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ENHANCEMENT OF THULIUM–YTTERBIUM DOPED FIBER LASER EFFICIENCY USING DUAL-PUMPING METHOD

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ABSTRACT: *Performance enhancement of laser acquired from a newly developed double-clad* Yb^{3+}/Tm^{3+} *codoped fiber (YTDF) is demonstrated using dual-pumping scheme. The laser uses a 2 m long YTDF fiber with a core dopant concentrations (in wt%) of 2.00* Yb_2O_3*, 0.5* Tm_2O_3*, 1.0* Al_2O_3*, and 3.00* Y_2O_3 *as a gain medium in conjunction with a pair of fiber Bragg grating in a linear cavity resonator to generate lasing at 1901.6 nm. The best efficiency of 2.9% and the highest output power of 27 mW are obtained by combining 927 nm pump with 905 nm pump. As compared to a single pumping scheme using 927 nm pumping source, about 0.43% increment in efficiency is observed with no evidence of rollover at the highest output power. The best combination is to use 200 mW of 800 nm pump with 927 nm pump, wherein only a total pump power of 1900 mW is required to generate 20 mW of 1.9 µm laser output.* © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:285–287, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28827

Key words: Yb^{3+}/Tm^{3+} *codoped fiber; 2-µm fiber laser; cladding pumping; dual-pumping method*

1. INTRODUCTION

In recent years, the development of Thulium-doped optical fiber lasers operating at near 1900 nm has caught the interest of many researchers [1–3]. This is attributed to the possibility of producing laser that is highly efficient, high in output power, and safe for retina. Lasers operating near 2 µm also have many promising applications in remote sensing, metrology, and biomedical engineering [4]. Several approaches have been proposed to enhance laser emission at 2 µm wavelength including codoping the fiber with Yb^{3+} ions as a sensitizer to the Tm^{3+} ions [5–7]. This approach is feasible because the Yb^{3+} emission at 1200 nm wavelength is one of the absorption bands of Tm^{3+}. The excited Yb^{3+} ions at $^2F_{5/2}$ release their energy which is (quasi-) resonant to the Tm^{3+} energy level of $^3H_5$. In addition, the high absorption of Yb^{3+} ions and the uniqueness of the energy level of Yb provide sufficient contribution to the high power laser application. The low quantum defect of the Yb enables pumping at high power [8].

Higher output power can be achieved either by adding doping concentration or applying dual-pumping method [9,10]. A very high doping concentration may induce clustering effect among the ions that prevents ion excitation. Adding host modifiers such as aluminium ions may reduce the effect, but it may also compromise the fiber's mechanical property. Dual-pumping approach has been proposed and demonstrated for gain enhancement of Thulium-doped fiber amplifiers in a number of research works, [11–13]. However, the focus of these works is on the enhancement of S-band gain wherein, the emphasis is more on the emission of $^3H_4$ level of the thulium ions. In this article, a dual-pumping scheme is utilized to improve the efficiency of Thulium–Ytterbium codoped fiber laser operating at 1.9 µm wavelength. The proposed laser configuration is based on a newly fabricated double-clad Yb^{3+}/Tm^{3+} codoped fiber (YTDF) as the gain medium and a pair of fiber Bragg grating (FBG) that form a linear cavity resonator. To our knowledge, this is the only experimental laser demonstration of the thulium transition $^3F_4 \rightarrow {}^3H_6$ in a silica fiber which uses the dual-pumping scheme.

