Single-crystal, rare-earth doped YAG fiber lasers grown by the laser-heated pedestal growth technique

Craig D. Nie[*a], James A. Harrington[a], Yuan Li[b], Eric G. Johnson[b], Elizabeth F. Cloos[c], Stephen C. Rand[c], Pedro Machado[c], Ramesh K. Shori[d]
[a]Dept. of Material Science and Engineering, Rutgers University, Piscataway, NJ 08854;
[b]Dept. of Electrical and Computer Engineering; The Center for Optical Materials Science and Engineering Technologies (COMSET), Clemson University, Clemson, SC 29634
[c]Dept. of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109
[d]SPAWAR System Center, San Diego, CA

ABSTRACT

High concentrations of the rare-earth elements erbium, holmium and thulium have been successfully doped into single crystal (SC) yttrium aluminum garnet (YAG, $Y_3Al_5O_{12}$) fibers by use of the laser heated pedestal growth (LHPG) method. The spontaneous emission spectra and fluorescence were measured in the near-infrared (NIR). The results show progress towards forming a solid state laser able to produce a wavelength in the NIR, for high power applications.

Keywords: LHPG, single-crystal fibers, infrared fiber optics, rare-earth dopants

1. INTRODUCTION

1.1 Background

The laser heated pedestal growth (LHPG) method for growing SC fibers is a relatively old technique, first done by Haggerty at MIT in 1972. Since then, other universities and companies have followed and expanded upon Haggarty's initial procedure. There are two other primary fabrication methods used to make SC fibers – the Edge-Defined Film-Fed Growth Method and the Micro-Pulling-Down Method. Both melt powders in a crucible and insert a seed crystal into the melt. Their use of a crucible can be undesirable due to the possibility of contamination from the crucible material.

1.2 Single Crystal Fibers

Like glass, SC fibers can be both passive and active. However, SC YAG fibers have many notable advantages over silica glasses, the combination of which offers the potential to produce a higher power laser in the NIR. First, many SC fibers can be doped to higher concentrations without clustering, unlike glass. Secondly, their mechanical properties are excellent – due to a higher Young's Modulus they exhibit superior structural integrity. YAG also has superior thermal properties, with melting points greater than 1900 degrees Celsius and a thermal conductivity that is approximately seven times greater than that of most glasses, offering a higher damage threshold when being pumped at high powers.[1] At high powers glass is limited by Stimulated Brillouin Scattering (SBS), whereas SC fibers have a much higher SBS threshold, thus allowing for greater output powers. YAG fibers have the potential to deliver five times the peak power due to the Brillouin gain coefficient being significantly less than silica fiber.[1]

The critical issue that must be overcome when using SC fiber lasers rather than glass fiber lasers is producing a proper cladding. Cladding SC fibers poses a big challenge, and although there have been some attempts by universities and companies to clad SC fibers, no definitive method has been achieved. Extensive experimentation and research is still to be performed.

*craig.nie@rugters.edu: phone 319-239-9219, irfibers.rutgers.edu

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1.3 Absorbance

YAG is an excellent host material for producing a fiber laser in the NIR because of its transmittance range of 1.5 to 4 µm. Figure 1 shows the absorbance for a pure SC YAG fiber in the IR. The small peak around 3 µm is possibly due to an OH impurity.[2] The double peak around 3.5 µm is possibly due to a cation impurity. The region between 4.0 and 5.0 µm is due to multiphonon effects inherent to YAG material, followed by the IR absorption edge. At Rutgers, attenuation measurements of SC YAG fibers have been made using the cutback method and annealing in air at 1000°C for 12 hours, yielding losses of 1.3dB/m and 1.1dB/m at wavelengths of 1.06 µm and 2.94 µm respectively. These losses are still well above the intrinsic losses for YAG.[3]

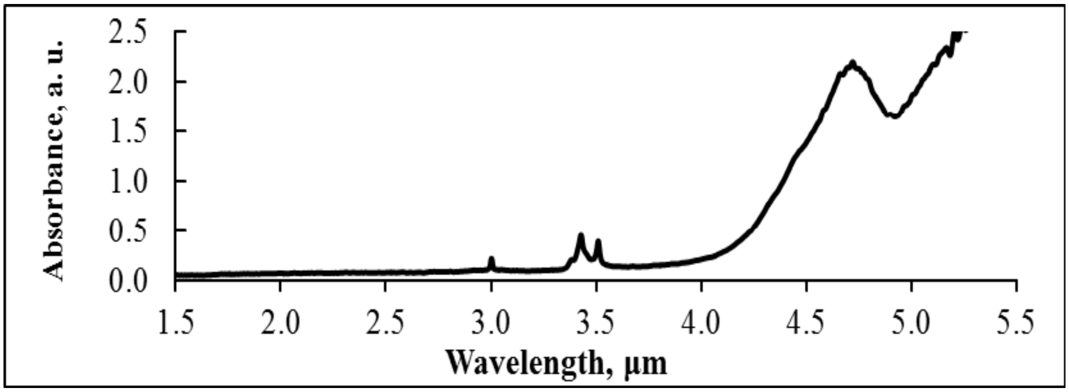

Figure 1. Absorbance of YAG.[3]

