

Hydrothermal Shelling Synthesis of β -NaYF₄ Microparticles

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Abstract

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This thesis paper covers my research on the shelling of ytterbium (Yb³⁺) doped β -NaYF₄ for application as a radiation balanced microlaser. In general, laser designs rely on either flash pumping or a custom diode. Both of these methods produce a significant amount of energy in the form of heat and therefore require a reliable cooling system. Radiation balanced microlasers have been proven to operate reliably without an external cooling system using what's referred to as laser refrigeration. This results in both high beam quality and high efficiency. One particular synthetic material proven capable of use in laser refrigeration and lasing is called β -NaYF₄. It is made using Sodium, Yttrium, Fluoride, and sometimes a ligand. It's hexagonal crystal structure combined with proper lanthanide doping can allow for anti-stokes luminescence and laser refrigeration. Therefore, it holds its place in use of this specific laser type. However, getting a properly doped and shelled β -NaYF₄ that is capable of both laser refrigeration and lasing is quite difficult. Although these two phenomena have been produced and proven individually, getting a β -NaYF₄ sample that is capable of both at the same time is far more

difficult. This thesis also hopes to discuss and review our attempts to improve current methods of producing these doped β -NaYF₄ samples capable of lasing, our encountered problems and solutions, and what it all means for the technology.

Introduction:

Laser technology has been an ongoing topic of research since the 1960s, when the first ever laser using ruby was developed. This would lead to the use of a phenomenon called flash pumping to make lasers that have a pulsed output, resulting in megawatt levels of output power being possible. Today, lasers made using a special diode are more common and widely available and capable of various levels of output power. All these laser designs suffer from generally low efficiency due to the several step processes required to get the desired lasing output where each step will have some energy loss in the form of heat. If this heat is not regulated and minimized, it has serious negative effects on the laser such as damaging it, decreasing the efficiency even more, or completely killing the output and the device itself.

Since then, multiple designs have been proposed in attempt to midgait these problems. This includes using an optical fibre core to amplify an initial signal (4), flash pumping a signal using “slabs” of crystal in a laser diode to improve efficiency (5) and using a disk-shaped medium essentially as an amplifier once the laser beam goes through it (6). While all these have continuously improved efficiency, the risk of excess heat damaging the device has continued to be a hurdle. To help combat this, many of these designs implement things like heat sinks or water cooling. For heat sinks, despite working as intended they can only remove a limited amount of heat and can hold on to heat even after the laser is powered off, making them not ideal for long operation times without some other mechanism to promote cooling once the laser is powered off. Water cooling can potentially remove more heat but is not applicable for smaller lasers due to the need for a pumping system for the continuous flow of cooling water and a single leak could be determinantal to the device. These systems tend to be very expensive, require scheduled

maintenance, and are bulky and heavy, therefore being mostly reserved for use in large surgical lasers.

Which leads us to one of the newer laser technologies, known as radiation balanced microlasers. This method works to eliminate heat generated from the lasering process by being what is known as an athermal laser, meaning the laser can operate without an external cooling system. This is possible because the microparticle used for the lasing is capable of both laser cooling and lasing at the same time. Essentially, the microparticle acts as both the lasing and cooling source.

Some of the potential applications for these lasers involve using them in a detector that can be tuned to be so sensitive that it could detect high frequency gravity waves. This would allow us to measure and learn more about these waves, which are an ongoing topic of research with currently few reliable ways to measure and observe them. They can also be used in the development of optical traps. Basically, by trapping particles in the focal point of the laser beam, the electric field created at this point is enough to trap individual particles in the field and oppose gravitational forces. However, if the air around it is not perfectly still, the trap will be unsuccessful as any breeze will be enough to push the particles out of the trap.

Background:

The use of various rare-earth doped particles for an athermal laser goes as far back as the 1920s but wasn't proven until the 1990s. This was done using an ytterbium doped fluorozirconate (fluoride, zirconium, and a few other transition metals). Using anti-Stokes

luminescence, the sample was cooled to only around 0.3K below room temperature (around 300K) without a separate cooling system. After this proof of concept and system, research swiftly began on other possible lanthanide doped particles capable of these feats (2). This paper will focus on the use of the microparticle widely known as β -NaYF₄ and our choice of dopants.

NaYF₄ particles can take on two potential phases, one is known as the α phase and the other being the β phase. These differentiate through α having a cubic crystal structure and β phase having a hexagonal crystal structure shown in fig 1a) 1. NaYF₄ particles in the α phase also tend to be smaller than the β phase due to the α phase being more thermodynamically stable when the particles are under a certain size (4). The phase can also be affected by the temperature and pressure of the reaction environment, as we will see in our use of a hydrothermal synthesis. NaYF₄ in the α phase has been applied in the medical field due to its small size but high sensitivity to various biological detection methods (7). It has also proven to be capable of anti-stokes luminescence, but the optical quality is lower and therefore less efficient. For this reason, we conducted our shelling experimentation on the β phase specifically.

This difference in crystal structure is another reason why the use of x-ray diffraction (XRD) for analysis of the particles is important. The X-rays diffracted from the cubic and hexagonal crystals are detected at different angles and intensities, making XRD the chosen method to see if the shelling procedure still contains the α phase after synthesis completion.

The creation of the microparticles themselves can be done using a few different methods such as thermal decomposition of lanthanide trifluoroacetate precursors (12) and solvothermal methods using non-aqueous solvents instead of water like in a hydrothermal procedure (13). For our purpose of shelling β -NaYF₄ cores, it was determined through previous research headed by

Greg Felsted in Dr. Peter Pauzauskie's research lab that hydrothermal production is the best choice due to the ability to consistently grow single-crystalline β -NaYF₄, lower cost of production, and controlled morphology of the product (10).