2. EXPERIMENTAL SETUP

The experimental setup of the double-clad Yb^{3+}/Tm^{3+} codoped fiber lasers (YTDFLs) based on dual-pumping scheme is shown in Figure 1. A multimode pump is used as a main pump and a double-clad YTDF as the gain medium. The YTDF has D-shaped cladding structure with a core diameter and N.A. of 14.21 µm and 0.26, respectively. Its core has dopant concentrations (in wt%) of 2.00 Yb_2O_3, 0.5 Tm_2O_3, 1.0 Al_2O_3, and 3.00 Y_2O_3 which corresponds to Yb and Tm ratio (Yb:Tm) of 4:1. Figures 1(a) and 1(b) shows the proposed configurations with a multimode main pump and another multimode or single mode pump as an auxiliary pump, respectively. The experiments were performed using various combinations of pump wavelengths. In this experiment, the length of the YTDF was fixed at 2 m for optimum laser performance. It was fusion spliced to an output port of a multimode coupler (MMC). An FBG with a reflectivity of 99% was spliced to the input signal port of the MMC while another FBG with a reflectivity of 50% was fusion spliced to the output end of the YTDF to create a cavity. Both FBGs operate at the center wavelength of 1901.6 nm and 3 dB spectral bandwidths are measured to be around 1.5 nm and 0.6 nm for the reflectivity of 99.6 and 50%, respectively. In the setup of

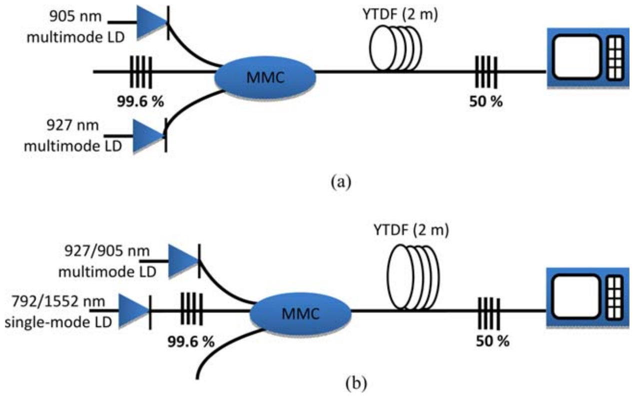

Figure 1 Configurations of the proposed YTDFL with dual-pumping scheme when the auxiliary pump is (a) multimode and (b) single mode. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

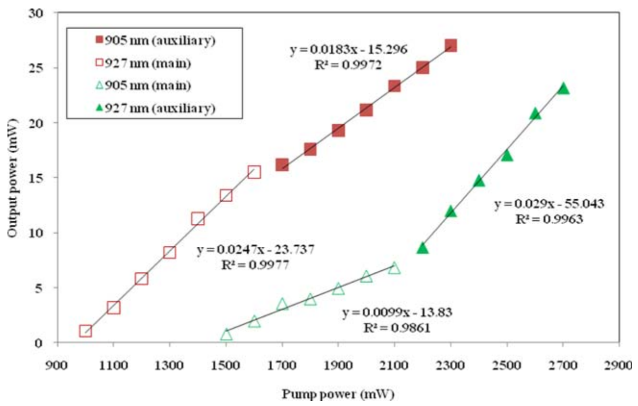

Figure 2 The performance of the YTFL as another multimode pump is added as an auxiliary pump. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

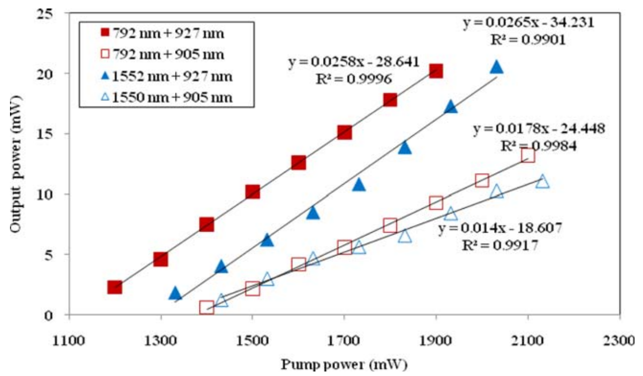

Figure 3 The performance of the YTDFL as another single mode pump is added as an auxiliary pump. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 1(a), 905 and 927 nm multimode pumps are used alternately as the main and auxiliary pump. Both pumps are injected into the inner cladding of the YTDF via a multimode combiner to create a population inversion and then amplified spontaneous emission which oscillates in the linear cavity to generate laser at the Bragg wavelength of 1901.6 nm. In Figure 1(b), a single mode pump of 792 or 1552 nm is used as the auxiliary pump while a multimode pump of 905 or 927 nm is used as the main pump. The output of the laser is tapped out from the cavity via the output port of the second FBG with 50% reflectivity. The output spectrum and power are measured by the OSA and power meter, respectively.

