Effects of Yb/Tm Concentration and Pump Wavelength on the Performance of Ytterbium-Sensitized Thulium-Doped Fiber Laser

A 1901.6-nm laser is demonstrated using the newly developed double-clad ytterbium-thulium-doped fiber (YTDF) samples in conjunction with 931-nm pumping through the transition of thulium ion from $^3F_4$ to $^3H_6$ with the assistance of ytterbium to thulium-ion energy transfer. The YTDF used was drawn from a D-shape preform, which was fabricated using the modified chemical vapor deposition and solution-doping technique. The laser operates at 1901.6 nm with an efficiency of 2.47% using 2-m-long YTDF in a Fabry-Pérot cavity with two fiber Bragg gratings. It is found that the higher ytterbium-to-thulium concentration ratio contributes to more efficient energy transfer between the sensitizer and acceptor ions in YTDF, which in turn lowers the threshold of the proposed ytterbium-thulium-doped fiber laser (YTFL). The lowest threshold pump power of the proposed YTFL is around 961 mW. The use of multimode pump with a wavelength slightly lower than 931 nm is also observed to improve both the laser's threshold and efficiency of the YTFL.

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SECTION I
INTRODUCTION

RECENTLY, the development of Thulium doped optical fiber lasers (TDFLs) operating at near 2000 nm has become an interesting topic for many researchers [1], [2], [3]. This is attributed to the possibility of achieving laser of high efficiency, high output power, and retina safe in addition to specific applications plausible for this wavelength, such as for remote sensing and biomedical applications [4]. However, there are still many issues to be addressed such as low quantum efficiency of generated laser in high-phonon energy glass host matrix such as silica-based glass fibers. Therefore, Thulium-doped fibers (TDFs) are adopted since they normally employ low phonon energy glass hosts, eg. —Fluoride glass, in which the up-conversion intensity is reported to be quite high in ultraviolet region [5]. Nevertheless, since the fluoride host is a rather soft type of glass, it is very hard to draw optical fiber from the preform due to its lower melting temperature. Recently, the interest has shifted back to silica based host TDFs as the phonon energy of silica glass can be reduced by incorporating silica network modifiers like Aluminum (Al) and Germanium (Ge). Thus TDFs with modified silica host have emerged as a promising gain medium for achieving an efficient TDFL [6].

Of late, a Ytterbium-sensitized Thulium-doped fiber laser (YTFL) was demonstrated for oscillation around 2 micron based on Ytterbium (Yb) to Thulium (Tm) energy transfer [7]. Yb^{3+} has the advantage of possessing only two multiplets: the ground-state level $^2\mathrm{F}_{7/2}$ and the excited-state level $^2\mathrm{F}_{5/2}$, resulting in highly efficient absorption in the range of 900 nm–1000 nm [8]. This opens a possibility of developing an economic but stable low power fiber laser in the wavelength range of 1800 to 2100 nm using a cheap 980 nm diode pumping. This laser has tremendous application for sensing toxic gases due to their specific IR absorption. Most of the previous work dealing with TDF or YTDFs was confined to particular host compositions or $\mathrm{Tm}^{3+}{:}\mathrm{Yb}^{3+}$ ratio for investigation of fluorescence or lasing mostly in visible and S-band regions. No systematic investigation was carried out on the influence of fiber core composition on lasing from $^3\mathrm{F}_4$ level through energy transfer from $\mathrm{Yb}^{3+}\rightarrow\mathrm{Tm}^{3+}$.

In this paper, the performance of the laser resonator utilizing FBGs and newly developed double-clad D-shaped YTDF with different host compositions and $\mathrm{Tm}^{3+}/\mathrm{Yb}^{3+}$ concentrations is investigated. The proposed laser operates in the wavelength region near 2000 nm based on energy transfer from $\mathrm{Yb}^{3+}\rightarrow\mathrm{Tm}^{3+}$ using a multimode pump which operates at around 930 nm. The performance of YTFL is demonstrated using two different fiber samples and pumping schemes. In this work, $\mathrm{Y_2O_3}$ was selected as the host material as it is a refractory oxide with a high melting point of 2380°C and a very high thermal conductivity of $\mathrm{k_{Y2O3}}=27\mathrm{W/mK}$ (which is twice as high as that of YAG with $\mathrm{k_{YAG}}=13\mathrm{W/mK}$). Another interesting property of Y2O3 is that it allows radiative transitions between electronic levels wherein the dominant phonon energy is 377 cm^{-1} which is one of the smallest phonon cut-off among oxides [9].