For properly shelled and doped β -NaYF₄, one must analyze whether it is capable of laser cooling and outputting a laser. The cooling is done by the Yb³⁺ dopant conducting anti-stokes luminescence as described below in fig 1b). The Yb³⁺ dopant has energy levels that are split into sublevels because of the Stark effect. Basically, this effect is the splitting of energy transition levels of an atom due to an external electric field. This cooling is done when an electron is excited between the top and bottom (or ground) sublevels, The emitted photons from this event have a wavelength on the long end of the absorption spectrum, resulting in a "cooling cycle" and in some cases, a "lasing cycle" as well. This total cooling event is Anti-Stokes luminescence. In other words, these emitted photons can remove the heat from the system (2).

For the lasing itself, the shell must be doped with a rare earth metal capable of inversion population, meaning more electrons existing in an excited state instead of a ground state. Therefore, making further electron excitation possible, which contributes to upconversion which occurs where two lower energy photons are absorbed thereby causing the release of one higher energy photon. The shelled particles must also be in what's called Whispering Gallery Mode. This where a photon experiences total internal reflection along a medium. This phenomenon has been observed previously using Tm³⁺ doped β -NaYF₄ capable of outputting few different colors of light, and even potentially combining outputs together to create white light (19).

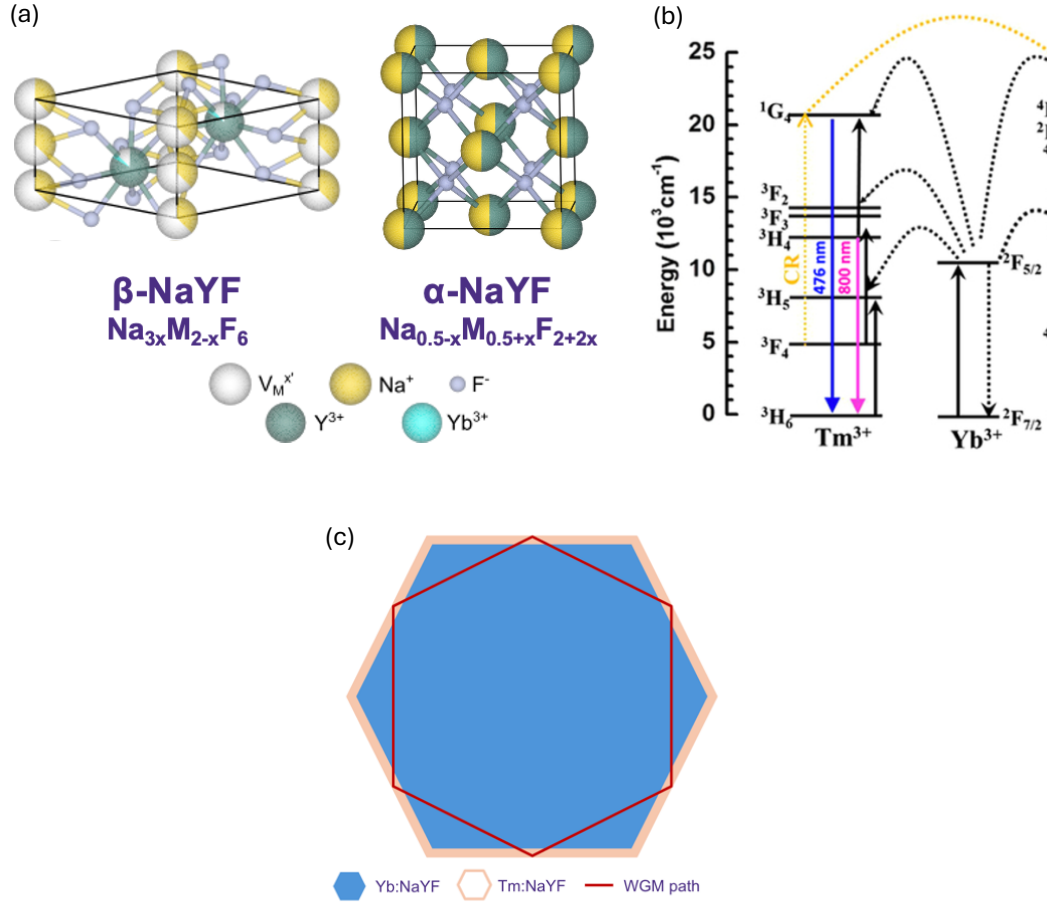


Fig 1a) β -NaYF₄ and α -NaYF₄ non-stoichiometric crystal structures (23), 1b) Schematic of energy level diagram for Tm³⁺ and Yb³⁺ ions and up conversion mechanism for various colors and emissions (22), 1c), Whispering Gallery Mode (WGM) path on Yb³⁺ doped β -NaYF₄ with Tm³⁺ doped shell (24)

Despite its amazing potential, the actual production of β -NaYF₄ with doped shells that are capable of the laser cooling and lasing output is not without several problems. Due to the technology being based around just one particle working as a laser, a low or even medium particle surface quality could be detrimental to the functionality of the product. It is also observed that getting perfect, or even preferable particle morphology is quite difficult due to NaYF₄ being what's referred to as a non-stoichiometric compound, meaning that the ion locations in the crystal can vary greatly from the theoretical result. Also, due to just one of these

particles possibly being able to operate as an athermal laser, doing optical analysis on a single particle is very difficult. My research was aimed at getting a synthesis procedure that could reliably produce properly shelled and doped β -NaYF₄ particles.

Experimental Methods:

This optical microparticle is made using both what is referred to as the “core” and the “shell”, both synthesized separately. It is worth noting that the cores used in these various procedures came from multiple different core batches due to the generally low core synthesis yields. The Yb³⁺ doped β -NaYF₄ used as our cores were synthesized by Material Science PHD student Lars Forberger. The shelling synthesis is conducted using a fluoride source (NaF), a rare earth source, being a combination of (Y(NO₃)₃·4H₂O) plus TmCl₃ as our dopant, and a ligand made of Ethylenediaminetetraacetic acid (EDTA) to help promote the formation of flat, hexagonal faces instead of a “rod” – like structure (10) as was observed when synthesizing without a ligand. It is required that a base, our choice being NaOH be added to our EDTA to allow it to be dissolved in water, as neutral EDTA is not water soluble. The overall volume amounts were as follows: 5mL total fluoride source (NaF stock + H₂O), 4mL total rare-earth source (YCl₃ stock + H₂O), and 5mL total ligand (solid EDTA + NaOH + H₂O). Stock solutions of each component were used and individually diluted with water before being mixed and put under pressure in what’s called a “liner” that is put in an autoclave at 220C for 72 hours (10). It is best to use pre-made stock solutions of each in order to make sure the volumes are as accurate as possible and the required 4:1 molar ratio of fluoride to RE is maintained.