3. RESULTS AND DISCUSSION

The performance of the proposed YTDFL is first investigated with and without the auxiliary pump using two different multimode pumps of 927 and 905 nm according to the setup of Figure 1(a). Figure 2 shows the experimental result where the unshaded legends indicate the results of the lasers without the auxiliary pump. With 927 nm pumping, the YTFL has an efficiency of 2.47% with threshold pump power of 1000 mW. However, using 905 nm pumping, the efficiency drops to 0.99% and the threshold pump power increases to 1500 mW. This is most probably due to two main reasons; the first reason is the absorption/emission cross-section of the YTDF is slightly higher at 927 nm compared to the one at 905 nm. The second reason is the cavity loss is slightly lower at longer wavelength and thus the operation of the laser is more efficient with the use of 927 nm pump. To measure the effects of dual pumping on the efficiency and output power of the laser, a main pump is used to initiate lasing before launching of an auxiliary pump which help to increase the output power. First, 905 nm pump is used as the main pump alone and its power is increased from 1500 mW to the maximum level of 2100 mW. Then, the auxiliary 907 nm pump is launched and its power is increased every 100 mW to record six new readings until it max out at the total power of 2700 mW. From the graph, the efficiency is seen to improve by 1.91 to 2.90% with the incorporation of the auxiliary pump. As the 905 nm photons are inefficiently absorbed, the amount of excited Ytterbium ions is limited. When the 927 nm light is launched into the gain medium, more Ytterbium ions occupy the excited state thereby increasing the energy transfer process. Therefore, the population of Thulium ions at the upper state level also increases, and hence the laser efficiency improves. Conversely, by adding 905 nm pump as auxiliary pump for 927 nm pumped YTDF, the efficiency of the laser slightly reduces from 2.47 to 1.83%. This is most probably due to the saturation of the Yb^{3+} ions absorption at 927 nm as the 905 nm pump was turned on [14]. This reduces the energy transfer to the Tm^{3+} ions as the 905 nm pump power increases. However, the overall output power obtained is still better in this 927/905 nm combination pumps compared to that the previous combination of 905/927nm.

Figure 3 shows the experimental results obtained by the proposed YTDFL of Figure 1(b) where another dual-pumping scheme combining a multimode and single mode pump is implemented. First, the performance of the YTFL is investigated when a single mode 1552 nm is added in the cladding-pumped fiber laser. For this experiment, a fixed 1550 nm pump power of 32 mW is launched into the system before we start increasing the power of the multimode pump. As shown by the blue shaded triangle legend in Figure 3, when the 1550 nm pump is coupled with the 927 nm source, the laser is generated at 1.9 μm at the threshold pump power of 1332 mW with an efficiency of 2.65%. The efficiency was improved by 0.18% as compared to the result of using 927 nm laser diode alone as a pump source. By combining 1550 nm single mode pump with 905 nm multimode pump, the efficiency of the laser increases by 0.41% from 0.99 to 1.40% with laser threshold at 1400 mW as shown by the unshaded triangle legend in Figure 3. It is found that the combination of single mode 1550 nm and multimode 927 nm pumps provides a better lasing operation compared to than the combination of 1550 and 905 nm pumps. This is due to the pump absorption by Ytterbium ions, which is higher at 927 nm than 905 nm. In addition to photon absorption donated by Ytterbium