SECTION II
EXPERIMENTS

The YTDF was obtained by drawing a D-shape preform, which was fabricated using a deposition of porous layer by the MCVD process in conjunction with solution doping technique. In the MCVD process, a pure silica glass tube of outer/inner diameter 20/17 mm was used for the deposition of 3–8 multiple porous unstinted SiO_2-P_2O_5 soot layers to make a preform while maintaining a suitable deposition temperature at around 1400–1450°C. An alcoholic solution containing doping metals i.e., Tm, Yb, Y, Al in the form of their chlorides of Alfa standard, was used to soak the porous layer with for about 30 to 45 min to achieve efficient doping. Then, dehydration and oxidation were performed at the temperature of around 900–1000°C. Sintering of the un-sintered layers was also done by slowly increasing the temperature from 1500 to 2000°C. Upon the completion of sintering and oxidation, the tube was slowly collapsed to transform it into optical preform. The fabricated preform was then drawn at the temperature of 2050°C into a double-clad D-shaped fiber with an outer cladding diameter of 125 μm. The characteristics of the two fiber samples used in this experiment is shown in Table I. From fabrication point of view we have carried out various experiments by systematically increasing the ratio of Y/Al. When the ratio becomes greater than 3 the core glass becomes opaque in nature and loss of the fabricated fiber is also increased. For this reason we have selected only two fibers having Y/Al ratio of 1.0 and 3.0 respectively.

Sample No.	Avg. Weight Percentage of Dopants	Yb and Tm Ratio (Yb:Tm)	Core Diameter	N.A.
YTDF 1	Al_2O_3: 2.00, Y_2O_3: 1.90, Tm_2O_3: 0.80, Yb_2O_3: 1.98	2.5:1	15.87 μm	0.22
YTDF 2	Al_2O_3: 1.00, Y_2O_3: 3.00, Tm_2O_3: 0.50, Yb_2O_3: 2.00	4.0:1	14.21 μm	0.26

TABLE I CHARACTERISTICS OF THE FABRICATED DOUBLE-CLAD D-SHAPED YTDF

Fig. 1 shows the experimental setup for the proposed YTFL using the fabricated double-clad YTDF as a gain medium in conjunction with cladding pumping approach. In this approach, the double-clad fiber is forward pumped by a multimode pump via a multimode combiner (MMC). As opposed to the conventional single mode fiber where the pump light is coupled directly into the core, the pump light travels down the fiber in the first cladding and get absorbed by the dopants, in this case the Yb ions when it overlaps with the core. The D-shape geometry of the cladding improves the pump absorption and furthermore it is cheaper to be fabricated compared to other geometries such as hexagonal and rectangular. The FBGs with a reflectivity of 99.6% and 50% are fusion spliced to signal port of MMC and the active fiber respectively to establish a Fabry–Pérot laser cavity. The forward pumped YTDF generates an ASE centered at 1900 nm region, which oscillates in the cavity to lase at the peak wavelength of the overlapping spectrum between the two FBGs. Fig. 2 shows the transmission spectra of the FBGs used in the experiment. 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. The spectrum and power of the output laser are obtained from the output port of the 50% FBG and measured using an optical spectrum analyzer (OSA) and power meter, respectively.