2. METHOD

2.1 Method: Laser Heated Pedestal Growth (LHPG)

While other methods use a crucible to contain the melt from which the seed fiber is pulled, LHPG holds the molten zone in place by surface tension, thus eliminating the container and consequently reducing possible contaminants. To melt the source rod and create the molten zone, LHPG uses an ultra-clean, amplitude-stabilized 30-W CO_2 laser, further preventing contamination. The seed fiber is inserted into the molten tip of the source rod; the seed can then be pulled continuously upward at a speed of about 1 mm/min.

In his thesis, Fejer studied the characteristics of the molten zone. His findings have determined from the dynamics of the molten zone, that the low viscosity of the molten YAG region limits the source-to-fiber diameter reduction to 3:1.[4] Multiple growths are necessary to achieve smaller diameter fibers. Thus, the fiber length is only dependent upon the length of the source rod.

Figure 2 shows a schematic of the LHPG apparatus with the main components: CO_2 laser, reflaxicon optics, source belt drive, fiber belt drive, and the Laser Mike. The optics convert the beam into a collimated ring, which is focused with a uniform 360 degree heat from a parabolic mirror on to the tip of the source rod. While growing, the Laser Mike sends the diameter at the molten-solid interface to a LabView feedback loop. The feedback appropriately adjusts the fiber motor's velocity. This feedback, as well as the stabilized laser, reduce instability in the molten zone and produce better diameter control. However, there are two differences in LHPG compared to glass fiber drawing and EFG SC fiber growth: only one fiber can be grown at a time, and growth is very slow compared to drawing glass fibers.

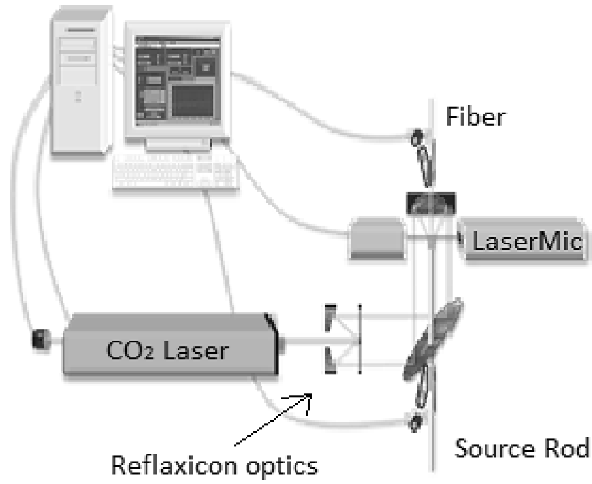

Figure 2. Schematic of LHPG.

3. DISCUSSION OF RESULTS

3.1 Materials Grown by LHPG

We have grown SC YAG fibers from both single crystal and ceramic polycrystalline sources. In addition to pure YAG, we have grown YAG fibers doped with varying amounts of Er^{3+}, Ho^{3+}, and Tm^{3+} – with as much as 50% erbium as seen in Table 1. The rare-earth doped fibers range in size from 200 µm to 450 µm, and velocities range from 0.8 mm/min to 1.5 mm/min. After only a single diameter reduction, a fiber can be as long as ten times the length of the original source rod.

Table 1. YAG materials fabricated by LHPG.

Material	Rare- Earth Dopant Concentration
Er:YAG	0.25%, 0.5%, 50%
Ho:YAG	0.5%, 4.0%
Tm:YAG	6.0%

3.2 Fluorescence

Fluorescence intensity was measured for a 50% erbium-doped YAG fiber. The fluorescent data in Figure 3 show the transitions which are signatures of erbium when pumped at 532 nm.