Before conducting hydrothermal syntheses, we conducted an experiment to determine the dilution limit of NaYF₄ microparticles so that we could conduct syntheses near that limit to test how different levels of supersaturation would affect the particle morphology and the chances of new particles forming during the synthesis. At room temperature and pressure, we combined 0.2mL 0.25M YCl₃ stock and 0.25mL 0.8M NaF stock to get 0.45mL total NaYF₄ in solution to maintain the described 4:1 fluoride to RE ratio. This process was repeated in multiple tubes, and each was diluted to various levels.

A typical hydrothermal synthesis began with measuring out how much of each stock solution we needed for each component and calculating how much water we needed to add to each. Given the molarities of our stock solutions and the required 4:1 fluoride to RE ratio, those values were used to calculate how much of each stock solution we would need to use. Using those volumes of fluoride source and RE source, we could then calculate how much water to combine to each in order to maintain the proper molar ratio while still getting 400uL total of RE solution and the 500uL total fluoride solution. Then using the amount of mols of RE in the solution, the desired mol of EDTA and NaOH can be calculated (10). Following the synthesis diagram below in fig 2, once all three components are mixed and no solid particles remain the RE and ligand solutions are mixed in a liner for five minutes, then the fluoride solution is added along with your desired β -NaYF₄ cores then mixed for half an hour. That liner is then placed in the autoclave heated to 220C.

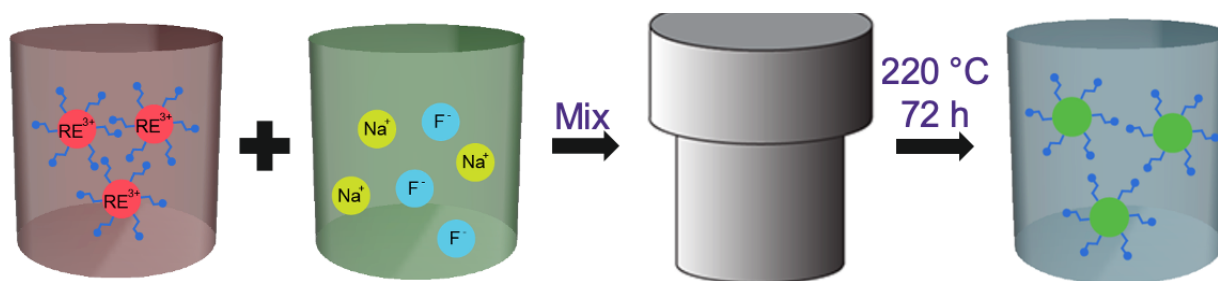


Fig 2) General hydrothermal synthesis diagram of β -NaYF₄ (diagram does not include dopant) (23)

After three days, the liner is removed and allowed to cool to room temperature and pressure. The solution is centrifuged to separate the particles from solution and excess liquid is poured out. DI water is then added, the solution is remixed, centrifuged again, and excess is liquid is poured out. This process is repeated three times using DI water, and three times with ethanol to remove impurities. After the wash, the remaining particles are dried in a low oven and weighed to calculate percent yield.

Measuring the lasing emission can be conducted a couple different ways, but the key for all of them is to get the particles in an arrangement that we can measure the photons only one particle is emitting. Unfortunately, getting only a single particle in a sample for measuring is extremely difficult, so our method of optical measuring was done by collecting samples on an optical fibre. Essentially, by gently inserting a thin optical fibre into a sample of the shelled particles, Van Der Waals forces between the particles and the fibre will hold the particles in place. Placing that in the focal point of the laser with proper calibration and recording equipment allowed us to measure the wavelength and intensity of the output.

Results and Discussion:

Before conduction of hydrothermal syntheses, dilution experimentation was conducted at room temperature and pressure. It was theorized that mixing the two components and conducting our syntheses just above the supersaturation limit would help prevent the formation of new particles, prevent the pre-existing particles from redissolving, and potentially even help gain a higher final product yield. Using the described procedure, various dilutions were conducted and whether the mixed particles redissolved in the water was recorded.

