A Tm^{3+}-Ho^{3+} Codoped Tellurite Glass Microsphere Laser in the 1.47 μm Wavelength Region

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In this work, a Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere laser in the 1.47 μm wavelength region is described. Using a traditional tapered microfiber-microsphere coupling method, multimode and single mode lasing around the wavelength of 1.47 μm is observed using an 802 nm laser diode as a pump source. This Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere laser can be used in near-infrared telecommunications, biomedical and astrophysical applications.

OCIS codes: *(140.3460) Lasers; (140.3945) Microcavities; (140.3510) Lasers, fiber.*

1.47 μm lasers have the potential to be widely applied in the fields of laser surgery and telecommunications. Traditional laser treatment for varicose veins targets the lining of the blood vessels, potentially resulting in blood coagulation, vein damage, bruising and swelling. Since the peak wavelength of λ~1.47 μm (near-infrared) lasers corresponds to strong water absorption in skin, it causes significantly less pain and hence no post-operative bruising or swelling [1, 2]. Tm^{3+}-doped glass has recently attracted interest as a suitable material for optical laser sources and amplifiers that operate in the telecommunication S-band (λ~1450-1510 nm) [3]. Indeed, Tm^{3+} is an appropriate rare earth ion for the generation of λ~1.47 μm laser output due to the $^3H_4 \rightarrow {}^3F_4$ transition [4]. However, there are two problems in realizing such an efficient 1.47 μm laser. Firstly, the lifetime of the $^3H_4$ level is shorter than that of the $^3F_4$ level, so the transition is sometimes described as self-terminating [5]. This problem can be solved through 1) adding trivalent rare-earth ions, such as Ho^{3+}, Nd^{3+}, or Tb^{3+} to reduce the population of the long-lived $^3F_4$ state [6-8] or 2) using a dual-wavelength pump method to depopulate the $^3F_4$ state by exciting thulium ions from the $^3F_4$ state to a higher energy level [9]. Secondly, the glass host material should have a very low phonon energy, as in silica and phosphate glasses laser and amplification are essentially impossible [10]. Tellurite and other heavy metal fluoride glasses have been considered as key-materials for thulium doped fiber amplifier operation in the S-band mainly due to their low phonon energies (~580 cm^{-1}). Tm^{3+}-doped glasses have been previously demonstrated for a broadband amplifier at λ~1.47 μm in telluride glasses [11], codoped with Ho^{3+} in ZBLYAN glasses and a Tm^{3+}-Nd^{3+} codoped fiber amplifier [8, 12]. A λ~1.5-μm-band thulium-doped microsphere laser originating from self-terminating transition has also been demonstrated [13].

In this paper a Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere laser at λ~1.47 μm is described and fully characterized. Ho^{3+} is codoped to Tm^{3+} to reduce the population of the long-lived Tm^{3+} $^3F_4$ state through a resonant energy transfer process. Whispering-gallery mode (WGM) optical microcavities have been chosen because they combine high quality factors (up to 10^{10}) and small mode volumes (of the order of 100 μm^3), thus significantly enhancing light matter interactions, resulting in excellent optical laser cavities with low threshold values and narrow linewidth outputs [14-18]. As a low phonon energy oxide glass, rare-earth elements doped tellurite glass has relatively small phonon relaxation rates and is therefore a good host material for microsphere lasers.

