Optics Letters

Single-frequency blue laser fiber amplifier

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An all-fiber amplifier for a single-frequency blue laser was demonstrated for the first time, to the best of our knowledge. Over 150 mW continuous-wave single-transverse-mode blue laser output was obtained with a 10 m 1000 ppm thulium-doped fluoride fiber pumped by a 1125 nm fiber laser at a power of 2 W. The output power was limited due to the onset of the competitive lasing at 783 nm. Photodarkening and photo-curing of the thulium-doped fiber amplifier were also studied and analyzed.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (140.3280) Laser amplifiers; (140.3613) Lasers, upconversion; (140.7300) Visible lasers.

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Thulium (Tm^{3+}) doped ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) features a large number of possible laser transitions with emission wavelengths ranging from ultraviolet (UV) to mid-infrared due to the low phonon energy of ZBLAN (550 cm^{-1}), while these transitions are typically non-radiative in Tm^{3+}-doped silica [1]. For instance, the transition from state $^3H_4$ to state $^3F_4$ can generate a laser at 1480 nm that can be used for optical communications, while the transition from state $^3H_4$ to state $^3H_5$ can produce light around 2.3 μm, making it a good candidate for hydrocarbon gases detection. In addition, transitions between the $^1G_4$ and $^3H_5$ states and $^3H_4$ and $^3H_6$ states have broad emissions in a band around 800 nm which is in demand for medical applications. However, the most attractive property of Tm^{3+}-doped ZBLAN is its capability of lasing at UV and blue wavelengths [1], where robust and reliable laser sources are needed for a variety of applications, including light detection and ranging [2], optical data storage [3], imaging [4], and spectroscopy. Tm^{3+}-doped ZBLAN fiber lasers were extensively studied in the 1990s for making compact blue lasers for these applications, considering the advantages of fiber lasers such as guided laser beam, high-power scalability, very low thermal effects, low maintenance, and compactness.

The first Tm^{3+}-ZBLAN fiber laser in the blue was demonstrated by Grubb *et al.* [5]. A Nd^{3+}:YAG laser at 1120 nm was used as the pump source and a 60 mW output was obtained at 480 nm. After that, various Tm^{3+}-ZBLAN fiber lasers were demonstrated with either increased output power or increased efficiency, or reduced threshold [1]. However, to the best of our knowledge, the lasers of all these experiments were neither single-transverse mode nor single-longitudinal mode. Single-frequency blue lasers are in great demand for optical metrology, interferometry, high-order harmonic generation, quantum cryptography, high-resolution spectroscopy, and undersea communication. In this Letter, to the best of our knowledge, we report the first demonstration of an all-fiber blue laser amplifier with single-frequency and single-transverse mode output.

The energy level diagram of Tm^{3+} is shown in Fig. 1(a). Blue laser emission around 480 nm can be obtained by directly exciting the ground state $^3H_6$ to $^1G_4$ by 465 nm pumping. Since there is no readily available high-power single-mode laser source at 465 nm, this is not a practical option at this time. Therefore, upconversion pumping at 1125 nm was used in our experiment. Due to the long lifetimes of some metastable energy levels between $^3H_6$ and $^1G_4$, ions can be excited to the upper laser level $^1G_4$ by absorbing three pump photons, as shown in Fig. 1(a). There are three radiative transitions from energy level $^1G_4$ to lower energy levels with emission wavelengths at 480, 650, and 784 nm. The branching ratios of the three transitions are 0.378, 0.077, and 0.384, respectively [6]. Figure 1(b) shows the measured fluorescence from a Tm^{3+}-doped ZBLAN glass. The emissions at 480 and 650 nm correspond to the transitions from state $^1G_4$ to $^3H_6$ and $^3F_4$, respectively. The emission peak near 800 nm, however, is the combination of two transitions: $^1G_4 \rightarrow {}^3H_5$ and $^3H_4 \rightarrow {}^3H_6$. Both transitions influence the operation of the 480 nm amplifier. Population inversion for the 784 nm transition is much more easily achieved than that for the 480 nm emission due to the empty lower level $^3H_5$. On the other hand, an 810 nm emission depletes the population of the $^3H_4$ state which is important for the multiphoton excitation. Therefore, a technique has to be implemented in order to suppress the competitive lasing at the 800 nm band.

