

# Single frequency fiber laser at 2.05 $\mu\text{m}$ based on Ho-doped germanate glass fiber

Jianfeng Wu, Zhidong Yao, Jie Zong, Arturo Chavez-Pirson  
NP Photonics, 9030 S. Rita Road, Tucson AZ 85747, USA  
Nasser Peyghambarian

College of Optical Science, University of Arizona, Tucson AZ 85721 USA  
Jirong Yu  
NASA Langley Research Center, 5 N. Dryden Street, Hampton VA 23681, USA

## ABSTRACT

A single frequency fiber laser operating near 2 micron with over 50 mW output power has been demonstrated by using a short piece of newly developed single mode holmium-doped germanate glass fiber. Laser from 2004 nm to 2083 nm was demonstrated from a short Ho-doped fiber laser cavity. A heavily thulium-doped germanate fiber was used as an in-band pump source for the holmium-doped fiber laser. The single frequency fiber laser can be thermally tuned.

Keywords: Holmium, Single frequency fiber laser, thulium

## 1. Introduction

Coherent Doppler Lidars and Differential Absorption Lidars (DIALs), working with 2-micron pulsed lasers, enable the measurement of wind, CO<sub>2</sub>, aerosols, clouds and river flow.<sup>[1,2]</sup> Next generation LIDARs require a seed laser with wavelength tunability, frequency stability, narrow linewidth, efficient operation, compact size, and low thermal load. Recently the development of diode-pumped single frequency fiber lasers has drawn more and more attention due to its narrower linewidth, longer coherent length, multiple wavelength choice, reliability, ruggedness, and compactness.[3-5] The wide ranges of operating wavelengths of fiber lasers provide the flexibility for those applications where operation wavelength is vital, such as laser spectroscopy, remote sensing, and coherent laser seeding application.

Thulium-doped single frequency fiber laser at 1893 nm with output power over 50 mW was reported.[6] However one favorable LIDAR wavelength of 2053 nm is far away from the gain peak of thulium doped germanate glass fiber. Meanwhile, the maximum output power of a commercial available fiber-pigtailed single mode pump laser diode at 800 nm is limited to be 100 mW. The combination of small gain and the lack of powerful pumping source makes it difficult to achieve a single frequency laser operation at 2053 nm from a very short thulium doped fiber laser cavity.

Holmium is another well-known rare-earth material for emission near 2 micron region.[7] The emission peak of Ho<sup>3+</sup> is 200 nm longer than the emission peak of Tm<sup>3+</sup>. Hence, holmium ions have a much higher gain at 2050 nm. The energy level diagram of holmium ions and thulium ions are shown in Fig. 1. The transition of  $^5I_8 \rightarrow ^5I_7$  is the transition for 2 micron emission. But the down side of Ho-doped glass laser is the lack of commercial laser diode that can be used as pump source for holmium ions. Four meaningful absorption bands of holmium ions locate at 0.5 micron, 0.6 micron, 1.2 micron and 1.9 micron. None of those absorption bands overlaps with commercial high power laser diodes. Most commercial Ho-doped solid-state lasers still use flash lamp as pumping source, which makes the laser itself very bulky and unreliable.

We demonstrated a 2053 nm single frequency Ho-doped fiber laser with output power of 60 mW. The design of this short cavity laser is similar to NP's Er/Yb and Yb doped phosphate glass fiber laser which has single frequency operation with narrow linewidth and excellent frequency noise properties.[8] The Ho-doped fiber laser was pumped by a

multimode laser diode pumped double cladding Tm-doped fiber laser. Acoustic damping package was used to stabilize the DBR laser cavity.

