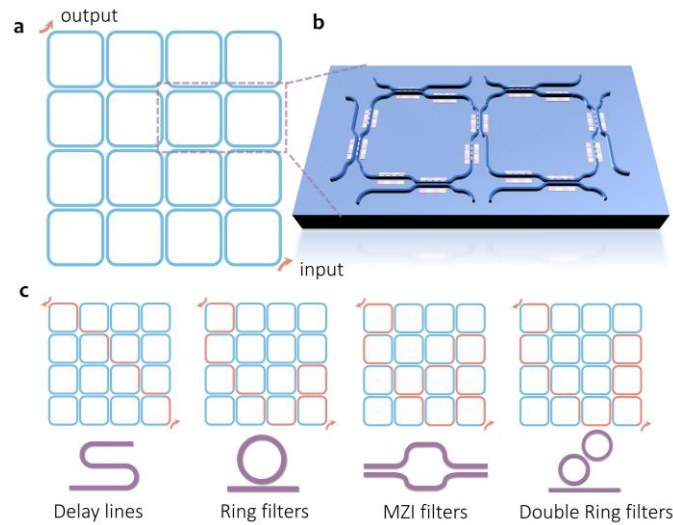


Figure 6.4: **Non-volatile programmable gate arrays based on PCMs.**

(a) Schematic of a non-volatile programmable gate array in a rectangular mesh. **(b)** Schematic of two meshes shown in the dotted purple box. Each edge of the mesh denotes a programmable unit. **(c)** Working principles of OPGAs. The light traveling path, denoted by orange, can be changed by reprogramming the OPGA. In this way, the OPGA can implement various functions on the same chip, such as delay lines, ring filters, MZI filters, and double ring filters.

The resulting chip can perform various functions by appropriately programming the array, as shown in Figure 6.4(c). The functionalities of the OPGA are optimal when each unit is non-resonant, making them applicable over a broad wavelength range. Obviously, this type of PIC does not require frequent reconfiguration. So “set-and-forget” type devices are demanding. To date, most of the demonstrated OPGAs are, however, based on thermo-optic effects^{39,41,143,212}, consuming an enormous amount of static energy, see Table 8. Besides, the compactness of PCM devices offers more available meshes and functionalities³⁹. We see many exciting opportunities in PCM-based zero static-energy OPGAs using the wide-bandgap PCMs and the electrically controlled quasi-continuous tuning devices.

6.6 Visible phase-change material photonics

While integrated photonics research was pioneered in the infrared telecommunication bands, in recent years, visible integrated photonics has generated strong interest for many applications, including optogenetics²⁴⁶, spectroscopy^{247,248}, augmented reality visors²⁴⁹, and quantum optics^{250,251}. Barring some rudimentary demonstrations of PCM-integrated visible photonics⁵⁴, this field remains largely unexplored due to the narrow bandgap of traditional PCMs and ensuing strong absorption in the shorter wavelengths. For example, traditional PCMs, such as GST⁵², GSST⁵³, GeTe⁴⁵, and GSSe⁵⁶, are very lossy at visible wavelengths in both amorphous and crystalline phases, see Table 1. Sb₂S₃, explored in the late twentieth century for memory applications²⁵², has a wide bandgap and zero loss in the amorphous state down to a wavelength of $\sim 600\text{nm}$ ^{104,105}. Table 1 compares different PCMs at 640nm, and Sb₂S₃ shows the best performances in all three FOM. Thus, Sb₂S₃ is particularly suitable for visible or near-IR (>600nm) applications, specifically for routing of single photons emitted from semiconductor color centers, such as silicon-vacancy (SiV)²⁵⁰ and nitrogen-vacancy (NV)²⁵¹ centers in diamond.

The finite $c\text{-Sb}_2\text{S}_3$ loss in visible wavelength could be mitigated using ring resonators⁵⁴ or three-waveguide directional couplers⁵⁸ on a Si_3N_4 platform. In Figure 6.5(a), we show the schematic of a tunable beam splitter made of Sb_2S_3 on Si_3N_4 , where the state of Sb_2S_3 can be switched by external heaters such as ITO, graphene, or tungsten. Another possible approach can be to integrate Sb_2S_3 on wide bandgap semiconductors, such as gallium phosphide²⁵³, which can be directly doped to create a heater, similar to what has been demonstrated in silicon photonics^{55,59,95}.

