Watt-level short-length holmium-doped ZBLAN fiber lasers at 1.2 μm

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In-band core-pumped Ho3+-doped ZBLAN fiber lasers at the 1.2 μm region were investigated with different gain fiber lengths. A 2.4 W 1190 nm all-fiber laser with a slope efficiency of 42% was achieved by using a 10 cm long gain fiber pumped at a maximum available 1150 nm pump power of 5.9 W. A 1178 nm all-fiber laser was demonstrated with an output power of 350 mW and a slope efficiency of 6.5%. High Ho3+ doping in ZBLAN is shown to be effective in producing single-frequency fiber lasers and short-length fiber amplifiers immune from stimulated Brillouin scattering. © 2014 Optical Society of America

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Fiber lasers at the 1.2 μm region have attracted increasing attention in recent years because they have extensive applications in oxygen atmospheric sensing [1], photodynamic therapy [2, 3], and noninvasive medicine [4]. They are also used as efficient pump sources for Tm3+ lasers [5] and nonlinear wavelength converters to produce high-performance yellow–orange lasers, blue lasers, and ultraviolet (UV) lasers. These lasers are in high demand for applications in laser guide-star systems [6, 7], medical treatment [8–10], and spectroscopy [11, 12]. In the last several years, significant progress in high-power 1178 nm fiber lasers and amplifiers has been achieved. This achievement was motivated in part because frequency doubling of these lasers can yield high-power 589 nm yellow lasers, which can be used to excite the atmospheric sodium layer and produce guide stars for astronomical adaptive optics [13–21].

So far, direct transitions of ytterbium (Yb3+) and bismuth (Bi) ions, as well as stimulated Raman scattering of fiber host glasses have been extensively utilized to produce high-power fiber lasers at the 1.2 μm region with tens and even over 100 W being achieved [13–21]. However, tens of meters of gain fiber are required in these demonstrations due to the relatively small gain coefficients of Yb3+ [15–18] and Bi [22, 23] ions at the 1.2 μm region and low Raman gain coefficients of silica. Furthermore, in Yb3+-doped gain fibers complicated photonic bandgap structures must be used to suppress strong amplified spontaneous emission (ASE) and parasitic lasing at short wavelengths. Bi-doped fiber lasers can suffer from deleterious excited state absorption [24], which is an obstacle to power scaling. Raman fiber lasers generally suffer from high threshold, high-intensity noise, broadened spectrum, and energy transfer to higher-order Raman Stokes lines. All these disadvantages limit the practical use of these approaches toward compact and efficient high-power single-frequency fiber lasers and amplifiers, in which stimulated Brillouin scattering needs to be effectively suppressed. Holmium (Ho3+)–doped ZrF4-BaF2-LaF3-AlF3-NaF (ZBLAN) fibers have been demonstrated as high-gain media for 1.2 μm lasers [25, 26] and a 1.2 μm single frequency distributed Bragg reflector (DBR) fiber laser using a 22 mm long, highly Ho3+-doped ZBLAN fiber was reported recently [27]. However, the output power of this DBR fiber laser was about 10 mW and its slope efficiency was only 3.8%. Further investigation of this gain medium is of great interest for efficiency improvement and power scaling of single-frequency fiber lasers at the 1.2 μm region. In this paper, we report watt-level 1.2 μm fiber lasers with a slope efficiency up to 42% in which newly designed Ho3+-doped ZBLAN fibers with lengths less than 20 cm were used. Our experiments demonstrate that Ho3+-doped ZBLAN fibers can be used to develop compact and efficient single-frequency lasers at the 1.2 μm region.

As illustrated by the partial energy-level diagram and transitions shown in the inset of Fig. 1, the 1.2 μm emission is generated through the transition from the excited state 5I6 to the ground state 5I8 of Ho3+. The laser mechanism associated with the 1.2 μm emission of Ho3+ ions