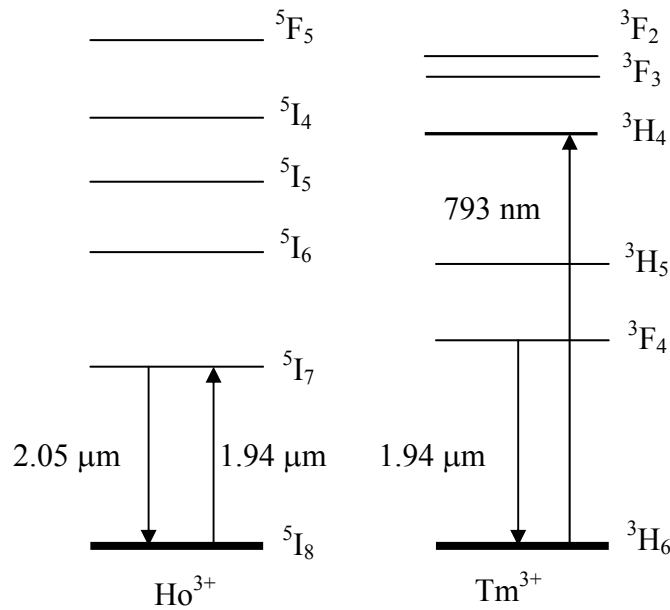


Fig. 1 The energy level diagram of thulium and holmium ions

## 2. Experiment

In the family of holmium doped glasses, germanate glass is one favorable host because of its low phonon energy that can reduce the probability of multiphonon decay which is a serious problem for host materials used as infrared emission sources.[9] The germanate glass consists of a random three-dimensional network of Ge-O-Ge bonds which is similar to silicate glass. Heavy metal oxides are used in glass matrix to shift the IR absorption edge to longer wavelengths. Compared with other low phonon energy glass material, germanate glass has a higher glass transition temperature and, therefore, higher laser-damage threshold, excellent durability and mechanical stability. It is good for fiber drawing, as well.

Ho<sup>3+</sup> doped germanate glass with Ho<sub>2</sub>O<sub>3</sub> doping concentration of 0.5 wt%, 1wt%, 2wt%, 3 wt% were prepared by melting-casting technique in house. The absorption spectrum of holmium-doped germanate glass sample was measured and shown in Fig. 2. It shows that Ho<sup>3+</sup> does not have any absorption band that overlaps with the spectrum of commercial available high power pump laser diodes. The strongest absorption band (> 700 nm) of Ho<sup>3+</sup> is from the transition of <sup>5</sup>I<sub>8</sub> → <sup>5</sup>I<sub>7</sub>, which is also the transition well known for 2-micron emission. It has an absorption peak at 1.94 μm which locates well within the lasing range of thulium-doped fiber laser. Hence, a Tm-doped fiber laser can be used as a high power and efficient in-band pumping source for Ho-doped fiber laser at 2.05 μm. With multimode laser diodes pumped double cladding Tm-doped fiber laser, one can easily get higher than 500 mW single mode Tm-doped fiber laser. Another advantage of using Tm-doped fiber laser as pumping source is that laser wavelength of Tm-doped fiber laser can be stabilized by fiber Bragg gratings (FBGs). The steady pumping laser wavelength helps to stabilize the pump laser absorption and the performance of single frequency fiber laser. By changing different FBGs, laser wavelength of Tm-doped fiber laser can be optimized in order to find the most efficient pumping wavelength for Ho-doped single frequency fiber laser. The absorption cross section of Ho<sup>3+</sup> at 1940 nm is only about 1/3 of the absorption cross section of Er<sup>3+</sup> at 980 nm. Therefore, it's very important to increase the pump absorption by Ho<sup>3+</sup> ions in a 2 cm long active fiber.

