Ytterbium-sensitized thulium-doped fiber laser with a single-mode output operating at 1 900-nm region

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A single-mode laser is demonstrated using a newly developed double-clad thulium-ytterbium-doped fiber (TYDF) in a linear cavity formed by two fiber Bragg gratings (FBGs). The YTF used is drawn from a D-shape preform fabricated using the modified chemical vapor deposition and solution doping technique. The laser is operated at 1 901.6 nm via the transition of thulium ions from $^3F_4$ to $^3H_6$ with the assistance of ytterbium to thulium ion energy transfer. The efficiencies of the laser are 0.71% and 0.75% at 927- and 905-nm multimode pumping, respectively. The thresholds of the launched pump power for 927- and 905-nm pumping are 1 314 and 1 458 mW, respectively. A 7-mW output is obtained at a 905-nm pump power of 2 400 mW.

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High-power fiber lasers have generated a significant amount of interest and are commonly demonstrated at 1 μm from ytterbium-doped silica fiber[1,2]. Thulium-doped fiber lasers (TDFLs) of nearly 2 μm have recently drawn research interest because of the possibility of combining high efficiency, high output power, and eye-safe operation in a single laser application. Specific applications associated with this wavelength have been developed, such as remote sensing and biomedical applications[3−5]. TDFL uses thulium-doped fibers as a gain medium that can be efficiently pumped at ∼800, ∼1 200, or ∼1 600 nm[6,7]. From the so-called cross-relaxation process, efficient 2-μm laser operation may be achieved using the $^3F_4 \longrightarrow {}^3H_6$ pump transition of thulium ions near 800 nm. In this process, two ground-level thulium ions are excited to the upper lasing level of the $^3F_4 \rightarrow {}^3H_6$ transition by absorbing only one pumped photon near 800 nm, which suggests that one excited Tm^{3+} ion at the $^3H_4$ level could generate two Tm^{3+} ions at the $^3F_4$ upper lasing level[8]. However, the availability of high-power diodes for this wavelength range is rather scarce, making such diodes very costly. Pumping TDFs at 1 200 or 1 600 nm is complicated due to the need for an intermediate laser source; high-power laser diodes are not commercially available for this wavelength.

Aside from high power applications, an inexpensive and stable low-power fiber laser in the wavelength range from 1 800 to 2 100 nm with all-fiber configurations has tremendous application prospects for sensing toxic gases due to their specific infrared (IR) absorptions. Such a system can be achieved using an inexpensive 980-nm pump laser to build an erbium-ytterbium fiber laser as the pump source of the TDFL. Alternatively, a thulium-ytterbium-doped fiber (TYDF) can be used as a gain medium because Tm^{3+} has a level ($^3H_5$) that is (quasi)-resonant to the excited Yb^{3+} -level ($^2F_{5/2}$) and that permits energy transfer[9]. Yb^{3+} has the advantage of possessing only two multiplets, the ground-state level $^2F_{7/2}$ and the excited-state level $^2F_{5/2}$, resulting in highly efficient absorption in the range from 900 to 1 000 nm. This particular energy level structure is highly desirable for an efficient absorption using commercially available laser diodes that emit 980-nm outputs, thus avoiding undesirable excited-state absorptions under intense optical pumping. In the previous work[9], a thulium-ytterbium co-doped fiber laser (TYDFL) was demonstrated using a unidirectional dual pumping approach with very low power at 1 600 nm coupled with a primary pump at 980 nm. In this letter, a TYDFL is demonstrated by a newly developed double-clad Tm^{3+}/Yb^{3+} co-doped alumino-silicate fiber as a gain medium using a single pumping technique. The TYDF is obtained by drawing a D-shaped preform that was fabricated by the deposition of porous layers by the modified chemical vapor deposition (MCVD) process in conjunction with the solution doping technique. The laser consists of 1.2-m TYDF pumped by a multimode laser diode via multimode combiner in a Fabry–Perot cavity with two fiber Bragg gratings (FBGs). The TYDFL performance is investigated for two pumping wavelengths at 905 and 927 nm.

