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Ytterbium-sensitized Thulium-doped fiber laser in the near-IR with 980 nm pumping

Atasi Pal[1], Anirban Dhar[1], Shyamal Das[1], Shu Ying Chen[2], Tong Sun[2], Ranjan Sen[1]*, and Kenneth T V Grattan[2]

[1]*Fiber Optics Laboratory, Central Glass & Ceramic Research Institute,196, Raja S.C. Mullick Road, Kolkata, India*
[2]*School of Engineering & Mathematical Sciences, City University London, U.K.*
**rsen@cgcri.res.in*

Abstract: The use of an unidirectional auxiliary pump at approximately 1600 nm in conjunction with a 980 nm primary pump for Ytterbium (Yb^{3+})-sensitized-Thulium (Tm^{3+})-doped single mode silica fiber (YTDF) is found to be very effective to activate the most significant resonance energy transfer from Yb^{3+} to Tm^{3+}, in order to obtain significant emission in the near-infrared. The resulting laser performance of the YTDF at 1874 nm is reported here. The influence of the Tm^{3+}/Yb^{3+} concentration, their relative proportions and the host glass composition on the lasing efficiency has also been investigated to optimize the fiber parameters for maximum laser output power.

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1. Introduction

Lasers in the near-infrared (NIR) region have significant potential for a variety of medical and biosensor applications due to the strong absorption of water at a wavelength of 1910 nm. In Thulium doped silica glass, Tm appears as a trivalent ion with its energy levels showing Stark splitting into six different absorption bands of which the most broadened band is ranging over the wavelength from 1600 to over 2000 nm. As a result, Tm^{3+} doped fiber lasers attract considerable attention for the generation of coherent emission with broad tunability in the 'eye safe' wavelength range. The doping of Tm^{3+} in low phonon energy glasses like fluoride,

telluride etc. provides high quantum efficiency. Further, the phonon energy of silica glass can be reduced by incorporating silica network modifiers like Aluminum (Al) and Germanium (Ge). Thus the modified silica host doped with Tm^{3+} has emerged as a promising candidate for achieving lasing in visible, S-band and NIR region [1].

A variety of pumping schemes using pump sources operating at wavelengths in the region of ~790, ~1200 and ~1600 nm have been explored to achieve Tm^{3+} doped fiber laser near 2000 nm [2–4]. An alternative approach to this is co-doping the fiber core with Yb^{3+} and pumping over the wavelength region from 910 to 980 nm. Tm^{3+}-doped fiber sensitized with Yb^{3+} has been used extensively for up-conversion systems [5,6] and recently has been exploited for high power lasing in the wavelength region around 2000 nm in a double clad fiber configuration [7]. The quasi-resonant energy levels of Tm^{3+} with the excited Yb^{3+} level ($^2F_{5/2}$) allows possible $Yb^{3+} \rightarrow Tm^{3+}$ energy transfer which is similar to that in Yb^{3+} sensitized Erbium (Er^{3+}) doped fibers [8].

Instead of high power applications, an economic but stable low power fiber laser in the wavelength range of 1800 to 2100 nm with all fiber configurations has tremendous application for sensing toxic gases due to their specific IR absorption. The challenge of building up such fiber Bragg grating (FBGs) based fiber laser with cheap 980 nm diode pumping is to achieve efficient energy transfer from $Yb^{3+} \rightarrow Tm^{3+}$ by developing fibers with optimized parameters and compositions. All the previous work dealing with Tm^{3+} or Tm^{3+}/Yb^{3+}doped fibers or bulk glasses was confined to particular host compositions or Tm^{3+}: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 $^3F_4$ level through energy transfer from $Yb^{3+} \rightarrow Tm^{3+}$. In the present work, the performance of the laser resonator utilizing FBGs and YTDF in the wavelength region near 2000 nm is investigated on the basis of energy transfer from $Yb^{3+} \rightarrow Tm^{3+}$ using a series of fibers with different host compositions and Tm^{3+}/Yb^{3+} concentrations. In addition, unidirectional dual pumping employing very low power at 1600 nm coupled with primary pump at 980 nm is explored to enhance the lasing efficiency.