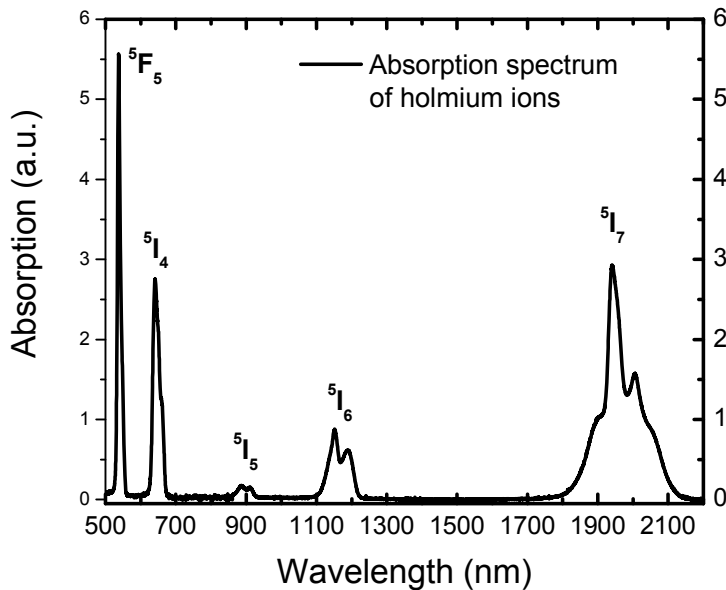


Fig. 2 Absorption spectrum of Ho-doped germanate glass sample

The emission spectra of Ho-doped germanate glass samples with different doping concentrations were measured at room temperature. A single mode thulium doped fiber laser at 1.9-micron was used to excite  $\text{Ho}^{3+}$  ions for the fluorescence properties characterization. The glass samples were polished down to 0.5 mm. The fluorescence from the glass sample was collected at 90degree angle to the pumping laser direction in order to avoid stimulated emission and re-absorption of ground level of  $\text{Ho}^{3+}$  ions. The fluorescence spectra of near 2-micron transition ( $^5I_7 - ^5I_8$ ) was dispersed by a ¼ meter monochromator, detected by a cooled InAs detector, and amplified by a lock-in amplifier. Figure 3 shows the fluorescence spectrum of glass samples with different doping concentrations. In order to avoid the strong emission from thulium-doped fiber laser, the emission spectrum of  $\text{Ho}^{3+}$ -doped glass sample was recorded from 1980 nm to 2150 nm. Two emission peaks were observed, one is at 2005 nm and another is at around 2050 nm. The long wavelength end of emission spectrum extends well beyond 2100 nm. Emission spectra in Figure 3 were normalized at the peak wavelength. There is no broadening effect was observed in glass samples with higher doping concentrations.