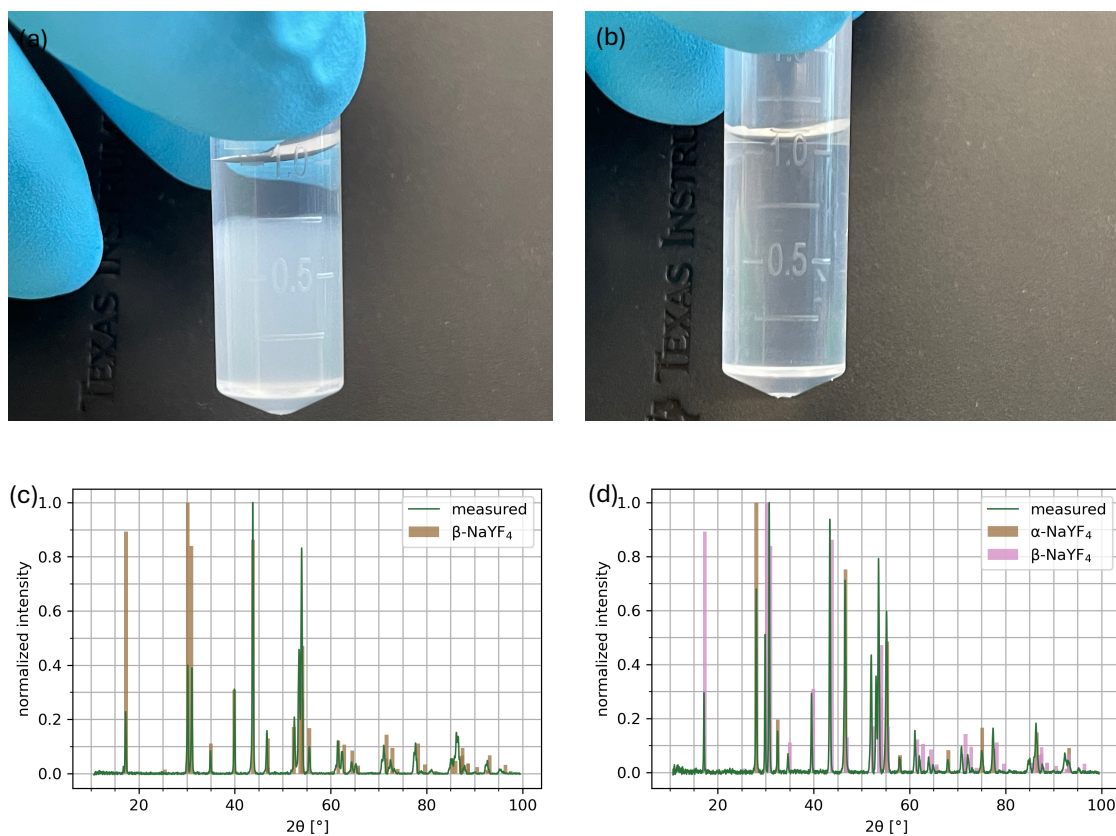


Fig 3a) (top left) Non-hydrothermal (room temperature and pressure) NaYF₄ solution diluted to 120%, 3b) (top right) Non-hydrothermal (room temperature and pressure) NaYF₄ solution diluted to 140%, 3c) (bottom left) XRD data of hydrothermal β -NaYF₄ diluted to 120%, 3d) (bottom right) XRD data of hydrothermal β -NaYF₄ diluted to 140%

It was observed that somewhere beyond 120% dilution, the NaYF₄ particles would redissolve in the water at room conditions. As seen in fig 3a), the 120% dilution has the cloudy look (NaYF₄ particles are not redissolved), and the 140% is clear, indicating the redissolving of the NaYF₄. XRD taken from later hydrothermal shelling syntheses that used these two dilutions (figures 3c and 3d) corroborates our theory of the formation of new particles and show that the higher dilution contained the α phase after the autoclave.

Considering these results from the dilution experiment, two shelling syntheses were conducted with the theory that the 140% would have better particle morphology than the 160%. SEM results below in fig 4a and 4b) show the higher presence of properly shaped hexagonal particles along with both α and β phase particles in the mix. We also saw inconsistency in how the particles grew. As described below, cores in the 140% grew in both width and thickness, while the ones from the 160% shrunk in size. This was theorized to be the result of particles partially redissolving in solution. However, the main reason these dilutions were decided to not be suitable for further testing was due to the presence of both types of unwanted particles, those being α phase and newly formed β phase particles. This undesirability is due to the described lower optical quality of the α particles and the unshelled nature of newly formed β particles.