2. Operation scheme

The energy level diagram of the Tm^{3+}/Yb^{3+} system in a silica host (Fig. 1 [9]) illustrates the strong resonance between the Yb^{3+} emission transition ($^2F_{5/2} \rightarrow {}^2F_{7/2}$) and the excited Tm^{3+} absorption ($^3F_4 \rightarrow {}^3F_2$) that indicates a very efficient energy transfer. The lifetime of the $^3F_2$ level can be expected to be extremely short because of narrow energy gap between the $^3F_2$ and $^3F_3$ energy levels of Tm^{3+}. This signifies that energy transfer will not occur in the 'backward' direction. Similarly, the lifetime of the $^3H_4$ and $^3H_5$ levels are sufficiently short and multi-phonon decay allows the relaxation of population in the $^3F_2$ and $^3F_3$ levels to the $^3F_4$ level via the $^3H_4$ and $^3H_5$ levels. This population mechanism of $^3F_4$ level activates the radiative transition from $^3F_4 \rightarrow {}^3H_6$ i.e. producing broad band emission in the NIR wavelength range. However, it would be expected that there would be some initially excited Tm^{3+} to activate the above-mentioned energy transfer. Additionally the quasi-resonant energy transfers from $^3H_6 \rightarrow {}^3H_5$ / $^3H_4 \rightarrow {}^1G_4$ also take place as soon as there is sufficient excited population of Tm^{3+} and blue ($^1G_4 \rightarrow {}^3H_6$) and dark red ($^3H_4 \rightarrow {}^3H_6$) emissions occur simultaneously with the NIR.

Consequently, the use of auxiliary pumping of Tm^{3+} at ~1600 nm is explored to achieve the initial $^3H_6 \rightarrow {}^3F_4$ excitation to trigger the efficient $Yb^{3+} \rightarrow Tm^{3+}$ energy transfer Yb^{3+} ($^2F_{5/2}$), Tm^{3+} ($^3F_4$) $\rightarrow$ Yb^{3+} ($^2F_{7/2}$), Tm^{3+} ($^3F_2$) when pumped with 980 nm primary pump. The proposed pumping scheme is highly effective for achieving lasing near 2000 nm in single mode silica fiber configuration. A FBG based laser resonator at 1874 nm is specifically designed using YTDF and unidirectional pumping with a low power Er^{3+} doped fiber laser centered at 1600 nm and a conventional laser diode at 980 nm. The laser performance is

investigated for different Tm^{3+}/Yb^{3+} concentrations with variations of their proportion in different host compositions. Fiber parameters are optimized on the basis of laser output power.

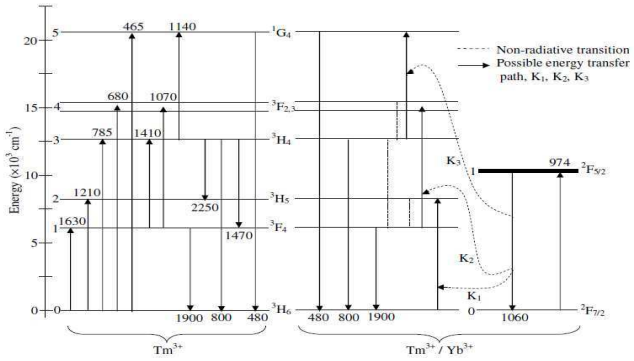

Fig. 1. Energy level of Tm^{3+}/Yb^{3+} in silica using Russell-Saunders Coupling. All transition wavelengths are in nm.