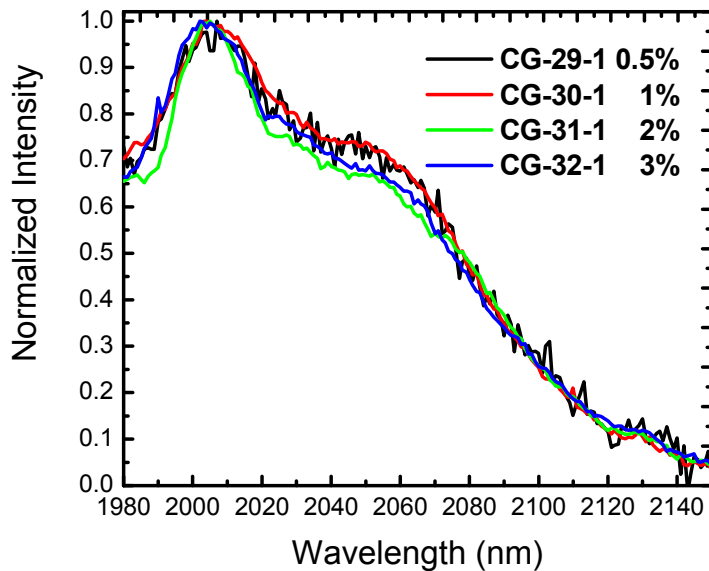


Figure 3. Fluorescence spectra of  $\text{Ho}^{3+}$ -doped germanate glasses

The fluorescence decay of  $^5I_7 - ^5I_8$  transition of  $\text{Ho}^{3+}$  ions near 2-micron was measured by a fast speed InAs detector and recorded by a digital oscilloscope. In order to avoid the delay of the lifetime due to re-absorption from unexcited ground state ions, the fluorescence was also collected at 90-degree angle from the incident pump laser. The pump laser is modulated by square pulse generated by function generator. The lifetime  $\tau$  is defined as the time for the fluorescence intensity to decrease to the 1/e of the beginning value. Figure 4 shows the fluorescence decay curves of glass samples with different doping concentrations. The fluorescence decays fit the exponential decay well, which indicated there is no other significant nonlinear energy transfer between  $\text{Ho}^{3+}$  ions involved. The fluorescence lifetime drops from 5.6 ms to 3.7 ms when the doping concentration of  $\text{Ho}_2\text{O}_3$  is increased from 0.5wt% to 3wt%. Due to the small absorption cross section of  $\text{Ho}^{3+}$  at 1940 nm, we chose 3 wt% as our  $\text{Ho}_2\text{O}_3$  doping concentration for the Ho-doped single frequency fiber laser in order to increase the pump absorption and amplification gain per unit length.

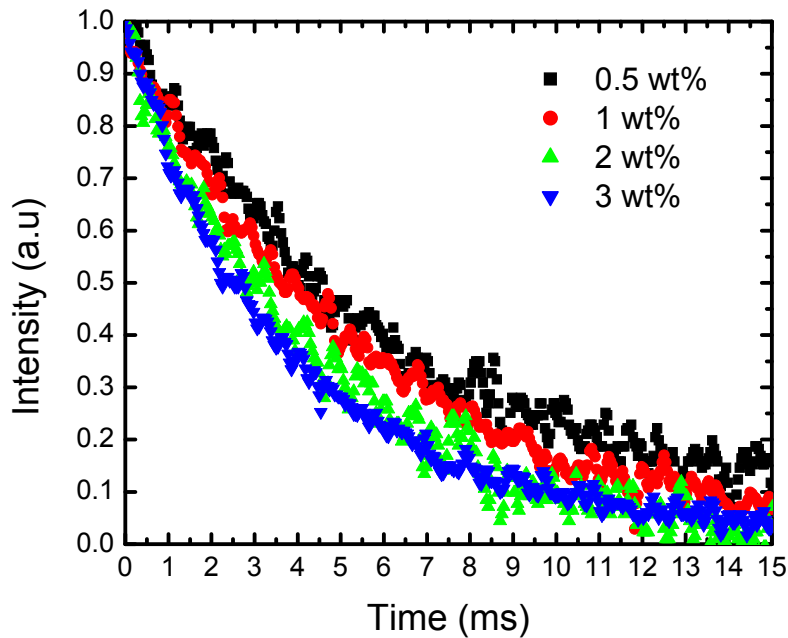


Figure 4. Fluorescence decay curve of  $\text{Ho}^{3+}$ -doped germanate glasses

A diode pumped thulium-doped fiber laser was constructed to generate about 800 mW laser at 1950 nm. A pair of fiber Bragg gratings (FBGs) written on double cladding fiber were used as laser reflectors. The fiber laser is used as a single mode pumping source for Ho-doped single frequency fiber laser. The double cladding Tm-doped fiber laser was pumped by multimode laser diodes at 800 nm. Residual multimode pump laser at 800 nm in the fiber inner cladding was stripped out, before the 1.95-micron pumping laser was launched into Ho-doped fiber laser. It helps to lower the possibility of excited state absorption (ESA) of  $\text{Ho}^{3+}$  from up lasing level ( $^5I_7$ ) and increase the laser efficiency.

The single-mode germanate glass fiber with 3 wt. %  $\text{Ho}_2\text{O}_3$  doping concentration that was fabricated in-house was used for 2-micron single frequency fiber laser. The numerical aperture of the fiber is 0.13, while the core diameter and outer diameter of the fiber are 10 and 125  $\mu\text{m}$ , respectively. The fiber exhibits a wide range of high laser gain. Laser operation was observed from 2004 nm to 2083 nm from 2 cm long Ho-doped fiber with FBGs as reflectors. Single frequency laser at 2004 nm and 2050 nm were achieved and characterized. Fig. 5 shows the set-up for single frequency fiber laser.