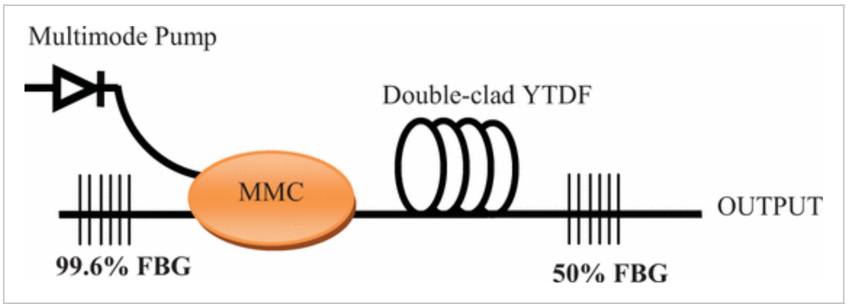

Fig. 1. Configuration of the proposed TYDFL.

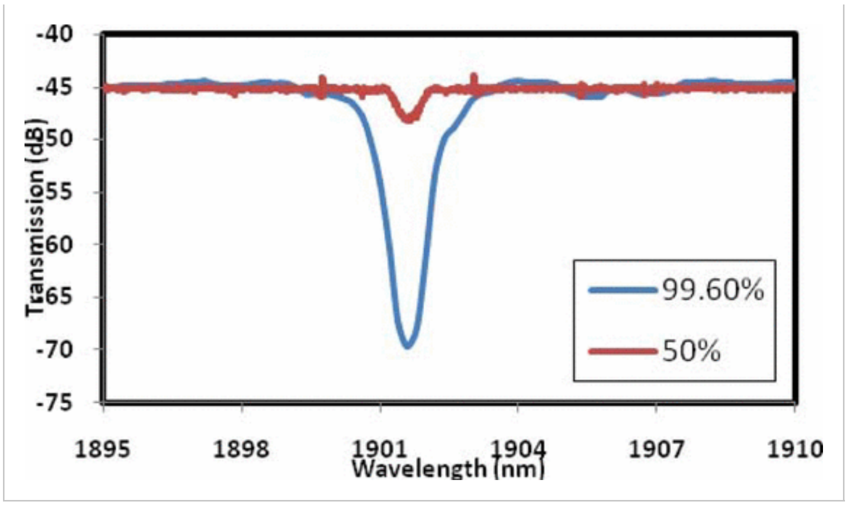

Fig. 2. Transmission spectrum of both FBGs used in the laser cavity.

SECTION III
RESULTS AND DISCUSSION

This experiment is firstly conducted to find the optimal length to operate the proposed YTFL for both fiber samples using 931 nm pumping (pump A). Fig. 3(a) and (b)show the laser output power against multimode pump power for YTDF samples 1 and 2 respectively at various fiber lengths. Both YTFLs configured with YTDF 1 and 2 show the best lasing action operation at 2 m length where they exhibit the highest efficiencies of 2.47% and 2.23% respectively with the lowest lasing threshold. By pumping the doped fiber using 931 nm pump, the Yb^{3+} ions are excited to $^2F_{5/2}$ state with multi-phonon assisted anti-Stokes excitation process. From $^2F_{5/2}$, the Yb^{3+} ions relax to the ground state and transfer their energy to the neighboring Tm^{3+} ions non-resonantly. The Tm^{3+} ions absorb the incident infrared photon from the Yb^{3+} ions thus promoting them from $^3H_6$ to $^3H_5$ level. The narrow gap between the $^3H_5$ and $^3F_4$ levels indicates a short ion lifetime at the $^3H_5$ level. Due to multi-phonon decay, ions at this level relax to the metastable level of $^3F_4$ which offers longer lifetime. The population inversion between the $^3F_4$ to $^3H_6$ level generates an ASE light centered at 1900 nm region, which oscillates in the Fabry–Pérot cavity to realize a laser at 1901.6 nm. However, the slope efficiency of the proposed laser is relatively low due to three possible reasons. The first reason is the size of the fabricated fiber core diameter, which is very large compared to that of the FBG fiber (around 7–8 micron). Therefore when both fibers are spliced together, it generates higher splicing loss of around 1 dB as a large portion of the pump power leaks out. The second reason is because we used 931 nm multimode pump source for which the absorption cross-section coefficient of Yb^{3+} peaks at around 975 nm. It is expected the proposed laser can produce a higher efficiency if the optimum pump wavelength is used. The third reason is that the higher possibility of multi-step energy transfer which leads to upconversion and blue emission. Fig. 4 shows the output spectrum of the YTFL with 931 nm pumping and TYDF 2 recorded by an OSA. 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 limited by the OSA resolution.