3. Design of Laser resonator

An Er^{3+} doped fiber laser at ~1600 nm was developed by using 1.5 m of Er^{3+} doped fiber (Er^{3+} concentration ~5000 ppm) and two FBGs centered at 1599.05 nm with reflectivities of 99.4% and 27.6%. A 980 nm laser diode with a maximum power of 480 mW was used as pump source to obtain the maximum laser output power of 73 mW at 1599.05 nm. This fiber laser at ~1600 nm was used as an auxiliary pump source, unidirectional with the standard 980 nm laser diode to excite the YTDF laser resonator. The schematic of the laser resonator is shown in Fig. 2. FBGs at 1874 nm with reflectivities of 98% and 38% were spliced with YTDF. All FBGs were fabricated and characterized in-house. The power of the auxiliary pump at ~1600 nm was fixed at a minimum level to prevent lasing at 1874 nm. Thus the 1600 nm pump was used to initially excite the Tm^{3+} and not for power scaling.

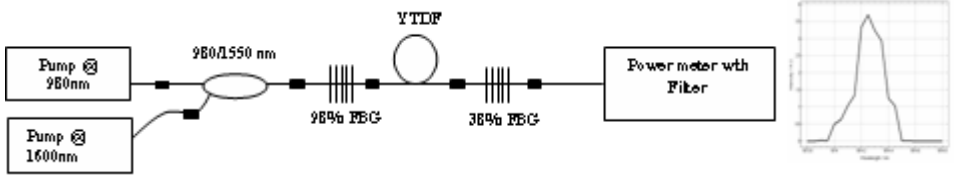

Fig. 2. Schematic of Laser set up at 1874 nm using Yb^{3+} sensitized Tm^{3+} doped fiber. Laser spectrum recorded in monochromator is shown in inset.

The laser spectrum and output power at 1874 nm (with pump power variations at 980 nm) were recorded by using monochromator and power meter respectively. A >80% transmission long-pass filter for wavelength greater than 1700 nm was used in the power meter to eliminate the unabsorbed pump power. The length of YTDF was optimized to achieve maximum laser output power. To study the $Yb^{3+} \rightarrow Tm^{3+}$ energy transfer efficiency as well as the lasing efficiency with pump at 980 nm, several fibers with variations of Tm^{3+}/Yb^{3+} concentration and proportion in different host compositions were tested in this laser configuration.

4. Laser fiber characteristics

In order to investigate the laser performance in the NIR range, fibers with three types of core glass compositions, i.e. alumino-silicate, alumino-germano-silicate and alumino-phospho-silicate were fabricated using the modified chemical vapor deposition (MCVD) process coupled with solution doping technique. Additionally, fibers having Yb:Tm ratios ranging from 1:1 to 12:1, with variation of individual Tm^{3+} concentration (200 to 1800 ppm) were

considered in order to evaluate the influence of individual Tm^{3+}/Yb^{3+} concentrations and their proportions on lasing performance.

The absolute concentration and distribution profiles of the different dopants i.e. Tm, Yb, Al, Ge and P were estimated in the preform sections by Electron Probe Microanalysis (EPMA). The Numerical Aperture (NA) and core diameter of all fibers were maintained at ~0.16 and ~8.5 µm respectively while the outer diameter was 125 µm. The spectral attenuation of the fibers was measured in the range of 350-2000 nm by employing classical 'cut-back' method. The Tm^{3+} and Yb^{3+} concentrations were also deduced from the 785 nm ($^3H_6 \rightarrow {}^3H_4$) and 915 nm ($^2F_{7/2} \rightarrow {}^2F_{5/2}$) absorption peaks respectively and showed a good agreement with results obtained from the EPMA.

Ground State Absorption (GSA) cross-section was calculated from the spectral attenuation and is shown in Fig. 3 with resolved energy levels. The GSA cross-section spectra allowed the prediction of the emission cross-section of the fiber through the McCumber equation [9]. The calculated GSA and emission cross-sections of YTDF (YTF-A-10) in the wavelength range of 1400-2000 nm are shown in Fig. 4. Taking into account the absorption and emission cross section peak and the linewidth, the radiative lifetime of the $^3F_4$ level was also calculated using Fuchtbauer-Ladenburg (FL) equation [9].

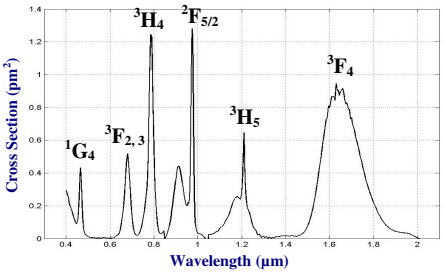

Fig. 3. GSA cross-section spectra of YTDF (YTF-A-10) with energy level designation for each absorption peak.