One promising application of this wide bandgap PCM could be to create a visible switching fabric to connect functional quantum devices and route single photons on-chip. Quantum devices, such as single-photon sources, on-chip superconducting detectors, or quantum frequency converters, have a moderate to low success probability, which diminishes as many such devices are hardwired. One way to circumvent this issue is the “pick-and-place” technique, where pre-characterized functional devices are picked up and placed on a previously defined PIC^{254,255}. However, the scalability of such approaches may be limited. In contrast, by using a non-volatile switching fabric, we can connect selected functional quantum devices on-chip.

The emission wavelengths of most solid-state single-photon sources and the atomic transitions of alkali and alkaline earth metals used in quantum memory are in the visible or near-infrared wavelength range. By using non-volatile and wide bandgap Sb_2S_3 , we can realize low-loss reconfigurable visible PICs. Additionally, unlike thermo-optic or free-carrier dispersion effects, PCMs can be efficiently tuned even at cryogenic temperatures. The relatively low energy density for switching PCMs^{55,95} will not provide a considerable energy burden to tune them inside a cryostat. Alternatively, these devices can even be programmed at room temperature before putting in a cryogenic environment. We note that, for quantum photonics, the loss per programmable unit needs to be even lower than what is required for classical applications; specifically, we estimate the required loss $< 0.01\text{dB}$ per unit²¹.

Sb_2S_3 can also enable biological applications. For example, Figure 6.5(c) shows the concept of a switching fabric that can be used in light delivery for optogenetics²⁴⁶, where by simultaneously stimulating selective regions in the brain, collective neural functions can be studied. PCMs render a much safer solution

than the previously reported thermal tuning²⁴⁶. Moreover, the programming process could even happen before placing the probe inside the brain, mitigating potential heat-related harm.

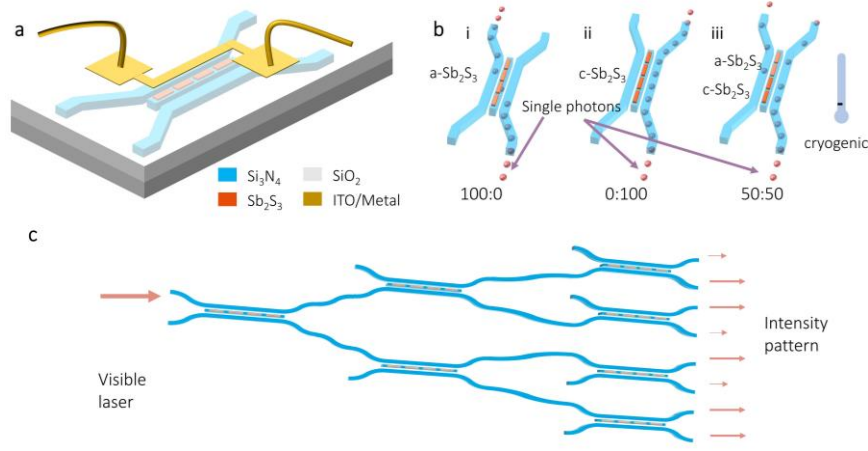


Figure 6.5: **Non-volatile active photonics in the visible employing emerging wide bandgap PCM Sb_2S_3 .**

(a) Schematic of an electrically tunable 2×2 tunable beam splitter in the visible spectrum. **(b)** Schematics for switching single photons for quantum applications in a cryogenic temperature, achieving on-demand splitting ratios. **(c)** Concept of a non-volatile switch for optogenetic applications²⁴⁶.

6.7 Laser rewriteable phase-change material integrated photonics

Lithography-free laser writing^{256–261} is becoming increasingly popular in integrated photonics as it provides significant flexibility for rapid prototyping and on-demand designs. However, traditional laser writing techniques in glass require costly fs-pulse lasers. Additionally, they only induce miniscule material refractive index change ($\Delta n \approx 0.02$) and are limited to large waveguides ($\sim 10 \mu\text{m}$ wide). Moreover, the writing process is generally irreversible²⁵⁶.

As the dominant optical data storage materials, PCMs have been reversibly switched with ns-lasers in commercial CD writers⁶⁰. Compared to fs-lasers, ns-lasers are significantly cheaper. In CDs, data is recorded by amorphizing PCM strips and erased with crystallization pulses. The minimal feature size of a commercial Blue-Ray CD is as tiny as $\sim 150 \text{ nm}$ ⁶⁰. For integrated photonics, one major obstacle was, again,

the high loss of traditional PCMs. However, the loss can be overcome by exploiting emerging wide bandgap PCMs and designing low-loss waveguides.