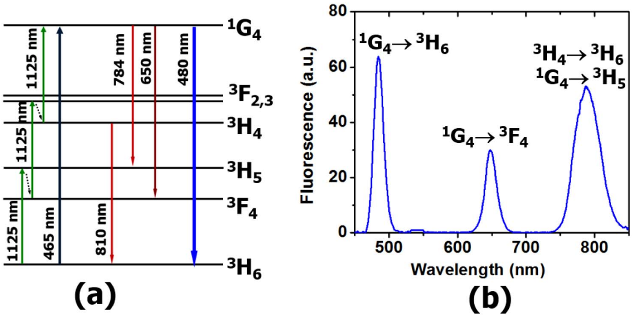

Fig. 1. (a) Partial energy level diagram of Tm^{3+} and transitions related to the blue laser emission; (b) measured fluorescence of Tm^{3+}-ZBLAN glass.

In order to obtain a single-transverse mode output, a Tm^{3+}-doped ZBLAN fiber with a core diameter of 4 μm and a numerical aperture of 0.07, corresponding to a V-number and cutoff wavelength of 2.095 and 365 nm respectively, was designed and fabricated. The microscope image of the end facet of the fiber is shown in Fig. 2(a). This fiber has a 12 μm inner cladding doped with 100 ppm neodymium (Nd^{3+}) which intentionally suppresses an 800 nm emission due to Nd^{3+} absorption in this wavelength region. The outer cladding of this fiber is 125 μm compatible with a standard silica fiber, enabling easy fusion splicing and the construction of all-fiber amplifiers. Figure 2(b) shows the 2D diagram of a refractive index profile of the fiber measured with an interferometric fiber analyzer (Interfiber Analysis, IFA-100). The refractive index difference between core and cladding is about 0.002. The fiber core is doped with 1000 ppm Tm^{3+} and the absorption of this fiber of 1125 nm light launched into the fiber core was measured at a low power level by a cutback experiment to be about 1.56 dB/m.

The schematic of the all-fiber blue laser amplifier is shown in Fig. 3. A single-frequency external cavity GaN diode laser at 478 nm coupled to a polarization-maintaining (PM) single-mode silica fiber (PM 460HP) was used as the seed laser. An ytterbium (Yb^{3+})-doped silica fiber laser operating at 1125 nm was used as the pump source. A PM wavelength division multiplexor (WDM) made of PM 460HP (signal port) and PM980 fiber (pump and common port) was used to combine the seed signal laser and the pump laser. The signal coupling efficiency is about 80%, and the pump coupling efficiency is about 92%.

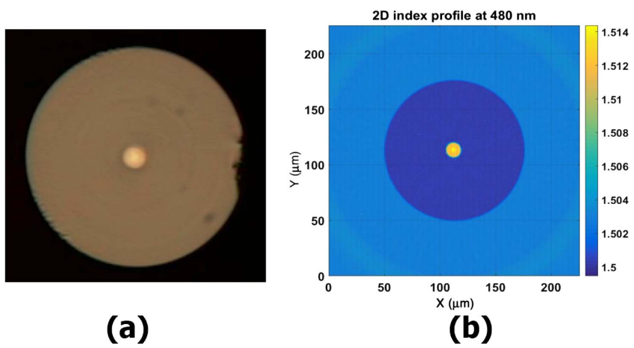

Fig. 2. (a) Microscope image of an end facet and (b) 2D refractive index profile of the single-mode Tm^{3+}-doped ZBLAN fiber.