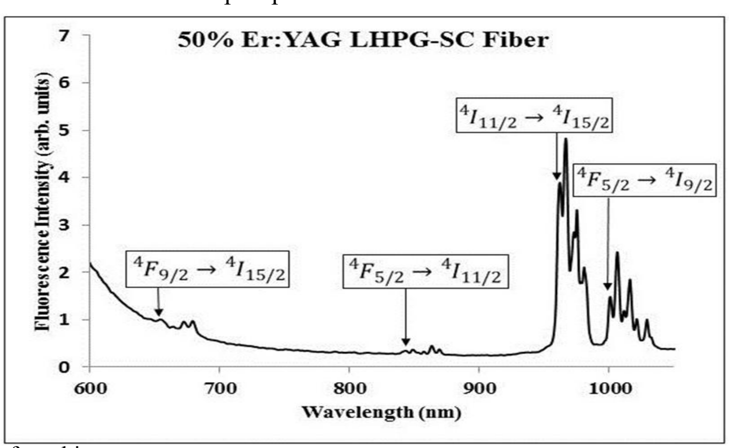

Figure 3. Energy transitions for erbium.

3.3 Spontaneous Emission: Erbium Doped YAG

Figure 4 shows the spontaneous emission of 0.5 % erbium- doped YAG when pumped at 975 nm. The results show that with increasing pump power the intensity increases linearly, but not exponentially. The power density is insufficient to achieve population inversion, possibly due to the large core diameter of 330 μm. With increasing pump power the spontaneous emission of erbium has two notable lasing peaks: first, at 1617 nm and second, at 1645 nm (both of which are in the eye-safe region.

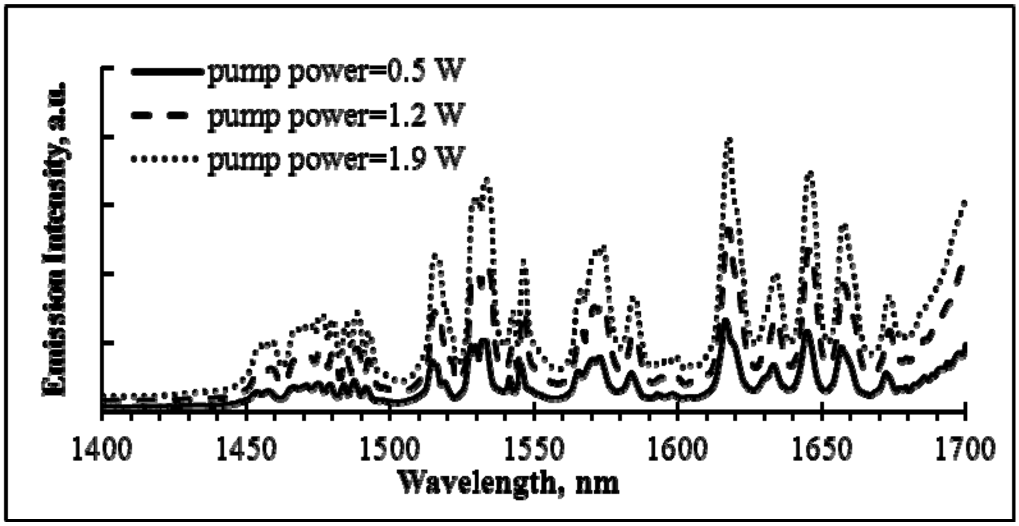

Figure 4. Spontaneous emission of 0.5% Er:YAG.

3.4 Spontaneous Emission: Holmium doped YAG

The peak spontaneous emission of Ho^{3+} arises from the transition of $^5I_7 \rightarrow {}^5I_8$ in a 0.5% doped holmium YAG fiber. Intra-band pumping at 1932 nm was chosen as a trade-off between slightly lower absorption intensity and greater laser output power. This three-level system has an operating range of 2,040 nm – 2,080 nm for glass fiber lasers. However, the spontaneous emission in SC YAG shows a peak value at ~2090 nm. Figure 5, similar to Figure 4, shows that intensity of the spontaneous emission increases with increasing pump power. The emissions are analyzed using a Yokogawa AQ6375 Optical Spectrum Analyzer (OSA).