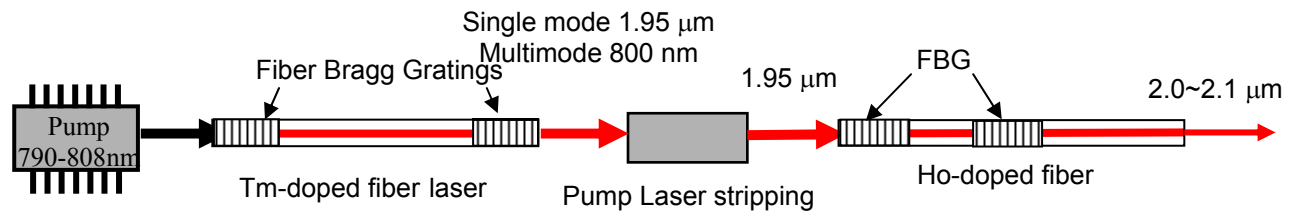


Fig. 5 Set-up of 2 micron single frequency fiber laser

The single frequency fiber laser cavity is established by two spectrally narrow FBGs at 2053 nm with an estimated bandwidth of 0.1 nm (or 8 GHz) and grating length of  $\sim 1$  cm. The FBGs were written on commercial single-mode fibers and they were fusion-spliced to a short piece of active Ho-doped germanate fiber to form the cavity. Total insertion loss of the fiber laser chain including the two splicing junctions and propagation loss was measured to be 0.5 dB at 1310 nm. The output coupler with  $R \sim 80\%$  was written into a polarization-maintaining (PM) fiber, while the high-reflectivity grating ( $R \sim 99\%$ ) was written into non-PM fiber. The birefringence of the PM fiber separates the two polarized reflection peaks (with the same grating period) at 0.3 nm apart. There is only one of those peaks overlaps with the reflection peak of the Non-PM FBG, which is a broadband grating. Such laser cavity has optical feedback in only one polarization and ensures the laser operation in one single polarization state. Two sets of temperature controllers are used to tune and stabilize the gratings wavelength separately. Temperature of narrow grating was tuned to reach the most powerful laser output due to the wavelength match of two gratings. The power curve of 2053 nm single frequency fiber laser is shown in Fig. 6. The inset shows the spectra of pump laser at 1950 nm and signal laser at 2053 nm recorded by a monochromator. The wavelength of single frequency fiber laser can be tuned thermally at a rate about  $18 \text{ pm}^\circ\text{C}$ .

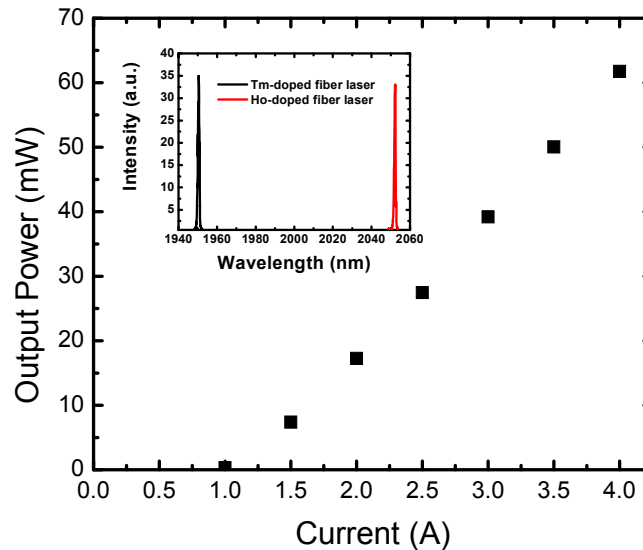


Fig. 6 Laser output power curve and laser spectrum

We used a homemade Michelson fiber interferometer to measure the frequency noise of the fiber laser. Figure 7 shows the experimental setup for the frequency noise measurement. The fiber laser cavity was packed in a compact, acoustically damped package, and it was forward pumped by a single mode laser at 1950 nm. In our latest version, Ho-

doped fiber laser was backward pumped from the output coupler by Tm-doped fiber laser through a fuse-based WDM for 1940/2050 nm. The other end of the Ho-doped fiber laser cavity was angle cleaved. By that design, there is only one laser signal at 2053 nm at the output.