Fig. 1. Fluorescence and energy-level diagram (inset) of Ho3+-doped ZBLAN.
has been addressed in detail in [26] and [27]. For the purpose of designing a short-length 1.2 μm fiber laser, we have measured the fluorescence and lifetimes of Ho^{3+}-doped ZBLAN glass samples with different Ho^{3+}-concentrations. The fluorescence was measured by a monochromator at 90° to the excitation light. A typical infrared fluorescence spectrum of Ho^{3+}-doped ZBLAN is shown in Fig. 1. The fluorescence at 1.2 μm is much stronger than that at 3 μm, which is consistent with a large branch ratio between the transition $^5I_6 \rightarrow ^5I_8$ and $^5I_6 \rightarrow ^5I_7$. The lifetime of the upper laser level $^5I_6$ was measured by modulating the pump laser and detecting the exponential decay of the fluorescence. The measured lifetimes of the 0.3, 0.5, 1, 3, and 6 mol. % Ho^{3+}-doped glass samples are shown in the inset of Fig. 2. The lifetime decreases with increasing doping level as is generally observed in rare-earth-doped glasses. Nevertheless, the decrease is not significant and highly doped fiber can be used to obtain large unit gain (dB/cm). The absorption coefficient of Ho^{3+}-doped ZBLAN was measured and is shown in Fig. 2. Ho^{3+} has an absorption peak with a cross section of $1.8 \times 10^{-21}$ cm$^2$ at 1150 nm, where semiconductor lasers or Raman fiber lasers are readily available. Moreover, when Ho^{3+} is pumped at 1150 nm, it is an in-band pumping configuration that usually yields high efficiency and produces less heat due to the small quantum defect and thus greatly improves power scaling in ZBLAN fiber lasers. In view of above considerations, we designed and fabricated a new 3 mol. % Ho^{3+}-doped ZBLAN fiber for high-power short-length fiber lasers at the 1.2 μm region.

The new fiber shown in Fig. 2 has a core diameter of 5.3 μm, a core numerical aperture (NA) of 0.14, and a cladding diameter of 125 μm. The 1150 nm absorption coefficient and the propagation loss of the fiber were measured to be 3.7 and 0.24 dB/m, respectively, by a cutback experiment using a white light source. Because of the small core size and NA, the competitive 2.9 μm lasing action that can build-up in highly Ho^{3+}-doped ZBLAN fibers is weakly guided and thus effectively suppressed by large propagation loss. The experimental configuration is depicted in Fig. 3. A short-length fiber laser chain was fabricated by splicing high-reflection (HR > 99%, 3 dB bandwidth 0.5 nm) and partial reflection (PR = 50%, 3 dB bandwidth 0.05 nm) fiber Bragg gratings (FBGs) to a 10 cm long Ho^{3+}-doped ZBLAN fiber. The whole fiber chain was fixed in a U groove on a copper plate by high-index glue as shown in Fig. 3. The FBGs were inscribed in Hi1060 silica fibers, which have the same geometrical specifications as the gain fiber. Successful low-loss fusion splicing between the Hi1060 silica fiber and the ZBLAN fiber, which have vastly different melting temperatures, was accomplished by Vytran FFS-2000 using the NP Photonics proprietary splicing technique [28]. The total propagation loss of the fiber laser chain was measured to be 0.9 dB at 1310 nm. An 1150 nm Raman fiber laser with a maximum output of 5.9 W was developed as the pump source and used to pump the fiber laser chain at the HR FBG end. The laser output emerged from the PR FBG end of the fiber laser chain. The laser and the residual pump were separated by a bulk grating. The output power was measured with a thermal detector (Newport 919P-010-16) and the spectrum was measured with an optical spectrum analyzer (OSA, Agilent 86142 B).

A pair of FBGs at 1190 nm were first used to investigate the laser close to the gain peak wavelength. The output power of the 10 cm long 1190 nm fiber laser as a function of the 1150 nm pump power was measured and is shown by upward triangles in Fig. 4. A maximum output of 2.4 W was obtained at the maximum pump power of 5.9 W. The slope efficiency of the 1190 nm fiber laser (the output power versus the launched pump power) is about 42%. In order to optimize performance of the Ho^{3+}-doped ZBLAN fiber laser, fiber chains with gain fiber lengths of 5, 7, 13, 15, and 20 cm were also fabricated and their outputs have been measured as shown in Fig. 4. Their slope efficiencies are 15.4%, 25.8%, 38.9%, 17.6%, and 5.5%, respectively. It is clear that the performance of in-band pumped Ho^{3+} fiber lasers strongly depends on the gain fiber length and the 10 cm long fiber chain exhibited the best performance among these fiber chains even though most pump power should be absorbed by the 5 cm fiber chain according to the absorption coefficient of 3.7 dB/m. This is due to the saturated ground-state absorption that usually occurs in a two-level energy laser system. The spectra of the 10 cm long fiber laser operating at different powers were measured and are shown in Fig. 5. The inset of Fig. 5 shows the spectrum of the 2.4 W laser measured by an OSA with a minimum resolution of 0.07 nm. The 3 dB bandwidth of this laser is
about 0.1 nm and signal-to-noise ratio (SNR) is over 60 dB, which is close to the stray-light suppression ratio of the OSA.