A pure silica glass tube with outer/inner diameters of 20 nm/17 mm was used for the deposition of 3–8 multiple porous unstinted SiO_2-P_2O_5 soot layers to make a preform; during this procedure, a suitable deposition temperature from 1 400 to 1 450 °C was maintained. An alcoholic solution containing doping metals, including Tm, Yb, Y, and Al in the Alfa standard form of their chlorides, was used to soak the porous layer for approximately 30–45 min to achieve efficient doping. Dehydration and oxidation were then performed at a temperature from 900 to 1 000 °C. Sintering of the un-sintered layers was done by slowly increasing the temperature from 1 500 to 2 000 °C using the conventional MCVD technique. After sintering and oxidation, the tube was slowly collapsed to form the optical preform. The fabricated optical preform consisted of Al_2O_3, Y_2O_3, Tm_2O_3, and Yb_2O_3s dopants with average weight percentages of 2.00, 1.90, 0.80, and 1.98, respectively. The presence of Y_2O_3 helped decrease the phonon energy of alumino-silica glass, which effectively assists in distributing Yb and Tm ions homogeneously into the core glass matrix, thus increasing the probability of radiative emission.

The fabricated preform was then drawn at temperatures of 2 050° into a double-clad D-shaped fiber with an outer cladding diameter of 125 μm. As opposed to conventional single-mode fibers where the pump light is coupled directly into the core, the pump light travelled down the fiber in the first cladding and was absorbed by the dopants, in this case, the Yb ions, when it overlapped with the core. The D-shaped geometry of the cladding improved pump absorption and is cheaper to fabricate than other geometries, such as the hexagonal and rectangular forms. The doping levels of Tm^{3+} and Yb^{3+} ions in the fabricated TYDF were measured to be around 5.55×10^{19} ions/cc and 13.50×10^{19} ions/cc, respectively, using an electron probe micro-analyser (EPMA). The numerical aperture (NA) and core diameter of the fabricated TYDF were measured to be 0.22 and 15.87 μm, respectively.

Figure 1 shows the experimental setup for the proposed TYDFL based on the cladding pumping approach using two FBGs to establish a laser cavity. The 1.2-m-long TYDF is forward-pumped by a multimode 905-nm pump via a multimode combiner (MMC) to generate an amplified spontaneous emission (ASE) centered at 1 900 nm. The ASE oscillates in the linear cavity to lase at the peak wavelength of the overlapping spectrum between the two FBGs. Figure 2 shows the transmission spectra of the FBG mirrors used in the experiment. Both FBG mirrors operated at the center wavelength of 1 901.6 nm, with transmission dips of 24 and 3 dB, representing reflectivities of 99.6% and 50%, respectively. The spectral bandwidths for the FBG mirrors were 1.5 and 0.6 nm, respectively. The spectrum and power of the output laser were obtained from the output coupler of 50%, and the FBG was measured using an optical spectrum analyzer (OSA) and a power meter. The experiment was then repeated using a 927-nm pumped beam for comparison.

Figure 3 shows the output spectrum of the TYDFL pumped at 905 nm as recorded by the OSA. The laser operated at 1 901.6 nm, coinciding with the center wavelength of both FBGs, with a signal-to-noise ratio of over 40 dB. A bandwidth of 3 dB was measured to be less than 0.02 nm, as limited by the OSA resolution. The inset shows the ASE spectra, which were obtained without the FBG mirrors for two pumping wavelengths. Both sets of ASE spectra were almost similar and peak-centered at around the 1 900-nm region. This phenomenon indicates that the pumping wavelength does not affect the emission spectrum characteristics and the optimum operating wavelength of the laser. Broad ASE emission at 1 900-nm region was achieved through the transition of thulium ions from $^3F_4$ to $^3H_6$. By pumping the YTDF using either a 905- or 927-nm pumped beam, Yb^{3+} ions are excited to the $^2F_{5/2}$ state through a multiphonon-assisted anti-stoke excitation process. From $^2F_{5/2}$, the Yb^{3+} ions relax to the ground state and transfer their energy to neighboring Tm^{3+} ions nonresonantly. The Tm^{3+} ions absorb incident IR photons from the Yb^{3+} ions, thus promoting them from the $^3H_6$ to the $^3H_5$ level. The narrow band gap between the $^3H_5$ and $^3F_4$ levels indicates a short ion lifetime at the $^3H_5$ level. Due to multiphonon decay, ions at this level relax to the metastable level of $^3F_4$, which offers a longer lifetime. The population inversion between the $^3F_4$ to $^3H_6$ level then generates the ASE spectrum.