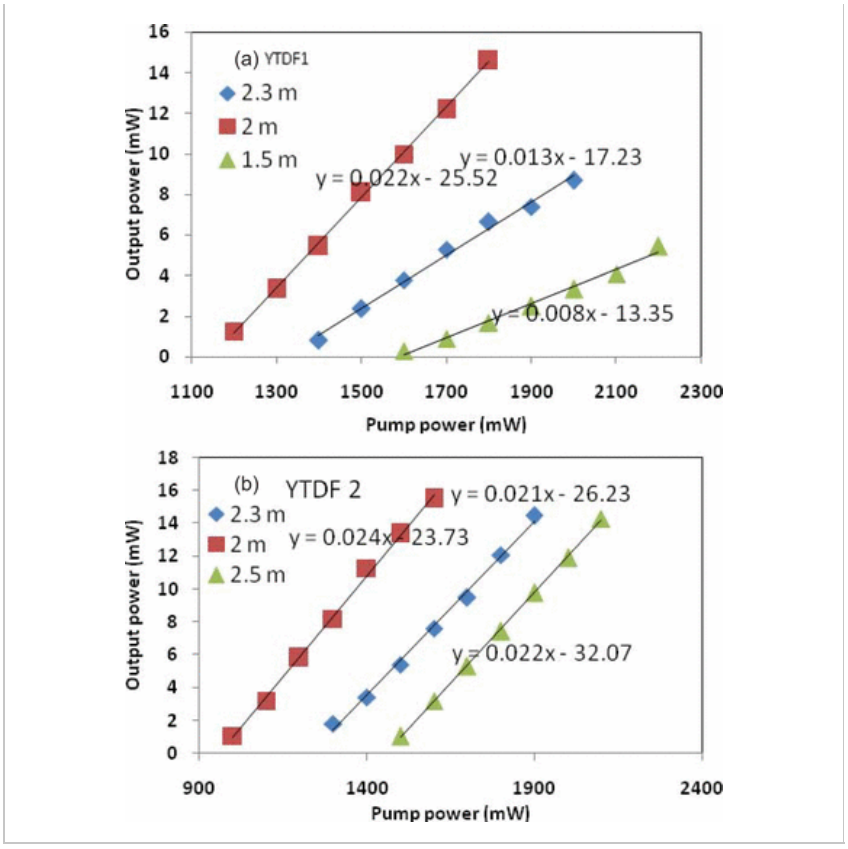

Fig. 3. Output power of the proposed YTFL against the pump power at different YTDF lengths using (a) YTDF 1 and (b) YTDF 2 samples as the gain medium.

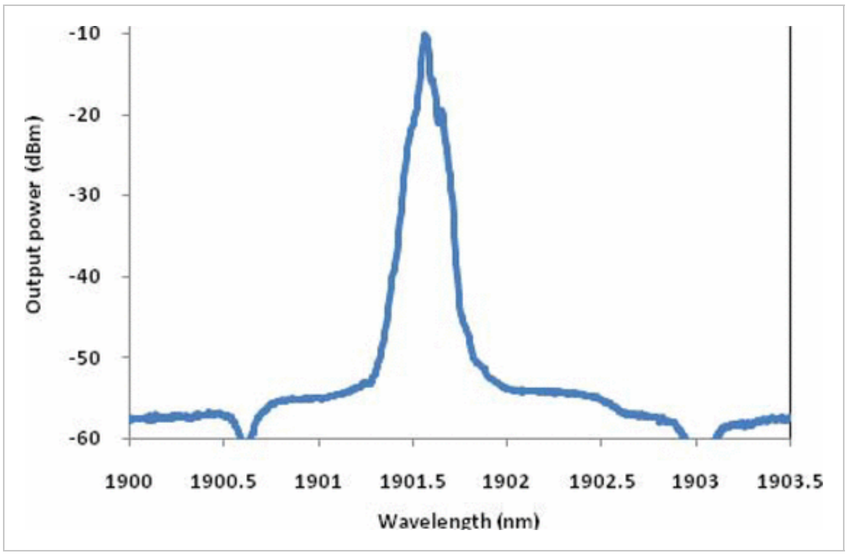

Fig. 4. Output spectrum of the YTFL with YTDF 2 in conjunction with 931-nm pumping.