The Tm^{3+}-Ho^{3+} codoped tellurite glass samples ($72TeO_2$-$20ZnO$-$5.0Na_2CO_3$-$2.0Y_2O_3$-$0.8Ho_2O_3$-$0.2Tm_2O_3$) were prepared using a conventional melt-quenching method. 30 g of high-purity TeO_2 (99.99%), ZnO (99.99%), Na_2CO_3 (99.99%), Y_2O_3 (99.9%), Ho_2O_3 (99.99%) and Tm_2O_3 (99.99%) were mixed and melted in a corundum crucible at 900 °C for 30 minutes, then poured into preheated stainless-steel molds and annealed around the glass transition temperature (300 °C) for 3 hours. The Tm^{3+}-doped tellurite glass samples ($72TeO_2$-$20ZnO$-$5.0Na_2CO_3$-$2.8Y_2O_3$-$0.2Tm_2O_3$) were prepared in a similar manner. The resulting glasses were then cut and polished in readiness for measurement. To fabricate the gain microspheres, the Tm^{3+}-Ho^{3+} codoped tellurite glass fibers and Tm^{3+}-doped tellurite glasses fibers were drawn from the melting glass using a diamond tip, similar to the method described elsewhere [19]. The tellurite glass microspheres were made in the standard manner using a circular ZnSe-lens to focus a CO_2 laser beam onto a section of the tellurite glass fiber. A small weight attached to the bottom of the tellurite glass fiber upon heating facilitated the formation of a very thin tapered region, which acts as the stem of the microsphere. The CO_2 laser was then used to cut the fiber and the remaining glass as the tip was reheated. The surface tension of the molten tellurite glass at the fiber tip causes a spherical morphology under the effect of gravity when subjected to a high temperature. Using the described method, Tm^{3+}-Ho^{3+} codoped and Tm^{3+}-doped tellurite glass microspheres with diameters ranging from several micrometers to several hundred micrometers were fabricated. Figs 1 (a) and (b) show the microscope images of the Tm^{3+}-Ho^{3+} codoped tellurite glass fibers and microspheres.

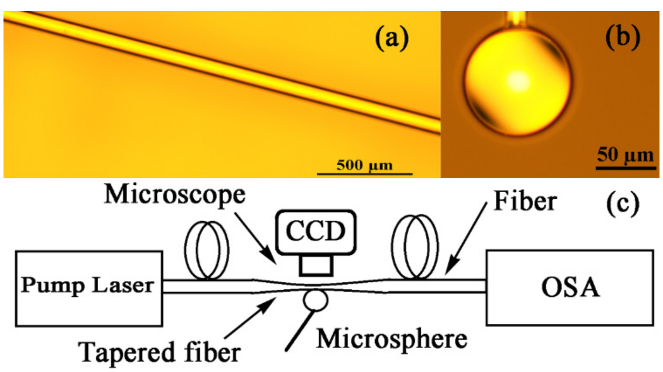

Fig. 1. Microscope images of (a) the Tm^{3+}-Ho^{3+} codoped tellurite glass fibers and (b) the Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere (c) Experimental setup.

The experimental setup for measuring the Tm^{3+}-Ho^{3+} codoped microsphere laser characteristics is shown in Fig. 1 (c). The tapered fiber used for light coupling was fabricated by heating a strand of 1060XP single mode fiber using a ceramic microheater (CMH-7-19, NTT-AT) and simultaneously stretching it at both ends. In this work, tapered silica fibers with diameters in the range 1.5 to 2.0 μm were used. Light from a λ~802 nm laser pump diode (LE-LS-808-200TFCS-LH, Leoptics, China) was launched into one end of the taper and then coupled into the microsphere. The transmitted spectrum was acquired and the output power of the laser was measured using an optical spectrum analyzer (OSA) (AQ-6375, Yokogawa, Japan). The coupling position between the taper and the microsphere was monitored from two orthogonal directions using two 20X microscope eyepieces attached to two charge-coupled device (CCD) cameras separately.

Fig. 2 (a) and (c) show the fluorescence spectra of Tm^{3+}-Ho^{3+} codoped and Tm^{3+}-doped tellurite glasses microspheres when excited by the λ~802 nm laser source. Because the pump laser has a weak emission at λ~1604 nm, the data at 1600-1605 nm has been removed. It is clear from Fig. 2 (b) and (d) that the lower level of Tm^{3+} is depopulated through the energy transfer process by codoping Tm^{3+} with Ho^{3+}. Tm^{3+} ions are excited to the $^3H_4$ energy level through the absorption of the λ~802 nm pump laser. The emission process originates from the Tm^{3+} $^3H_4 \rightarrow {}^3F_4$ transition, and the Tm^{3+} $^3F_4$ level was quenched by energy transfer to the matching Ho^{3+} $^5I_7$ level.