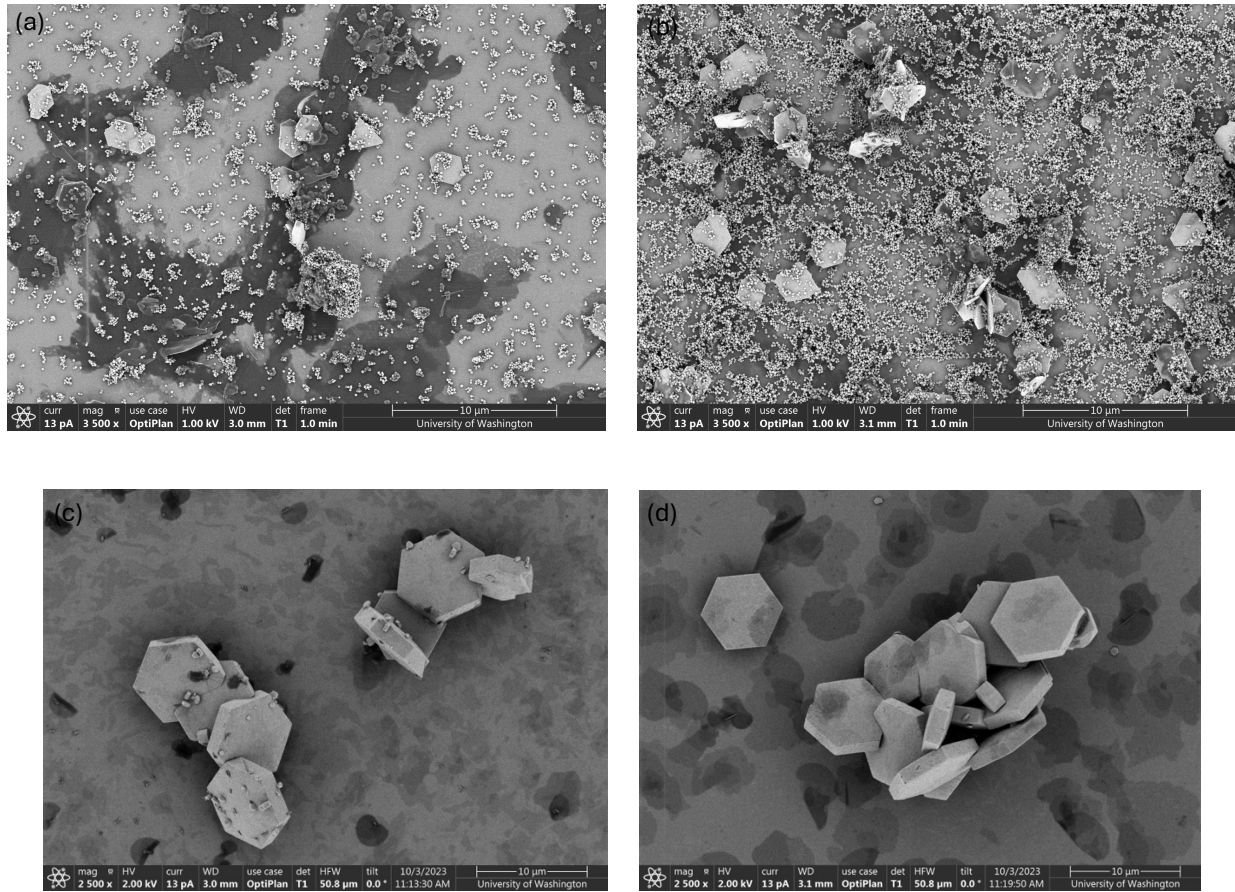


Fig 4a (top left) 140% dilution SEM results using 4:1 F:RE ratio and 10.8mg of cores, no Tm³⁺ dopant, 4b (top right) 160% dilution SEM results using 4:1 F:RE ratio and 10.0mg of cores, no Tm³⁺ dopant, 4c) (bottom left) 100% dilution SEM results using 4:1 F:RE ratio and 10.0mg of cores, no Tm³⁺ dopant, 4d) (bottom right) 120% dilution SEM results using 4:1 F:RE ratio and 11.8mg of cores, no Tm³⁺ dopant

Dilution Level	100% (4c)	120% (4d)	140% (4a)	160% (4b)
Avg Core Width (um)	8.05	8.05	1.18	1.18
Avg Core Thickness (um)	1.12	1.12	0.8	0.8
Avg Shell Width (um)	7.7	8.45	2.05	2.47
Avg Shell Thickness (um)	1.43	1.45	1.1	0.192

Table 1: Particle dimensions before and after shelling procedures shown in fig 4

For comparison, syntheses were also conducted at 100% dilution and 120% dilution (figures 4c and 4d). The prevention of α particles was successful in both and overall hexagonal morphology was much better, but particles in the 100% dilution experienced an overall increase in particle width, but decrease in particle thickness. Some smaller, newly formed β particles were also observed, again indicating the unfortunate presence of homogeneous nucleation. These could either be newly formed during the synthesis, or cores that were unaffected by the shelling. Our current theory is that these are the result of new particle growth in the solution and those particles not merging with the larger ones properly, which would normally lead to shelling. It was believed that an increase in cores added at this dilution would help mitigate this problem, but for our purposes, these results were sufficient in proving the importance of dilution level during synthesis and solidified 120% dilution as our primary choice.

The next step was to introduce Tm^{3+} dopant into our procedure. It was initially believed that this would not cause any major change in our particle morphology, but this theory was swiftly proven wrong. As shown below in fig 5a, we saw a massive increase in newly formed β_NaYF_4 particles and a drop in the quality of the morphology. In fact, the average width of the shelled β_NaYF_4 had over doubled and we were unable to get an exact average thickness measurement due to them being so thin. This unfortunate change meant new modifications to the procedure were required.

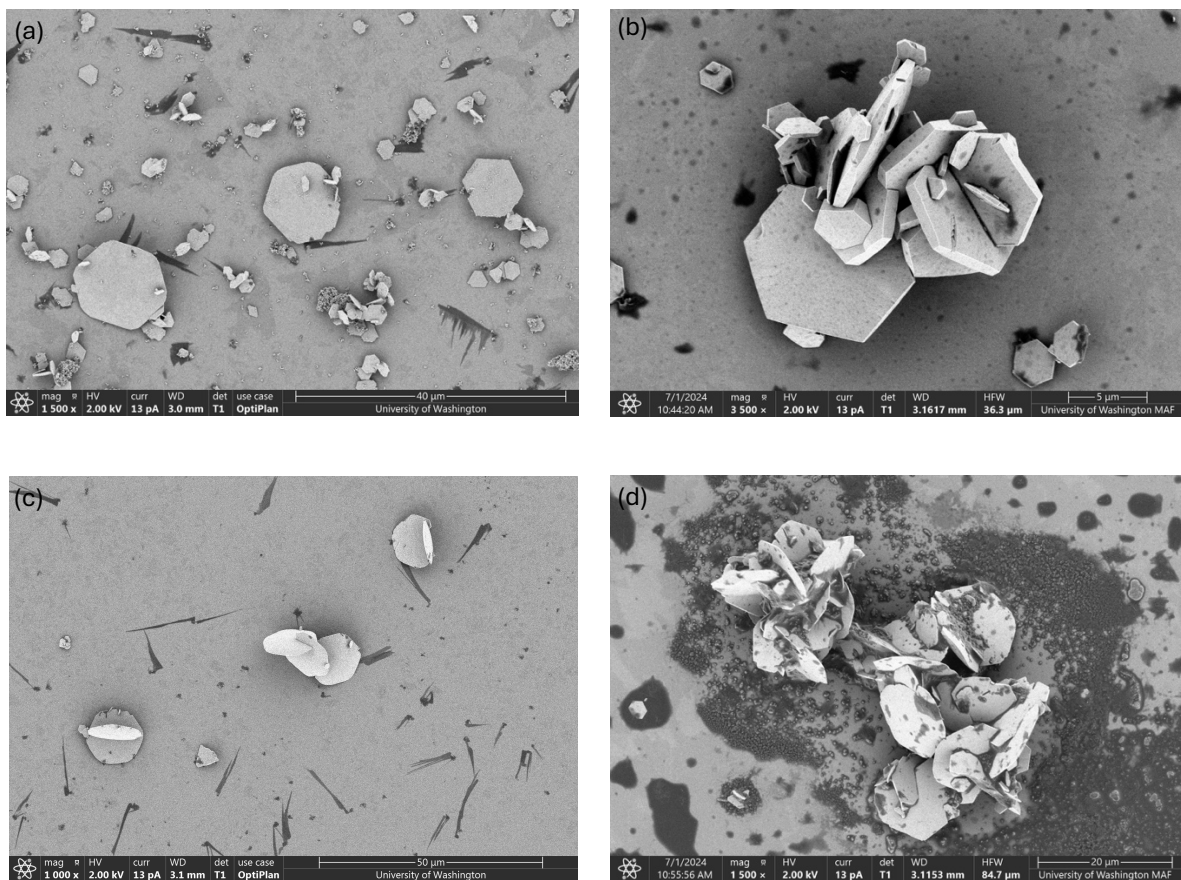


Fig 5a) (top left) 120% dilution SEM results using 4:1 F:RE ratio, 10.6mg of cores, Tm3+ doped, 5b) (top right) 120% dilution SEM results using 4.5:1 F:RE ratio, 10.0mg of cores, Tm3+ doped, 5c) (bottom left) 130% dilution SEM results using 4:1 F:RE ratio, 10.6 mg of cores, no Tm3+ added, 5d) (bottom right) 130% dilution SEM results using 4.5:1 F:RE ratio, 10.2mg of cores, Tm3+ doped