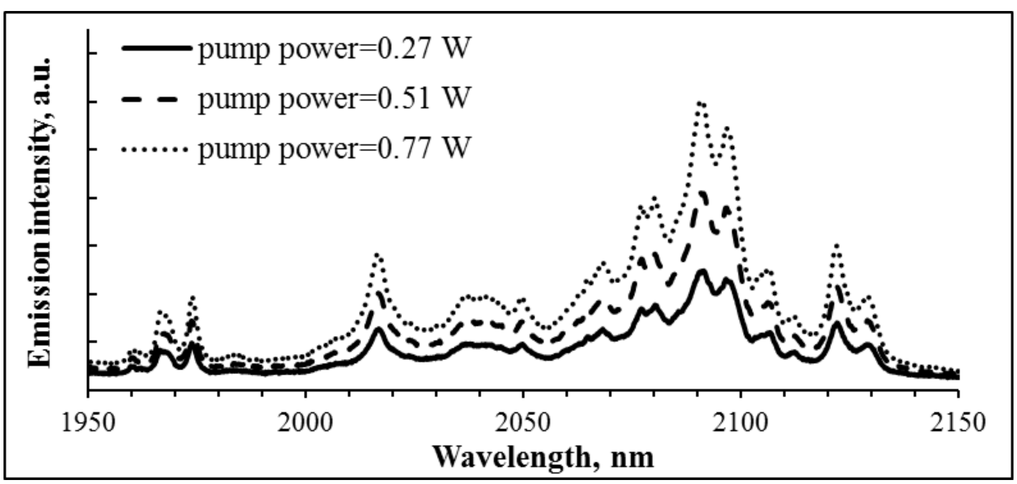

Figure 5. Spontaneous emission of 0.5% Ho:YAG.

3.5 Surface Defects

The facets seen in Figure 6 are common in SC YAG fibers with a diameter greater than 200 µm, and cause minor scattering at the surface of the fiber.[5] This fiber was grown at a velocity of 1 mm/min. While the average spacing between facets is approximately 8 µm, changing the growth rate has been shown to have an effect on the spacing between the facets.

Figure 7 gives the AFM profile of the fiber, showing the spacing between peaks as well as their height. The height valley-to-peak of the facets is approximately 35 nm. The sharp lines are a result of post-grown contamination.

This surface scattering poses a problem for unclad SC YAG fibers. If a cladding can be fabricated during growth then this surface scattering could become negligible. We hope to alleviate this problem by growing a SC YAG fiber with a graded index. The change in the index would come from a non-uniform radial distribution of rare earth ions, resulting in a core-clad SC fiber.[6] Therefore, the light would be guided through the core and would not be scattered by the outer surface of the clad.

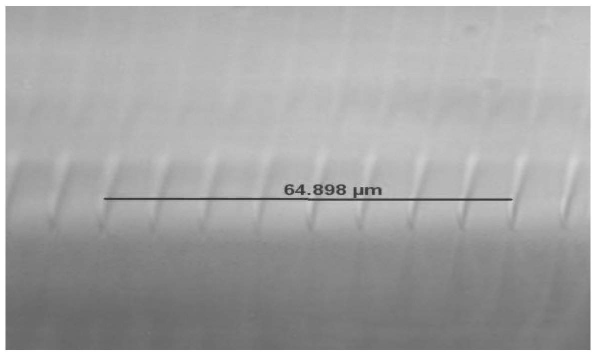

Figure 6. An optical microscope image, showing the average spacing approximately 8 µm.

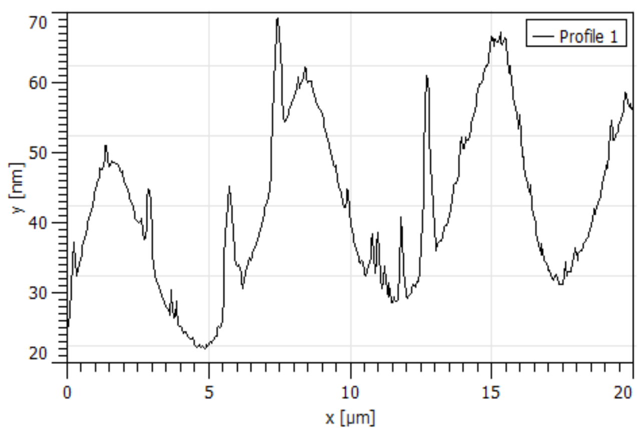

Figure 7. An AFM profile, showing the height of the facets.

4. CONCLUSION

Most of the SC fibers made to date lack a suitable cladding and, therefore, some applications such as SC fiber lasers have been slow in coming. However, the results obtained from our doped YAG fibers are encouraging and we are now working on cladding research forward. Using the LHPG technique, we were able to fabricate a wide range of SC rare-earth doped YAG fibers with different concentrations. Most notably one YAG SC was a 50% erbium. The spontaneous emission spectra of erbium and holmium were strong, showing the potential for laser emission at key wavelengths above 1.5 µm to produce an eye safe fiber laser.

Based on these initial results, we continue to investigate cladding as a means to achieve the necessary stimulated emission in YAG doped fibers. Our current focus is pulling a SC YAG active fiber with a graded index acting as a cladding that would lase on a range of 1.5 to 4 µm.

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