High thulium doping concentration for both YTDF samples lead to efficient stepwise energy transfer such that the optimum length for lasing is comparatively short. To avoid clustering from high concentration of rare earth ions doping, yttria and aluminium are added as host modifiers. The presence of Al_2O_3 and Y_2O_3 decreases phonon energy in the fiber and assists in distributing Yb and Tm ions homogeneously into the core glass matrix which also increases the probability of radiative emission and improves lasing efficiency. Several advantages of using short gain medium when generating laser are minimum re-absorption of pump power that results in high threshold and low efficiency laser, an increase in the stimulated scattering process threshold which prevents roll off in output power, less total propagation loss in the setup and less use of fiber materials.

In the present work, yttria-alumino rich Tm_2O_3 and Yb_2O_3 doped silica glass based optical fibers was fabricated because of the highest known vibrational energy in YAS $(Y_2O_3\text{-}Al_2O_3\text{-}SiO_2)$ glass, is about 950 cm^{-1} [10], which is less than the maximum vibrational energy, around 1100 cm^{-1}, in silica glass [11]. Consequently, we have chosen to combine the SiO_2 matrix with Al_2O_3 and Y_2O_3 to increase the optical efficiency of the rare-earth dopants and avoid clustering effects. Moreover, Al^{3+} and Y^{3+} have the same electronic valence as RE^{3+} ions, as well as similar lattice structures of Al_2O_3, Y_2O_3 and Yb_2O_3 oxides. In the fabricated fiber, we have also deposited $SiO_2\text{-}P_2O_5$ porous unsintered multiple layers where the doping levels of P_2O_5 content is very low, around 0.10–0.20 mol%, in order to provide good adhesion between layers [12]. Otherwise there will be disturbances of soot layer either during solution soaking process or thermal drying process. Such low content of

P_2O_5 does not increase the phonon energy of the glass host very much.

On the other hand the transition temperature of an oxide glass is normally related to a combination of several factors such as the density of covalent cross-linking, the number and strength of the coordinate links formed between oxygen and the cation, and the oxygen density of the network [13]. With increasing Y-content, more coordinate links are formed between oxygen and yttrium, which is opposed by the lower oxygen density of the network from the more open structure needed to accommodate larger yttrium ions and depolymerization in the network with decreasing silica content or increasing Y/Al. The fabricated YTDFs were characterized by non-exponential decays. It is found that the Yb^{3+} decay time was shorter than the decay comprised of the fluorescence contributions from both Yb^{3+} and Tm^{3+} ions. The time constant of the Yb^{3+} decay amounted to 540 μs as compared to approximately 650 μs of the decay of the gathered fluorescence from Yb^{3+} and Tm^{3+}. In fact, the quantum yield of the Yb^{3+} to Tm^{3+} energy transfer process of such kind of Tm_2O_3-Yb_2O_3 codoped glass preform is estimated to be about 0.98, whereas it reduces to about 0.02 in the rare-earths-poor phase [14]. This means that about every Yb^{3+} ion that is excited in the rare-earths rich phase transfers its energy to Tm^{3+} ions.