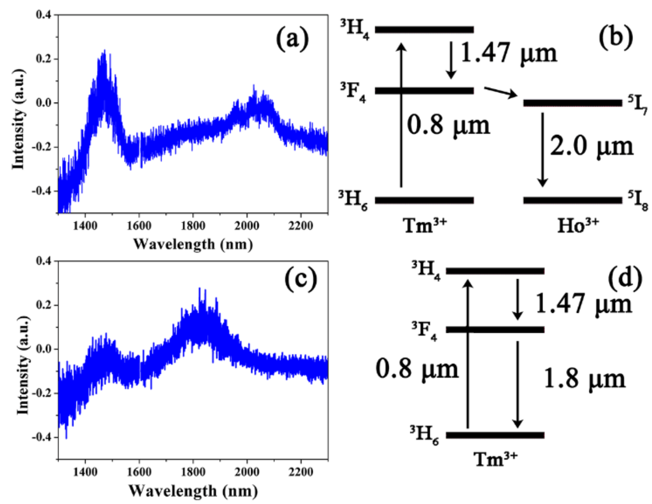

Fig. 2 (a). Fluorescence spectrum of Tm^{3+}-Ho^{3+} codoped tellurite glass microspheres excited at λ~802 nm and (b) related energy level diagram and energy transfer model. (c) Fluorescence spectrum of Tm^{3+}-doped tellurite glasses microspheres excited at λ~802 nm and (d) related energy level diagram and energy transfer model.

In Tm^{3+}-Ho^{3+} codoped and Tm^{3+}-doped tellurite glasses samples, the lifetime of Tm^{3+} $^3F_4$ level at λ~1.8 μm has been measured with a λ~0.8 μm pump, respectively. Fig. 3 show the fluorescence decay curves of Tm^{3+}-Ho^{3+} codoped and Tm^{3+}-doped tellurite glasses samples at λ~1.8 μm. As shown in the inset of Fig. 3, the lifetime of the 1.8 μm fluorescence is 2.32 ms in Tm^{3+}-doped tellurite glasses samples. Since the Tm^{3+} $^3F_4$ level was quenched by energy transfer to the matching Ho^{3+} $^5I_7$ level, the intensity at λ~1.8 μm is very weak in Tm^{3+}-Ho^{3+} codoped tellurite glass samples. In Tm^{3+}-Ho^{3+} codoped tellurite glass samples, the lifetime of Tm^{3+} the $^3F_4$ level is about 1.51 ms by the single-exponential curve fitting. Energy transfer efficiency (η) of the Tm^{3+} $^3F_4$ level to Ho^{3+} $^5I_7$ level can be estimated by the following formula: $\eta=1-(\tau/\tau_0)$, where τ and τ_0 are the lifetime of the sample Tm^{3+}-Ho^{3+} codoped and Tm^{3+}-doped [20]. After calculation, the energy transfer efficiency of the Tm^{3+} $^3F_4$ level to Ho^{3+} $^5I_7$ level is 34.9% in Tm^{3+}-Ho^{3+} codoped tellurite glasses sample.

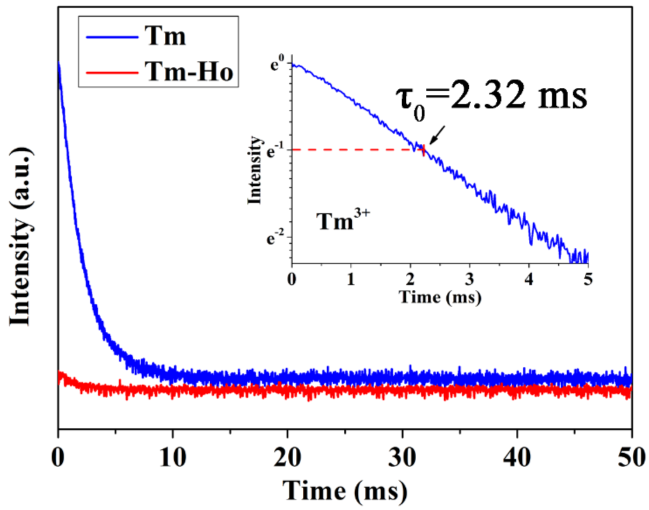

Fig. 3. Fluorescence decay curves of Tm^{3+}-Ho^{3+} codoped and Tm^{3+}-doped tellurite glass samples at 1.8 μm. Inset figure shows that the lifetime of Tm^{3+} at 1.8 μm is 2.32 ms in Tm^{3+}-doped tellurite glasses samples.