Dilution, F:RE ratio	120%, 4:1	120%, 4.5:1	130%, 4:1	130%, 4.5:1
	(5a)	(5b)	(5c)	5d)
Avg Core Width (um)	5.39	5.39	5.39	5.39
Avg Core Thickness (um)	1.36	1.36	1.36	1.36
Avg Shell Width (um)	12.4	9.95	11.8	12.1
Avg Shell Thickness (um)	<0.5	0.638	0.81	0.181

Table 2: Particle dimensions before and after shelling procedures shown in fig 5

The syntheses done using a dilution of 130% were used as a reference and supported more consistent results in terms of particle shape but still presented the problem of particles growing in one dimension but shrinking in another. The amount of growth and shrinkage was also found to be random. Not only does this indicate uneven nucleation, but it also suggests partial redissolving of particles, and due to the already thin design of cores, making them thinner risks them becoming too fragile for handling while also indicating that the surface quality will not be good enough for reliable lasing. Therefore, a change from the 4:1 ratio to 4.5:1 was proposed. It was believed that increasing this ratio will result in β -NaYF₄ particles becoming thinner and longer, or more “tube-like” (10). Examples of this effect are shown in fig 6 below.

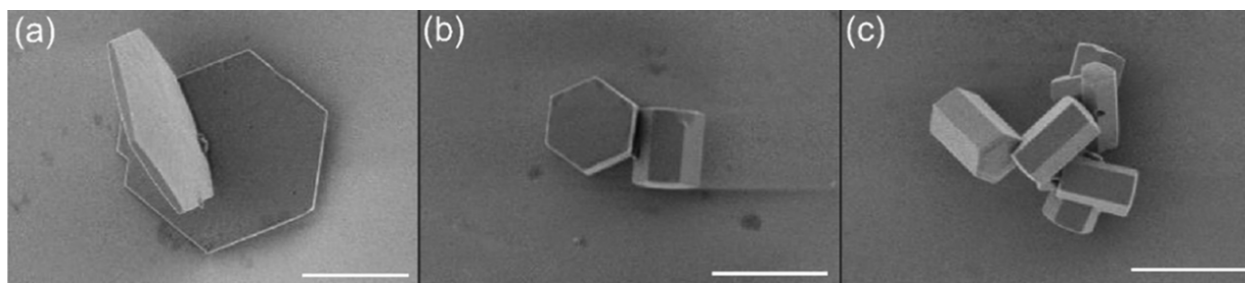


Fig 6) β -NaYF₄ core synthesis conducted using F:RE ratios of (a) 4:1, (b) 6:1, and (c) 8:1 (10)

We decided to apply this logic and use this adjusted ratio in our next shelling procedure in hopes to reduce the “thinning” aspect seen in the previous shelling results. Figures 5b and 5d show the results of this change of ratio and provide proof of this overall improvement in both shelling consistency and less newly formed particles or unshelled cores. Even though the

“thinning” aspect continued, the reduction of this phenomenon in combination with the Tm^{3+} doping lead us to maintain the 4.5:1 ratio for the rest of experimentation.

The next approach we decided to take was changing the amount of cores to use in the synthesis. Originally, 10mg of cores was chosen through previous syntheses done by Lars Forberger, a PHD student in Dr. Peter Pauzauskie’s research team. Therefore, it was suggested to run another synthesis that used 15mg of cores instead of the previous 10mg. This was also theorized to help prevent the described “thinning” of the particles due having more possible cores as nucleation cites would potentially make each core experience less overall nucleation, leading to more even morphology overall.

As shown in Fig 7 below, this change resulted in quite a few unexpected effects. It seems to have resulted in a mix of different size particles with varying quality. Although no $\alpha\text{-NaYF}_4$ was detected using XRD, we saw many different examples of particles far smaller than the cores we added. We decided to not give an exact average shelled particle width or thickness due to their wide range of hexagonal quality. As seen, few of the larger particles showed the desired hexagon shape and some are not properly formed at all. In fact, the smaller particles shown in fig 7b below show much more even morphology than the observed shelled ones. This could be due to them being cores that did not experience shelling, or they could be newly formed $\beta\text{-NaYF}_4$ from the shelling procedure. Due to the enclosed nature of the shelling procedure in the autoclave, we could not decide on a reliable way to differentiate which of the smaller particles were the result of which phenomena. These results were particularly surprising as in theory, having more nucleation cites should have helped promote heterogeneous nucleation instead of discouraging it.