From Fig. 3, it can be seen that the YTFL configured with YTDF 2 produces a better efficiency compared to that of YTDF 1. Referring to Table I, YTDF 2 has a higher Ytterbium to Thulium doping concentration ratio, higher NA and also smaller core radius compared to that of YTDF 1. Higher NA allows the fiber to maintain the launched pump brightness in spite of smaller core radius. As the core radius reduces, the ratio of doped core area to cladding area increases thus improving the overlapping between the pump light and the active core area. This enhances the pump light absorption and consequently the lasing action performance of the fiber. Apart from that, optical fibers with larger NA can collect more light especially in multimode structure there by allowing them to generate higher efficiency fiber laser. Since YTDF 2 has a higher ytterbium ion concentration, the rate of cross relaxation between these ions is higher resulting in more energy transfer to thulium which lowers the threshold of the generated laser. Furthermore, higher ytterbium to thulium concentration ratio contributes to more efficient energy transfer between the sensitizer and acceptor ions in YTDF 2. However, with the use of an unidirectional auxiliary pump at approximately 1600 nm in conjunction with a 980 nm primary pump, it was reported that an increase in Tm concentration along with Yb:Tm ratio of ~ 1 leads to the best laser performance [7]. The laser results in this work are clearly better than those obtained in [7], which are most probably due to the pump wavelength used and the improved dopants compositions.

By using a 2 m long YTDF 2 as the gain medium, the proposed YTFL performs the best with a threshold pump power of 961 mW with a slope efficiency of 2.47%. The performance of YTFL is also investigated for two different pump sources, which have almost identical operating wavelength at around 931 nm. They have slightly different spectrum as shown in Fig. 5 and thus they are expected to perform differently. Aside from demonstrating laser with the highest power at wavelength of 931 nm, pump A has another peak with considerable power at 926 nm whereas pump B does not. It is observed that the laser efficiency generated by pump A is better compared to that of pump B. This is attributed to the fiber's pump absorption, which peaks at around 920 nm and 975 nm and thus the fiber has more absorption at 926 nm compared to the wavelength longer than 931 nm. This results in an improvement of both laser's threshold and efficiency of the YTFL as shown in Fig. 6. With pump B, the laser threshold and efficiency are obtained at 1234 mW and 1.89% respectively, which are slightly inferior to that of pump A. The maximum power of 15.5 mW is obtained with pump A at the pump power of 1600 mW. It is obvious that higher output is expected with the use of higher pump power. Since the absorption cross-sectional area of $Yb3+$ is higher at 973 nm wavelength, the experiment is repeated using this pump source in order to achieve higher efficiency. The laser threshold is obtained at the higher pump power of around 2600 mW and the laser output power is obtained at 17 mW with pump power of 2700 mW. However, the laser is unstable and diminishs as the pump power is further increased. The proposed TYDFL is theoretically less efficient than the conventional Tm system with 780 nm pumping, but the cost of high power 931 nm laser diodes is so much lower than that of 780 nm laser diode. Another benefit of the proposed 2-μm laser system is its operation in eye-safer wavelengths, where permissible free space transmission levels can be several orders of magnitude greater than 1 μm.

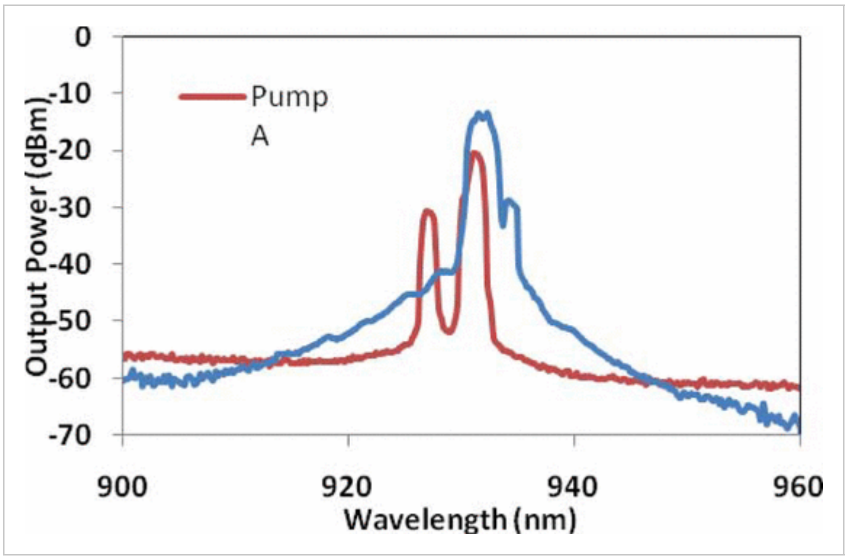

Fig. 5. Output spectra of two different 931-nm pump sources used in the experiment.