As the microsphere was aligned with the fiber taper, the pump laser light was coupled into the Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere and the resulting 1.47 μm emission from the microsphere was coupled out and transmitted through the fiber taper. As the pump power (i.e. the input power to the fiber taper) increased to 2.5 mW, characteristic multimode laser peaks were observed at 1.47 μm on the OSA with a spectral resolution of 0.05 nm (Fig. 4 (a)). The fundamental WGM easily absorbs more pump energy, hence it has a lower pump threshold power, and single mode laser output can be achieved using a lower pump power when the taper is contacted the microsphere equator [21, 22]. Changing the coupling position between the Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere and the silica fiber taper, a single mode lasing emission from the microsphere was observed and the resulting output spectrum is shown in Fig. 4 (b). The wavelength of the single mode laser peak is centered at λ~1494.9 nm, the peak power was measured as 46.0 nW and the linewidth was 0.06 nm when the pump power reached 2.8 mW. The output power of the microsphere laser as function of the pump power is shown in Fig. 4 (c). The threshold power for lasing in the case of the microsphere laser is less than 1.5 mW and the output power exhibits a linear relationship with the pump power above threshold. As much as 114 nW of output power was measured with the laser output remaining single mode. The output power did not saturate at any point in the experiment as the pump power was increased to 6.1 mW. Fig. 4 (d) shows the zoomed-in spectral output at λ~1.47 μm. The quality factor of the microsphere was measured to be 10^5 at λ~1.47 μm using the well-known formula Q = λ/FWHM, where FWHM is the full-width-at-half-maximum of a single-mode resonance peak. However, the FWHM of 0.0037 nm was obtained from the OSA spectrometer with a resolution of 0.05 nm, and hence the quality factor of the microsphere cannot be accurately calculated. The Q factor could be higher than 10^5 as this value is the maximum that could be determined due to the limited resolution imposed by the OSA used in this investigation.

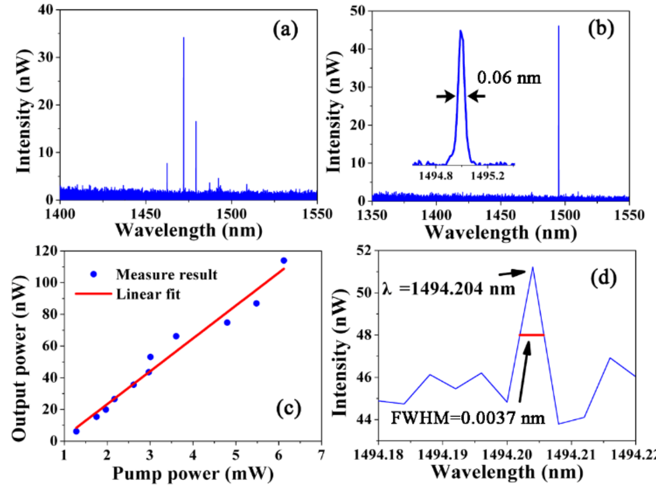

Fig. 4. (a) Laser emission spectra from the Tm^{3+}-Ho^{3+} codoped microsphere when the pump power was set to 2.5 mW (b) Single-mode laser emission spectrum from the Tm^{3+}-Ho^{3+} codoped microsphere at the pump power 2.8 mW. Inset: zoom-in of the laser peak. (c) Microsphere laser output power as a function of pump power. (d) Spectrum recorded around a WGMs observed when light is coupled into doped microsphere via the fiber taper coupler.

In conclusion, a Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere laser around 1.47 μm has been fabricated and experimentally demonstrated. Both the λ~802 nm pump light and the lasing emission were efficiently guided through a taper formed in standard silica single mode fiber. A single mode laser at λ~1494.9 nm was demonstrated. This Tm^{3+}-Ho^{3+} codoped tellurite glass microsphere laser could be useful in a number of applications, such as laser sources of integrated photonic circuits, near-infrared telecommunications, biomedical and astrophysical.

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