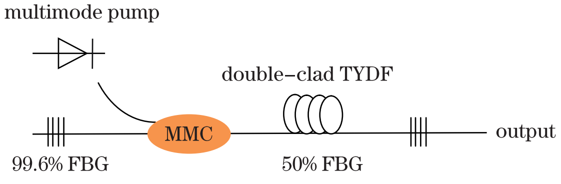

Fig. 1. Configuration of proposed TYDFL.

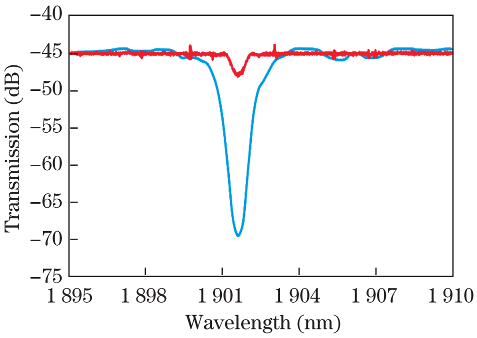

Fig. 2. Transmission spectra of both FBGs used in the laser cavity.

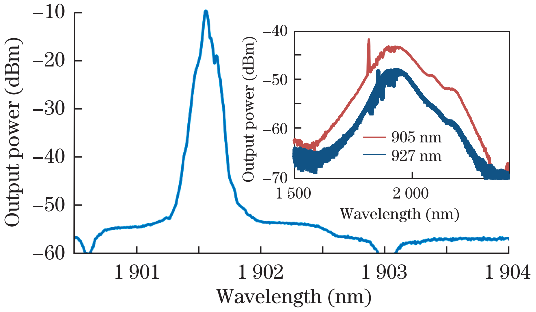

Fig. 3. Output spectrum of the 905-nm pumped TYDFL. Inset shows the ASE spectra at two pump wavelengths.

Figure 4 shows the output power of the laser as a function of the launched multimode pump power for two pumping wavelengths. Both FBG mirrors were fabricated on a single-mode fiber; hence, the output laser was considered on purely single-mode operation and the residual multimode pump was completely eliminated. As shown in Fig. 4, both output powers linearly increased with the multimode pumped power. Slope efficiencies of 0.71 % and 0.75 % were obtained at 927- and 905-nm pumping, respectively. Pumping at 905 nm was slightly more efficient than that at 927 nm because the absorption cross section of the former is slightly higher than that of the latter. The thresholds of the launched

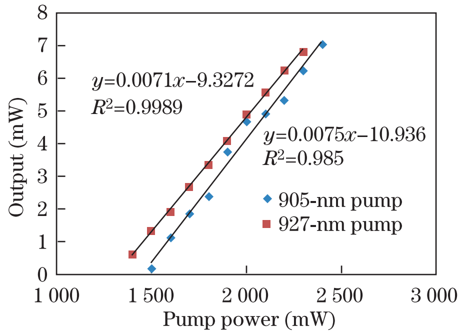

Fig. 4. Laser peak power against multimode pump powers at two different pumping wavelengths.

multimode pump power were 1 314 mW and 1 458 mW for 927- and 905-nm pumping, respectively. This result is attributed to cavity loss, which is slightly lower for pumping at 927 nm than that at 905 nm. In addition, the photon energy of the 927-nm-pumped beam is lower than that of the 905-nm-pumped beam; thus, the quantum efficiency is higher. A maximum output power of 7 mW was obtained for a 905-nm pump power of 2 400 mW, as shown in Fig. 4. The proposed TYDFL is theoretically less efficient than the conventional Tm system with 780-nm pumping but the cost of high-power 905- or 927-nm laser diodes is significantly lower than that of 780-nm laser diodes. Another benefit of the proposed 2-μm laser system is its operation in eye-safer wavelengths, in which permissible free space transmission levels can be several orders of magnitude greater than 1 μm.

In conclusion, a single-mode laser operating at 1 901.6 nm is demonstrated using a newly developed double-clad YTDF. The YTDF is forward-pumped by a 905- or 927-nm multimode laser to generate ASE at the 1 900-nm region via the transition of thulium ions from $^3F_4$ to $^3H_6$ with the assistance of ytterbium to thulium ion energy transfer. The ASE oscillates in a linear cavity formed by two FBG mirrors with the Bragg wavelength center at 1 901.6 nm to generate a single-mode laser output. The efficiencies of the laser are 0.71% and 0.75% for 927- and 905-nm pumping, respectively. The thresholds of the launched multimode pump power are 1 314 and 1 458 mW at 927- and 905-nm pumping, respectively.

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