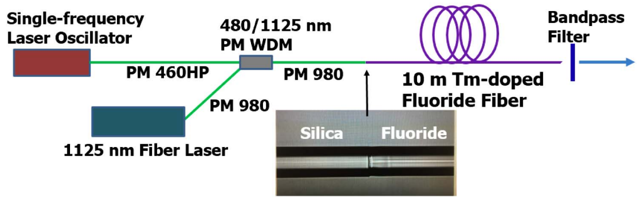

Fig. 3. Experimental setup of the all-fiber blue laser amplifier. Inset: a picture of the splice joint between the silica fiber and the fluoride fiber.

The polarization extinction ratio (PER) of the signal laser changes from an initial value of 25 to 18 dB after the PM WDM, indicating that most of the signal laser is coupled to the fundamental mode of the PM980 fiber, although this fiber has a cutoff wavelength of 705 nm and is multimode for the blue light. It should be noted that the common port fiber of the PM-WDM was fixed on the optical table to reduce power fluctuations and decrease the fundamental mode caused by small bending and other environmental effects. 10 m of Tm^{3+}-ZBLAN fiber was spliced to the common port PM980 fiber using the NP Photonics proprietary splicing technique [7]. The image of the splice joint between the PM980 silica fiber and the Tm^{3+}-doped ZBLAN fiber is shown in the inset of Fig. 3. The typical loss of the splice between a ZBLAN fiber and a silica fiber is less than 0.3 dB. 10 m ZBLAN fiber was chosen based on the cutback experiment because it produced the maximum output power. The output end of the ZBLAN fiber was angle cleaved to reduce backward reflections. A bandpass filter at 480 nm was used to remove the residual pump at 1125 nm.

In the experiment, single-frequency operation of the GaN diode laser was confirmed by a scanning Fabry–Perot interferometer (FPI), as shown in the lower right inset of Fig. 4. The blue signal laser power after the PM-WDM was approximately 15 mW. The optical spectra of the fiber amplifier with and without a pump were measured with an optical spectrum

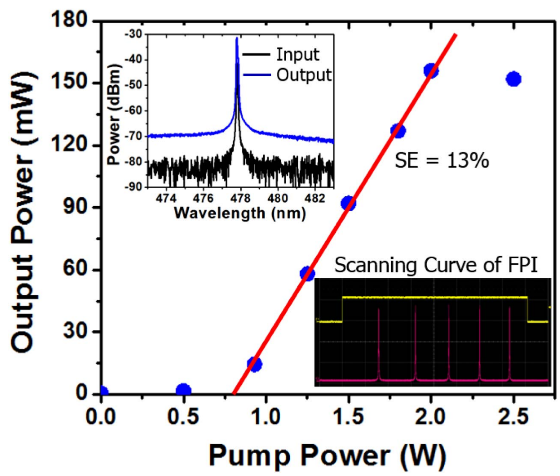

Fig. 4. Measured output power of the 478 nm fiber amplifier as a function of the launched pump power. Upper left inset, optical spectra of the input and output of the fiber amplifier; lower right inset, single-frequency operation of the GaN diode laser confirmed with a scanning FPI.

analyzer (Ando, AQ6351A) and is shown in the upper left inset of Fig. 4. The output power of the fiber amplifier as a function of the pump power was measured by a power meter (Thorlabs, PM100D) and is shown in Fig. 4. The pump threshold of the fiber amplifier is about 750 mW. The blue laser output increases with the pump power and saturates when the pump power exceeds 2 W. A maximum output power of 155 mW, corresponding to a net gain of 10 dB was obtained. The slope efficiency of this fiber amplifier is about 13%, which is smaller than those of previous experiments because of smaller overlaps of pump and signal lasers and the lower fiber NA, when compared to multimode fibers used in previous reports. The lower efficiency is the result of the trade-offs employed to achieve a single-transverse mode output beam using a low core NA fiber.