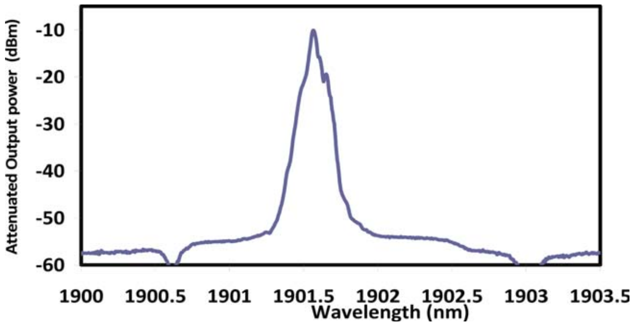

Figure 4 The attenuated output spectrum for the proposed laser. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

ions, 1550 nm incident pump increases the ground state absorption of Thulium ions caused by higher population inversion in the upper laser level.

In another experiment, 792 nm single mode pump is used as the auxiliary pump instead of 1552 nm pump. Similar to the previous experiment, a fixed 792 nm pump power of 200 mW is launched into the system before we start increasing the power of the multimode pump. As compared to the previous 1552 nm pumping, the efficiency of this laser was higher and the threshold was lower. By combining 905 and 792 nm pumps, the lasing efficiency was improved by 1.78% and the threshold was reduced to 1400 mW. As indicated by the shaded square legend in the figure, combining 927 and 792 nm pumps produces an even better lasing output with relatively higher efficiency up to 2.58% and a lower threshold pump power of 1200 mW. This is due to the 2:1 cross relaxation that occurs in the fiber which allows a large number of thulium ions to occupy the upper laser level of $^3F_4$ thus, improving the laser efficiency.

It is found that the best efficiency of 2.9% and the highest output power of 27 mW are obtained by combining 927 nm pump with 905 nm pump. Figure 4 shows the attenuated optical spectrum recorded by an OSA for the proposed laser. It operates at 1901.6 nm, which coincides with the center wavelength of both FBGs with a signal to noise ratio of more than 40 dB. The 3 dB bandwidth is measured to be less than 0.02 nm and is limited by the OSA resolution. The best combination of pumps is 200 mW of 792 nm pump with 1700 mW of 927 nm pump, where only a total pump power of 1900 mW is required to generate 20 mW of 1.9 μm laser output. As a comparison, the use of 1600 mW of 927 nm pump and 300 mW of 905 nm pump only produces 19.3 mW of output power.

4. CONCLUSION

A series of dual-pumping schemes are proposed to improve the lasing efficiency of YTDFL based on a newly developed double-clad YTDF with a linear cavity. The highest efficiency of 2.9% is obtained at the highest output power of 27 mW by combining 905 nm with 927 nm multimode pumps. Compared to a 927 nm singly pumped YTDFL, about 0.43% increment is observed with no evidence of rollover at the highest output power. The use of single mode pumps of 1550 and 800 nm as a secondary pump also improved the performance of the laser. The best combination of pumps is 200 mW of 792 nm pump with 1700 mW of 927 nm pump where only a total pump power of 1900 mW is required to generate 20 mW of 1.9 μm laser output.

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SWITCHABLE DUAL-WAVELENGTH SINGLE-LONGITUDINAL-MODE ERBIUM-DOPED FIBER LASER BASED ON A THIN-CORE FIBER COMB FILTER AND SATURABLE ABSORBER

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ABSTRACT: *A tunable dual-wavelength single-longitudinal-mode erbium-doped fiber laser using thin-core fiber comb filter (TCFCF) and a saturable absorber is proposed. TCFCF is achieved by splicing a thin-core fiber between two single-mode fibers. Two lasers incurred shifts of 1 and <3 pm, and corresponding 3-dB linewidths are 3.4 and 3.0 kHz, respectively.* © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:287–292, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28826

Key words: *dual-wavelength erbium-doped fiber laser; single-longitudinal mode; thin-core fiber comb filter; saturable absorber*

1. INTRODUCTION

Dual-wavelength fiber lasers have attracted much attention due to their wide range of applications in areas such as optical fiber