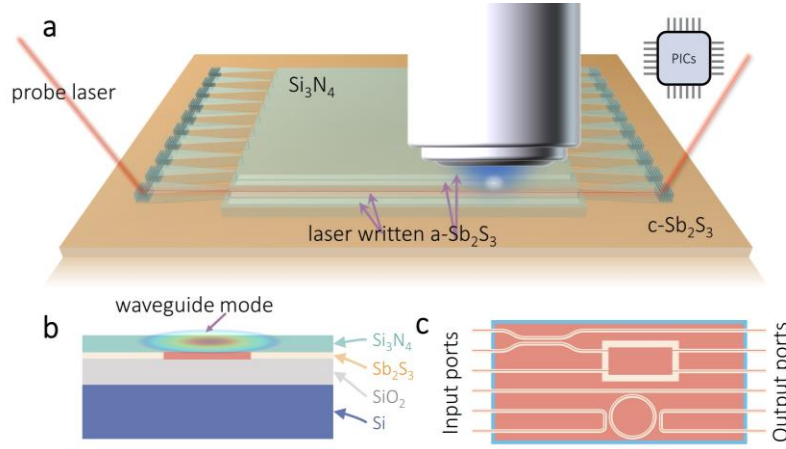


Figure 6.6: **Lithography-free rewritable PICs using ns-lasers and PCMs.**

(a) Proposed laser written PIC in wide bandgap PCM (Sb₂Se₃ or Sb₂S₃). Optical waveguides are defined by two Sb₂S₃ strips (in white, pointed by purple arrows) amorphyzed by a focused ns blue pulse laser and leaving the center portion crystalline. Prefabricated grating couplers can provide the input/ output interfaces. The photonic circuitry is completely reprogrammable and only limited by material loss and laser writing resolution.

(b) An example material stack consists of a silicon substrate, a few microns of silicon dioxide, tens of nanometers Sb₂S₃, and a few hundred nanometers Si₃N₄ cladding. When a strip of Sb₂S₃ is switched from crystalline (dark orange) to amorphous (light orange) phase, a waveguide mode can be confined, located mainly in the Si₃N₄ layer to reduce loss. **(c)** Concept of photonic devices beyond waveguides that can be implemented in this platform, such as directional couplers, multi-mode interferometers, and ring resonators. Here orange indicates the unwritten c-Sb₂S₃.

Laser-written PCM photonic devices have already been demonstrated for meta-optics⁶⁴ and tunable beam splitters⁹³, which were limited to a single device. In Figure 6.6(a), we envision expanding this technology to create large-scale rewritable PICs, and in fact a few recent works have been published on the perspective^{178,262,263}. A carefully designed material stack builds canvases for rewritable photonic architecture. An example material stack in Figure 6.6(b) includes tens of nanometer thick c-Sb₂S₃ on a few microns thick layer SiO₂, cladded with a few hundred nanometers of Si₃N₄. In this configuration, the optical guided mode is mainly confined within the Si₃N₄ cladding layer to ensure low absorptive loss from c-Sb₂S₃.

The relatively thin layer of Sb_2S_3 and Si_3N_4 also allows Sb_2S_3 to be switched entirely and reversibly with high spatial resolution from the top. A ns-pulsed laser at a shorter wavelength (e.g., 450nm), similar to a CD-writer, selectively “patterns” (i.e., amorphizes) the PCM. The probe laser at IR wavelength is guided by the total internal reflection at the interface of patterned a-PCM and unpatterned c-PCM. As illustrated in Figure 6.6(c), many other functionalities can potentially be implemented beyond simply routing through an optical waveguide, such as ring resonators, directional couplers, and multi-mode interferometers. The same chip/wafer can be switched back to its crystalline state by rapid thermal annealing⁶³ and rewritten again.

Compared with previously reported multi-purpose PICs^{39,41,143,212}, the achievable functions in rewritable PICs are only limited by the laser writing resolution and the material losses, and not by the discrete meshes. Thus, such laser-writable PCM can be considered as programmable PICs at the most extreme level, where each pixel can be programmed. This process can be much faster, and more cost-effective for simple designs and rapid prototyping than fabricating a PIC in a nanofabrication facility. However, we note that the proposed laser writing approach is unlikely to entirely replace traditional nanofabrication. The limited spatial resolution of laser writing and repeatability of PCM switching will limit possible applications. Instead, it should be considered as a new path - a fast, cheap, and rewritable platform for devices with large feature sizes.

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