The beam quality of the fiber amplifier output was measured with a beam profiler (DataRay Inc., Beam Map2). The 2D beam profile is shown in Fig. 5(a). The cross section of the beam profile and its Gaussian fit are shown in Fig. 5(b). There are two small side peaks in the measurement due to excited cladding modes. It should be noted that the beam profile was not stable, and the measured beam quality was about $M2 \sim 1.5$ at low pump powers because of interference between the cladding modes and the fundamental core mode supported by the long coherence length of the single-frequency signal laser with a typical linewidth <1 MHz. The beam quality improved with increasing pump power. A beam quality M2 of 1.06 was measured at the maximum output power. The PER of the output laser was measured to be approximately 11 dB, even though the Tm^{3+}-ZBLAN fiber is not designed to maintain the polarization of the signal laser.

As mentioned above, the 12 μm inner cladding of the Tm^{3+}-doped ZBLAN fiber was doped with 100 ppm Nd^{3+} in order to suppress the competitive 800 nm laser. Nd^{3+} has significant absorption near 800 nm due to transitions from $^4I_{9/2}$ to ($^2H_{9/2}$, $^4F_{5/2}$), as shown by the black curve in Fig. 6. Absorption of an 800 nm emission from Tm^{3+} occurs because of the partial mode overlap between the core mode field and the Nd^{3+}-doped cladding. However, the output power of this Tm^{3+}-ZBLAN fiber amplifier still saturated at a pump power of 2 W and decreased with further increasing pump power due to the onset of the laser at 783 nm, as shown in Fig. 6. When the pump power is 2 W, there is ASE at 800 nm, and Tm^{3+} long wavelength lasing is effectively suppressed by the Nd^{3+} absorption in the inner cladding. When the pump power is 2.5 W, the 783 nm laser starts, and the 478 nm signal power decreases, as shown by the blue curve. Further suppressing the 783 nm laser may be obtained with an optimized Nd^{3+} doping level, but we point out that Nd^{3+} also has some absorption at

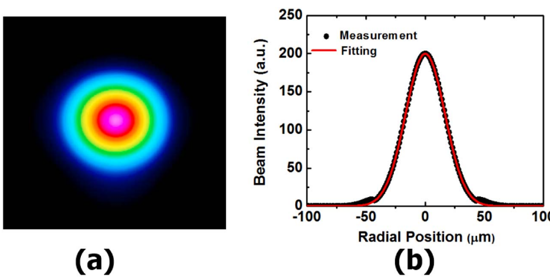

Fig. 5. (a) 2D profile of the fiber amplifier output beam; (b) cross section of the output beam profile and its Gaussian fit.

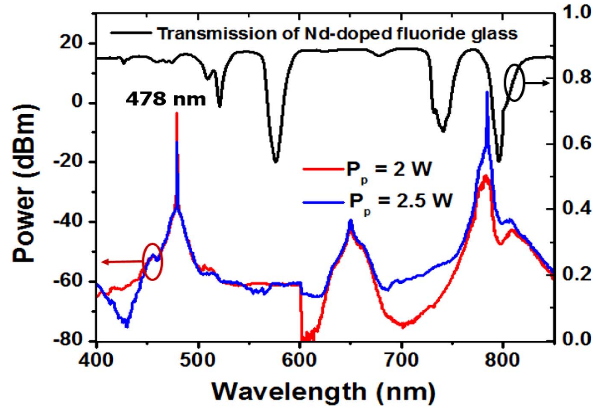

Fig. 6. Optical spectra of the fiber amplifier when the pump power is 2 W (red curve) and 2.5 W (blue curve), respectively. The black curve shows the transmission of a 1 cm thick Tm^{3+}-doped ZBLAN glass.

478 nm, which reduces the efficiency of the fiber amplifier correspondingly. Proper fiber design that can produce high loss at 783 nm while negligible loss at the wavelength of the blue laser could offer an attractive option to further suppress the competitive lasing.