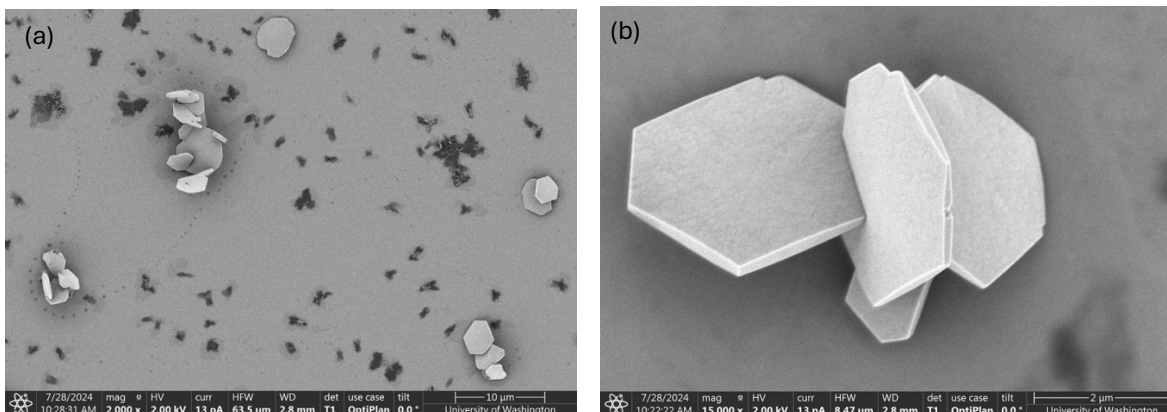


Fig 7a) 120% dilution SEM results using 4.5:1 F:RE ratio, 10.6mg of cores, Tm³⁺ doped SEM of shelled and unshelled β -NaYF₄, 7b) Close-up SEM of newly formed β -NaYF₄ indicated by their clean hexagonal shape and small size with most being under 3 μ m in width

Unfortunately, these results led us to not reach a solid conclusion on whether the increased amount of cores added affects to the reliability of the shelling process. Therefore, we decided to maintain this change in our next synthesis to see if the problem persisted. This would allow us to see if this unexpected change was due to a mechanic we had not considered or even human mistake.

Our next theory was that the high amount of water in the shelling process and the long time the particles spend submerged allows for a higher probability that partial resolving will occur even after nucleation has begun. Therefore, it was decided to decrease the volume of each of the components while maintaining the proper 120% dilution, the 4.5:1 ratio, and 15mg of added cores. The volumes of each component were halved to become 2.5mL of fluoride source, 2mL of rare-earth source, and 2.5mL of ligand. Results of this change are described using Fig 8 and Table 3 below.

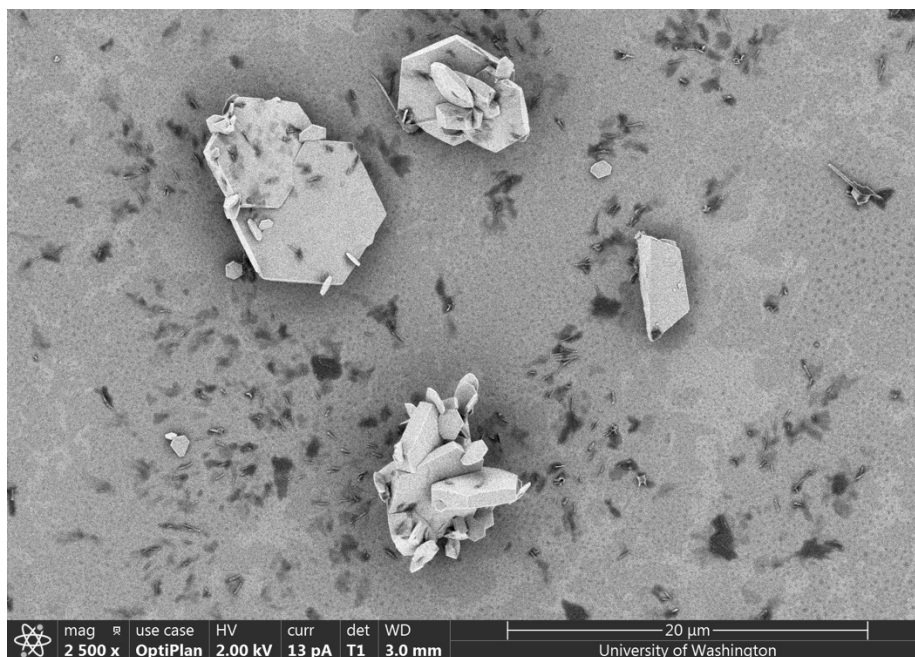


Fig 8) 120% dilution SEM results using 4.5:1 F:RE ratio, 15mg of cores, Tm³⁺ doped, halved volumes of precursors

Dilution	120%
Avg Core Width (um)	3.17
Avg Core Thickness (um)	1.36
Avg Shell Width (um)	7.33
Avg Shell Thickness (um)	0.87

Table 3: Particle dimensions before and after shelling procedure shown in Fig 8

As just shown, reducing the volumes of the components did have a significant impact in reducing the “thinning” of the particles during shelling and improving hexagonal morphology,

thereby proving our theory to be correct. We also saw a return of the abundance of shelled particles and a reduction in newly formed ones. Even though the “thinning” still occurred, it is believed that the reduced volumes drastically reduced the number of particles that experienced redissolving even if it did not have as much of an impact in achieving more even nucleation. It was also found that having less overall volume of solution to work with made the synthesis overall easier to conduct without spillage. The liners we used were barely large enough to hold the total 14mL of liquid in our previous syntheses, so reducing the volumes greatly helped minimize the chance of spillage when transferring the liner full of solution in and out of the autoclave.

Despite not achieving the fully desired speculations for the shelled β -NaYF₄, the results were deemed sufficient to begin optical analysis. This was determined due to the improved overall quality of the particles and their morphology showing the required hexagonal shape after being doped with Tm³⁺. This was conducted by using particles attached to the optical fibre as previously described and the focal point of a high-power infrared laser. Fig 9a and 9b below show the recorded wavelength and intensity of the photons emitted due to the Yb³⁺ doped cores and Tm³⁺ doped shells. Shown in comparison in figures 9c and 9d is optical data from previously synthesized Yb³⁺ and Tm³⁺ doped β -NaYF₄ (10, 17). It is worth noting that the optical measuring method we used cannot measure laser cooling, but only lasing output from the shell dopant along with WGM behavior.