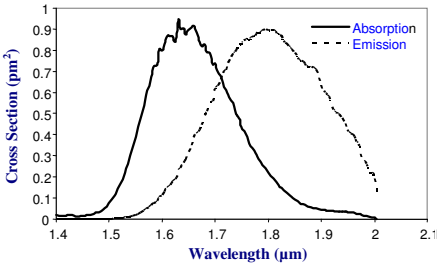

Fig. 4. Absorption and Emission cross sections of YTDF (YTF-A-10).

5. Results and discussion

Host composition: The host composition has an influence on the $Yb^{3+} \rightarrow Tm^{3+}$ energy transfer in the same way as it affects the radiative rates in individual rare earth (RE) ions. For Tm^{3+} in oxide glass, the energy gap between $^3F_4$ and $^3H_6$ levels (5800 cm^{-1}) is not high enough for efficient radiative transition ($^3F_4 \rightarrow {}^3H_6$) and thus the NIR emission is sensitive to the host composition. To study the effect of host composition on the lasing efficiency of YTDF laser, fibers with different core compositions were prepared with characteristics as presented in Table 1.

Table 1. Core composition and Tm, Yb, Al, Ge, P ion concentration of YTDF

Fiber ID	Host Composition	Yb ion (ppm)	Tm ion (ppm)	Yb: Tm	Al ion (ppm)	Ge ion (ppm)	P ion (ppm)	$^3F_4$ τ_{rad} (ms) calculated
YTF-A-1	Al_2O_3 + SiO_2	276	304	0.91	40200			6.4
YTF-G-2	Al_2O_3 + GeO_2 + SiO_2	263	270	0.97	9100	79400		7.1
YTF-P-3	Al_2O_3 + P_2O_5 + SiO_2	327	309	1.1	60000		59000	3.8

Figure 5 shows variation of laser output power at 1874 nm of the first two fibers with 980 nm pump power. The fibers with Alumino-silicate (YTF-A-1) and Alumino-germano-silicate

(YTF-G-2) host show very good laser output while phosphorus co-doped fiber (YTF-P-3) does not provide any detectable laser output power for 980 nm pumping. It produces only 15 µW powers at 1874 nm when pumped by 480 mW power at 980 nm; which indicates the population of Tm^{3+} ions in the $^3F_4$ level is not sufficient for lasing. The reason behind this appears to be the increase in phonon energy and reduction of lifetime due to the addition of P into the fiber core [10]. However, strong blue emission from the fiber (YTF-P-3) indicated energy transfer from Yb^{3+} to Tm^{3+}. Since the high lying $^1G_4$ level is metastable for Tm^{3+} in most of the glasses considered, the radiative transition from $^1G_4 \rightarrow {}^3H_6$ occurs when alumino-phospho-silicate fiber (YTF-P-3) was pumped with 980 nm, responsible for the blue emission. On the other hand, co-doping of Ge and Al reduces the local phonon energy of silica glass and consequently increases the lifetime of the Tm^{3+} energy levels. Ge is a four-coordinated network former, hence does not significantly alter the tetrahedral structure of the silica network. So it is expected that the effect of Ge is not very prominent in altering the lifetime [10]. Of the two fibers studied, the alumino-germano-silicate (YTF-G-2) host provides slightly better lasing performance as well as energy transfer compared to the alumino-silicate host fiber (YTF-A-1). It is noted that YTF-G-2 contains lower Al concentration than YTF-A-1. The influence of Al is in general beneficial to increase the lifetime (up to 3 times for $^3F_4$ and $^3H_4$ levels of Tm^{3+}) and thus the radiative transition of Tm^{3+} [1]. It should be noted that with the enhancement of the $^3F_4$ lifetime, there is also significant increase in the $^3H_4$ lifetime. For the configuration proposed in this work, a long $^3H_4$ lifetime will trigger the three step energy transfer ($^3H_4 \rightarrow {}^1G_4$), leading to more enhanced blue emission ($^1G_4 \rightarrow {}^3H_6$) arising due to up-conversion and radiative transition $^3H_4 \rightarrow {}^3H_6$, causing red emission. That will deteriorate the mechanism for population of the $^3F_4$ level from the $^3F_2$ level via non-radiative transition of the $^3H_4$ level. As the laser output in the NIR depends strongly on the population of the $^3F_4$ level, fiber YTF-G-2 provides a better laser output than does YTF-A-1.