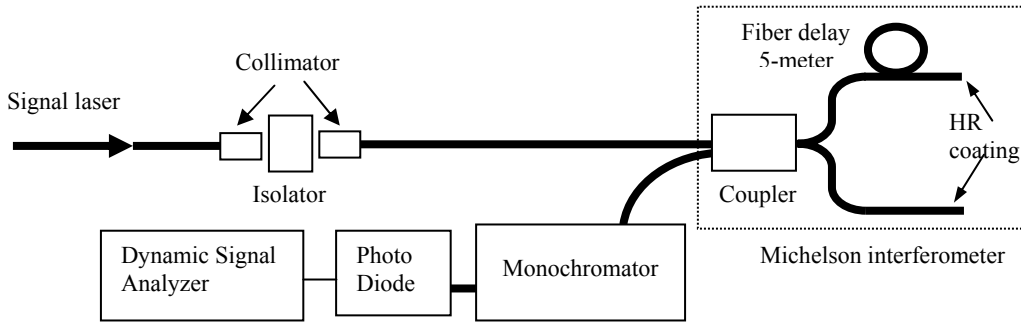


Fig. 7. Setup of frequency noise measurement

A free space isolator was used to prevent any feedback that will disturb the single frequency fiber laser cavity. A splitter was used to split the signal laser into two arms of Michelson interferometer. Both ends of two arms were coated with HR dielectric coating at 2 micron. A 5-m long delay fiber was used in one arm. A monochromator was used to separate the pump laser at 1950 nm and signal laser at 2053 nm. The beating signal was detected by a TEC-cooled InAs detector and analyzed by a Dynamic Signal Analyzer (DSA). The measured Phase noise was then converted into frequency noise. The frequency noise was shown in Fig. 8. The first spike of frequency noise was at 60 Hz. Those noise spikes were introduced by the InAs detector that was powered by a DC power supply converted from AC power supply. According to the frequency noise measurement, the estimated linewidth is ~ 10s of KHz. The linewidth can be improved further to the ~ kHz level with further improvements in the packaging and in Tm pump laser. NP Photonics' experience with single frequency fiber lasers gives confidence that such improvements are certainly possible.

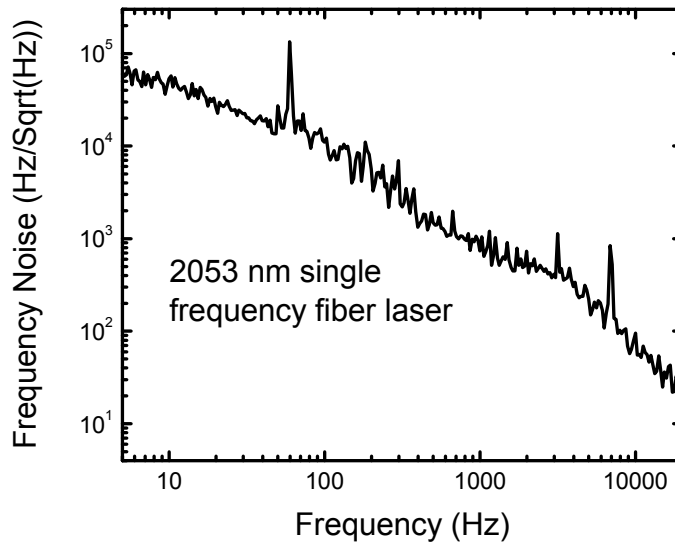


Fig. 8 Frequency noise of Ho-doped single frequency fiber laser

### 3. Conclusion

We demonstrated a 2053 nm single frequency fiber laser with output power of 60 mW. Ho-doped germanate glass and fiber was developed for single frequency fiber laser at wavelength longer than 2 micron. A short piece of Ho-doped germanate fiber was spliced to two fiber Bragg gratings to construct the single frequency DBR fiber laser cavity. Multimode laser diodes pumped double cladding Tm-doped fiber laser generated a stable single mode laser at 1950 nm, which was used as in-band pumping source for Ho-doped germanate fiber laser.

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