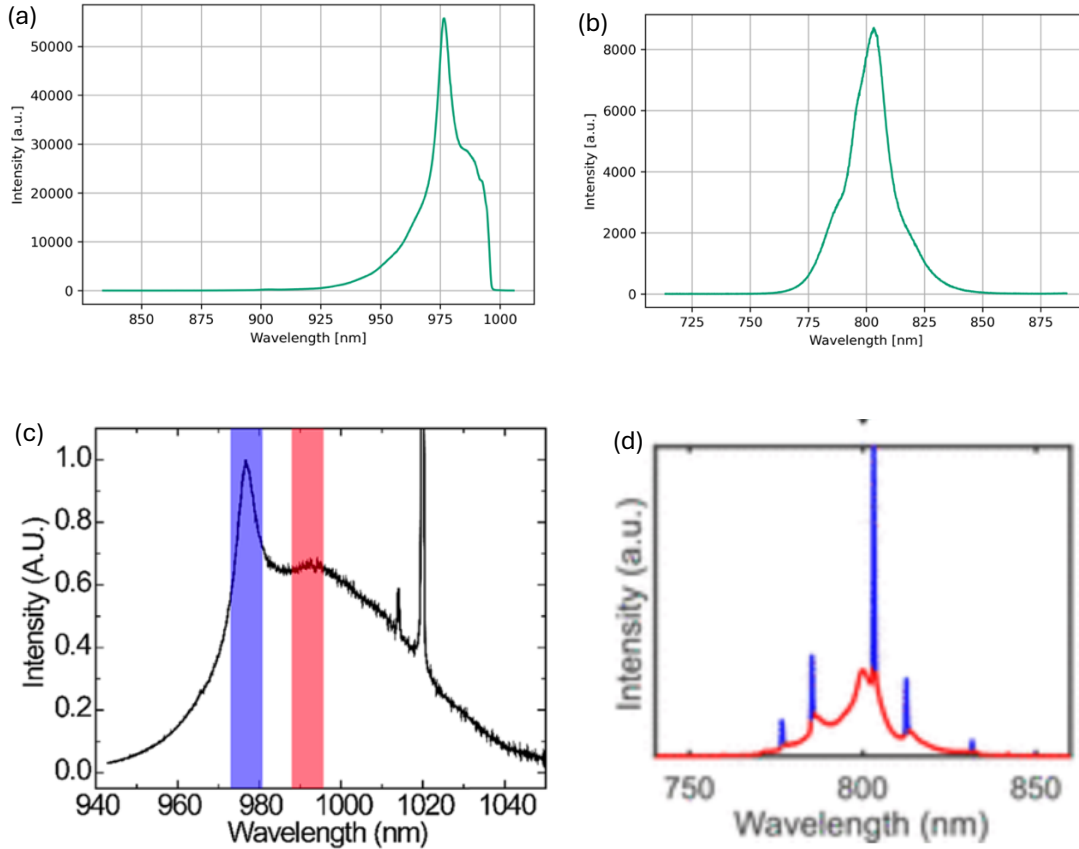


Fig 9a) Yb³⁺ luminescence spectrum of doped shelled β _NaYF₄ upon excitement by continuous infrared laser with 1000nm filter applied, 9b) Tb³⁺ luminescence spectrum of doped shelled β _NaYF₄ upon excitement by continuous infrared laser, 9c) Luminescence of 10% Yb³⁺ doped β _NaYF₄ crystals excited with a 1020nm laser at 295K (10), 9d) Emission spectrum of Tm³⁺ doped β _NaYF₄ mounted on polystyrene microsphere (17)

Despite our detection only being able to measure the output of several particles instead of individual ones, what these outputted wavelengths peaking at around 980nm for Yb³⁺ and 805nm for Tm³⁺ in combination with the peak's broad nature tells us is that the shelled particles are capable of luminescence, but not of WGM. Proper WGM and Tm³⁺ lasing would produce a spectrum similar to figure 9d with multiple sharp peaks instead of one broad one (17). We can conclude from these results that the Tm³⁺ and Yb³⁺ ions were properly doped, but the particles

in question used for analysis would not work as an athermal Tm³⁺ laser. However, we do believe that these particles would be capable of lasing given some more fine tuning and modifications.

Future Results:

All the described hypotheses, testing, and results have provided several useful insights in the production and performance of shelled and doped β -NaYF₄ particles. Despite the remaining inconsistencies, we have concluded on a few recommend changes for the shelling procedure, and some potential changes that we think need further testing.

For the formally recommended changes, the results prove that conducting at 120% dilution provides the best environment to promote heterogeneous nucleation on the cores and discourage homogenous nucleation. We also think that the volumes being reduced by half should be maintained due to the easier control of the solution during synthesis and the drastic observed improvement to the nucleation. It is also highly advised that, if possible, to use cores from the same batch when doing multiple shelling syntheses at once. This is to assure that the cores going into the shelling solution are as consistent as possible.

The changes we conducted which we are inconclusive on were the changed fluoride and rare-earth molar ratio from 4:1 to 4.5:1 and the increased amount of cores from 10mg to 15mg. This is because although we did observe that these changes had an effect, we do not believe that they provided a reliable enough improvement to the final product. This is compounded by the fact that even though we didn't observe major improvements from the changed ratio, previous research done by Dr. Pauzauskie's group proved the potential effects changing the ratio has (10). Therefore, we suggest another pair of syntheses be done at 120%, the halved volumes, and the

same amount of cores (the exact amount not being super important as long as they are the same) but to do one with the 4:1 ratio and one with the 4.5:1 ratio. We think this would provide better insight on whether this proposed change really provides any favorable results.

Furthermore, we think that doing a pair of syntheses where two different amounts of cores are used would also provide some good insight. Not only would it either prove or disprove the theory that changing the amount of cores has little effect, we think it would also provide good insight on the question of whether changing the core synthesis to get a higher percent yield is worth testing as well.

Conclusion:

We think this conducted research gives just a sample of the level of potential that shelled and doped β -NaYF₄ particles hold in the development of radiation balanced microlasers. Despite the remaining inconsistencies in the gained particle yields, the fact that the proper photon wavelength was detected at such high intensity proves that the product is very much capable of outputting easily detectable and tunable photons without the need for an external cooling source. I would also like to give special thanks to UW Material Science and Engineering professor Dr. Peter Pauzauskie and UW Material Science PHD student Lars Forberger for the chance to work with these materials over this last year. It is an experience I will forever appreciate and remember.

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