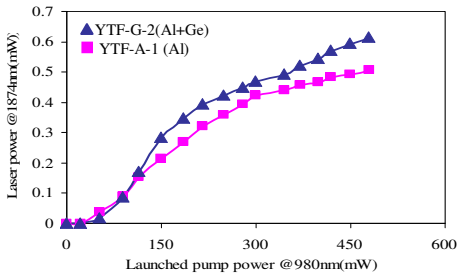

Fig. 5. Laser output power at 1874 nm against 980 nm pump for fibers with different host compositions.

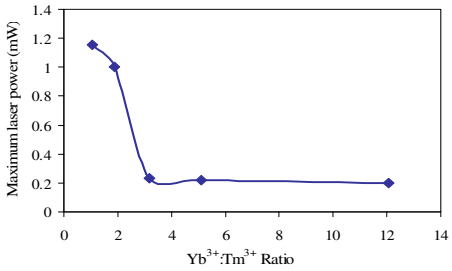

Fig. 6. Laser output power at 1874nm against 980nm pump (480 mW) for fibers with different Yb^{3+}:Tm^{3+}ratio.

The radiative lifetime of $^3F_4$ level, calculated from the measured absorption spectra (provided in Table 1), also shows that the lifetime of YTF-G-2 is slightly higher than that of YTF-A-1 whereas YTF-P-3 shows a very low value with respect to other two fibers. These calculated values are in good agreement with results shown in Fig. 5.

Proportion of Yb^{3+} and Tm^{3+}

In case of radiative energy transfer, i.e. one ion emitting a photon and being absorbed by another ion, the proportion of donor to acceptor ions plays an important role. In the Tm^{3+}/Yb^{3+} system, there are three possible energy transfer paths as discussed earlier and it is expected that an optimized Yb^{3+}:Tm^{3+} proportion exists which will allow one particular energy transfer path to be dominant. To study the effect of Yb^{3+}:Tm^{3+} proportion on the lasing performance in the NIR, the following fibers were considered as presented in Table 2.

Table 2. Proportion of Yb^{3+} and Tm^{3+} in YTDF

Fiber ID	Host Composition	Yb ion (ppm)	Tm ion (ppm)	Yb:Tm
YTF-A-4	$Al_2O_3 + SiO_2$	953	904	1.1
YTF-A-5	$Al_2O_3 + SiO_2$	1529	814	1.9
YTF-A-6	$Al_2O_3 + SiO_2$	2102	700	3.0
YTF-A-7	$Al_2O_3 + SiO_2$	4188	821	5.1
YTF-A-8	$Al_2O_3 + SiO_2$	9653	799	12.1

For each fiber the maximum output power at 1874 nm (for 480 mW pump power at 980 nm) was recorded. The variation of maximum laser output power with the Yb^{3+}:Tm^{3+} ratio is presented in Fig. 6. The result indicates that, laser output power of 1.5 mW was achieved when the Yb^{3+}:Tm^{3+} ratio is approximately equal to unity. It was also observed that laser output for the fibers with Yb^{3+}:Tm^{3+} ratio greater than 2 is initially high but within a very short time, power drops to a low value. On the other hand the blue and red emissions were very prominent. This indicates that in case of Yb^{3+}:Tm^{3+} ratio more than 2, each unexcited Tm^{3+} interacts with more than one excited Yb^{3+} thus supporting up-conversion through $Yb^{3+} \rightarrow Tm^{3+}$ energy transfer by reducing the laser power at 1874 nm. The result leads to the conclusion that a ratio close to unity is most suitable to populate the $^3F_4$ level of Tm^{3+} through energy transfer and consequently for the efficient lasing in the NIR range with minimum up-conversion loss.