Another obstacle to achieving long-term and stable high-power single-mode blue laser output is the degradation of the Tm^{3+}-doped ZBLAN fiber caused by the photodarkening effect. Photodarkening describes a significant increase of background loss at visible wavelengths due to the creation of color centers in the ZBLAN glass matrix of ZBLAN glass under illumination with a strong blue laser [8,9]. The photodarkening effect in Tm^{3+}-doped ZBLAN is particularly strong because Tm^{3+} has a large range of energy levels, including levels with energies higher than $^1G_4$ that are capable of absorbing and emitting UV light. In our experiment, it was found that a blue laser signal transmitted through the Tm^{3+}-doped ZBLAN fiber amplifier significantly decreased (from a few milliwatts to tens of microwatts) after running at the maximum output power and then leaving unpumped for one day. However, the photodarkened Tm^{3+}-doped ZBLAN fiber can be photo-cured by launching the blue laser into the fiber core and pumping it at a low pump power for a few hours. The maximum output power of the photo-cured fiber amplifier could be 75% of the initial maximum output power (155 mW). It was also found that photodarkening and photo-curing of the Tm^{3+}-doped ZBLAN fiber were repeatable.

In our experiment, the photodarkening effect in the Tm^{3+}-doped ZBLAN fiber was found to be non-uniform through the length of the fiber. The transmission spectra of the first 1 m segment at the beginning and the last 1 m segment at the end of the photodarkened amplifier fiber, and a 1 m of fresh fiber (never pumped) were measured using a white light source and an OSA, and are shown in Fig. 7. In contrast to our initial expectation, the first 1 m segment of the amplifier fiber, where the blue laser power is low, was severely photodarkened while the last 1 m segment of the amplifier fiber, where the blue laser power is much higher, experienced little photodarkening, indicating that the photodarkening is not solely induced by the blue laser and may be a function of the population at the upper laser level $^1G_4$. It was also observed that photodarkening occurs

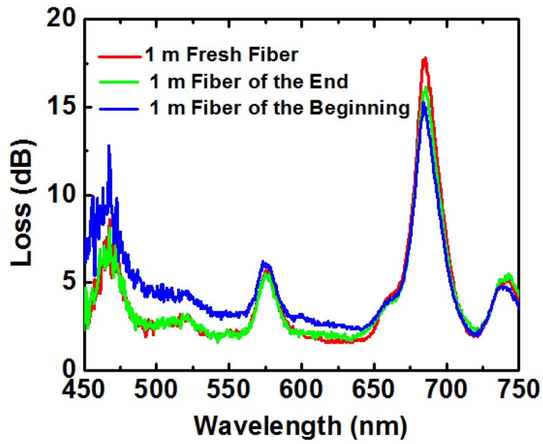

Fig. 7. Measured loss of 1 m fresh (unpumped) fiber, 1 m segment of the end, and 1 m segment of the beginning of the photodarkened amplifier fiber.

only after the parasitic 800 nm laser begins. Several previous papers have tried to help in the understanding of photodarkening [8,9], but none of them can be used to explain the phenomena observed in our fiber amplifier experiment. Therefore, further investigation and new interpretations of photodarkening in Tm^{3+}-doped ZBLAN fiber are essential for further developments of high-power fiber amplifier for blue lasers.

In conclusion, an all-fiber amplifier for a single-frequency blue laser was demonstrated for the first time, to the best of our knowledge. More than a 150 mW continuous-wave, single-frequency, and single-transverse-mode 478 nm laser output was obtained with a 1125 nm pump laser at a power of 2 W. The output power was saturated and began to decrease for the pump powers exceeding 2 W due to the onset of the 800 nm lasing. It was observed that the effect of photodarkening is not uniform across the amplifier fiber and further investigation of photodarkening in Tm-doped ZBLAN fiber amplifier is essential. Further power scaling of the Tm^{3+}-ZBLAN fiber amplifier can be achieved by sufficiently suppressing the 800 nm laser with optimized Nd^{3+} concentration in the inner cladding and a proper fiber design with a tailored guide at different wavelengths.

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