It should be noted that output power of the 1190 nm laser is limited only by the 1150 nm pump power in this experiment, and excellent power scaling is a highly attractive feature to be exploited. The output of a ZBLAN fiber laser is mostly limited by thermal damage and the quantum defect (3.4%) of this laser is nearly 20 times less than that (65%) of a passively cooled 20 W 2.8 μm all-fiber Er3+-doped ZBLAN fiber [26]. Because of this, we expect that an Ho3+ fiber laser can be pumped with much higher power than the 20 W Er3+ fiber laser, and tens or even 100 W output power at 1190 nm may be achieved by increasing the pump power. Because of the upconversion processes, observable as the strong green emission shown in Fig. 3, the slope efficiency of the in-band core-pumped Ho3+ fiber laser is presently much lower than that of a Yb3+ fiber laser [30]. Optimizing the doping level and employing cladding pumping configuration will be effective approaches to achieve high efficiency operation of the 1190 nm laser.

Interestingly, the gain bandwidth of this Ho3+-doped fiber extends to even shorter wavelengths. Because high-power 1178 nm fiber lasers are in high demand for astronomical adaptive optics, we have also demonstrated 1178 nm fiber lasers using these Ho3+-doped ZBLAN fiber chains and a pair of 1178 nm FBGs. The HR FBG has a reflection of >90% and the PR FBG has reflection of 50%. The output powers of the 1178 nm fiber lasers as a function of the 1150 nm pump power were measured and are shown in Fig. 6. A maximum output of 332 mW was obtained with the 13 cm long fiber chain. The slope efficiency of the 13 cm long 1190 nm fiber laser is about 6.5%. The output power and the slope efficiency of the 10 cm fiber chain are very close to those of the 13 cm chain. The slope efficiencies of 5, 7, 15, and 20 cm fiber chains are 0.94%, 2.9%, 4.2%, and 0.68%, respectively. Although the 1178 nm laser was produced with the 3 mol.% Ho3+-doped ZBLAN fiber, the efficiency was surprisingly low. This may mainly be attributed to the fact that the laser wavelength of 1178 nm is very close to the zero-line wavelength [27]. Optimizing the reflection of the output coupler (PR FBG) can improve the efficiency. Strong excited state absorption [31] of the 1178 nm laser may be another reason for the low efficiency. In-depth investigation into the factors leading to the low efficiency of the 1178 nm laser and how to improve its performance is currently under way. The spectra of the 13 cm long 1178 nm fiber laser operating at different powers were measured and are shown in Fig. 7. When the pump power was low, ASE was seen at long wavelengths. The ASE faded as the laser power became large. The spectrum of the laser operating at 332 mW was measured by an OSA with 0.07 nm resolution and shown in the inset of Fig. 7. The bandwidth of this laser is about 0.1 nm and the SNR is about 60 dB.

It is worth noting that a 5 cm long 1178 nm fiber laser shows the possibility of single-frequency operation with a wavelength down to the zero-line wavelength.
We have developed a single-frequency fiber laser at 1200 nm [27]. Therefore, the 3 mol. % Ho\textsuperscript{3+}-doped ZBLAN fiber is an effective gain medium for single-frequency fiber lasers across the 1.2 μm region. When a pair of FBGs at 1260 nm was used, however, single-frequency lasing operation was not observed at the maximum available pump power. Further investigation into the gain bandwidth and long wavelength operation of Ho\textsuperscript{3+}-doped ZBLAN fiber lasers is under way.

In conclusion, short-length 3 mol. % Ho\textsuperscript{3+}-doped ZBLAN fiber lasers at the 1.2 μm region were investigated. A 2.4 W 1190 nm and a 332 mW 1178 nm fiber laser were demonstrated, respectively. Further investigation into efficiency improvement and power scaling of Ho\textsuperscript{3+}-doped ZBLAN fiber lasers by optimizing doping level and the Q-factor of the fiber cavity is ongoing.

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