Concentration of Tm^{3+}

Since the spatial electronic distribution is different for each energy level, the overlap integral as well as the energy transfer probability of each path depends on the concentration in a different way. To investigate this, for a set of Alumino-silicate host fibers with increasing Tm^{3+} concentration but having the Yb^{3+}:Tm^{3+} ratio approximately unity, the laser output powers were measured at 1874 nm with variation of 980 nm pump. It was noted that, with the increase of Tm^{3+} concentration, a shorter fiber length is required to obtain maximum laser output power. Details of fibers are in Table 3.

Table 3. Variation of Tm^{3+} concentration in Alumino-silicate fiber

Fiber ID	Yb ion (ppm)	Tm ion (ppm)	Optimized fiber length (m)
YTF-A-1	276	304	2.8
YTF-A-9	560	521	2.4
YTF-A-4	953	904	0.7
YTF-A-10	1061	1111	0.25
YTF-A-11	1806	1779	0.20

The laser output power at 1874 nm (with variations of 980 nm pump power) was monitored and is shown in Fig. 7(a). Power level of auxiliary ~1600 nm pump was fixed in a range of 40 to 60 mW depending upon the ground state Tm^{3+} concentration. For each fiber, the laser output power increases with the increase of pump power. Maximum laser output power (with 480 mW pump power at 980 nm) increases with the increase of the Tm^{3+} concentration up to a certain level and beyond that, the laser power decreases, as shown in Fig. 7(b).

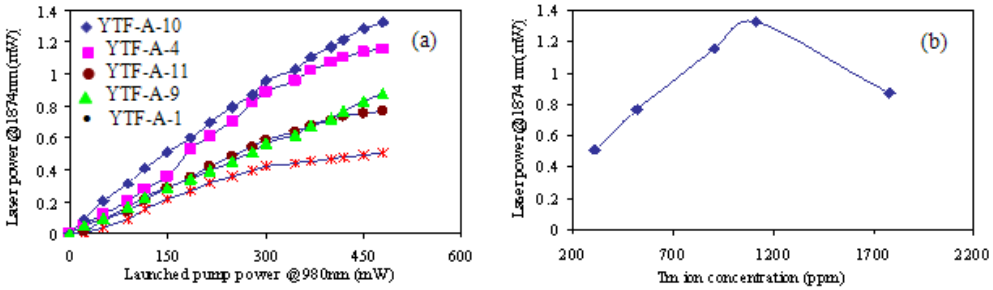

Fig. 7. (a) Laser output power at 1874 nm against 980 nm pump for fibers with different Tm3 + concentrations, with Yb^{3+}:Tm^{3+} ratio being 1 (b) The variation of the maximum laser output power with Tm^{3+} concentration.

These results indicate that the energy transfer rate of this process is proportional to the ground state Tm^{3+} concentration; however with the increase of Tm^{3+} concentration beyond 1200 ppm in a single mode fiber configuration, the laser performance deteriorates indicating the clustering of RE ions even for alumino-silicate glass host.

6. Conclusion

An optimized Tm^{3+}/Yb^{3+} single mode fiber laser, based on a resonant cavity formed by using Fiber Bragg Gratings, has been achieved with significant output power in the NIR range. A new pumping scheme comprising a ~1600 nm auxiliary pumping to support 980 nm primary pumping has been demonstrated. This facilitates effective population inversion between the relevant energy levels $^3F_4$ and $^3H_6$ of Tm^{3+} through promoting a strong energy transfer of $Yb^{3+} \rightarrow Tm^{3+}$. The experimental results demonstrate that alumino-silicate and alumino-germano-silicate with suitable amount of Al are good host materials for Tm^{3+}. An efficient energy transfer occurs for Yb^{3+}:Tm^{3+} proportion approximately equal to unity. The increment of ground state Tm^{3+} is found to be beneficial for better laser output.

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