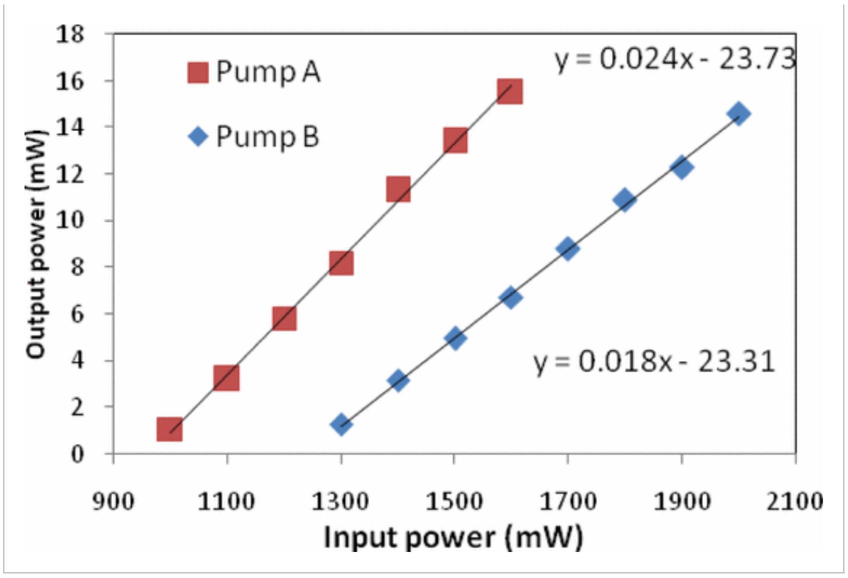

Fig. 6. Output power against pump power characteristics for the proposed YTFL with two different pump sources.

SECTION IV
CONCLUSION

A single mode laser operating at 1901.6 nm is demonstrated by employing a newly developed double-clad YTDF. The YTDF is forward pumped by 931 nm multimode laser to generate ASE at 1900 nm region via the transition of Thulium ion from 3F4 and 3H6 with the assistance of ytterbium to thulium ion energy transfer. The ASE oscillates in a linear cavity formed by two FBGs with the Bragg wavelength to generate a single mode laser output. As the pump power is increased above the threshold value of 961 mW, the laser operates at 1901.6 nm with an efficiency of 2.47% using 2 m long YTDF. It is found that the higher ytterbium to thulium concentration ratio contributes to more efficient energy transfer between the sensitizer and acceptor ions in YTDF leading to lower lasing threshold. The use of multimode pump with slightly lower wavelength than 931 nm is shown to improve both laser's threshold and efficiency of the YTFL.

FOOTNOTES

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INSPEC: Controlled Indexing

Bragg gratings, chemical vapour deposition, doping, fibre lasers, laser beams, laser cavity resonators, laser modes, laser transitions, optical fibre cladding, optical fibre fabrication, optical pumping, preforms, thulium, ytterbium

INSPEC: Non-Controlled Indexing

D-shape preform, Fabry-Perot cavity, YTDF samples, YTFL, acceptor ions, double-clad ytterbium-thulium-doped fiber samples, efficiency 2.47 percent, fiber Bragg gratings, laser efficiency, lowest threshold pump power, modified chemical vapor deposition, multimode pump, pump wavelength, sensitizer, size 2 m, solution-doping, thulium ion transition, wavelength 1901.6 nm, wavelength 931 nm, ytterbium-sensitized thulium-doped fiber laser, ytterbium-thulium-ion energy transfer, ytterbium-to-thulium concentration ratio

Authors Keywords

2-μm fiber laser, cladding pumping, component, ytterbium-thulium-co-doped fiber

CORRECTIONS

None