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Tm³⁺/Ho³⁺ codoped tellurite fiber laser

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Continuous-wave and *Q*-switched lasing from a Tm³⁺/Ho³⁺ codoped tellurite fiber is reported. An Yb³⁺/Er³⁺-doped silica fiber laser operating at 1.6 μm was used as an in-band pump source, exciting the Tm³⁺ ions into the ³F₄ level. Energy is then nonradiatively transferred to the upper laser level, the ⁵I₇ state of Ho³⁺. The laser transition is from the ⁵I₇ level to the ⁵I₈ level, and the resulting emission is at 2.1 μm . For continuous wave operation, the slope efficiency was 62% and the threshold 0.1 W; the maximum output demonstrated was 0.16 W. Mechanical *Q* switching resulted in a pulse of 0.65 μJ energy and 160 ns duration at a repetition rate of 19.4 kHz. © 2008 Optical Society of America

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Ho³⁺ lasers have numerous biomedical applications, including kidney stone fragmentation, treatment of enlarged prostates, general surgical procedures, and coronary angioplasty [1]. Ho³⁺ lasers are also well suited to range-finding and atmospheric monitoring and sensing applications because they emit within an atmospheric transparency window. Tellurite (TeO₂) glass has several properties that make it well suited as a host material for infrared lasing. Rare earths are highly soluble in it, allowing high doping levels to be achieved [2]. The low phonon energy of tellurite glass means that it is transparent much further into the infrared than either silica or germanate glass (up to $\sim 5 \mu\text{m}$) [3]. Several benefits are brought forth by its high refractive index (1.95–2.05): Fibers made from it can have a high numerical aperture (NA) and both absorption and emission cross sections are enhanced [4]. Tellurite glass is also more chemically, environmentally, and thermally stable than fluoride glass [5].

We recently reported [2] close to Stokes limited efficiency for an in-band pumped Tm³⁺-doped tellurite fiber laser emitting at 1.9 μm , establishing rare-earth-doped tellurite glass as a gain medium that can enable efficient infrared emission from fiber lasers. An in-band pumped Tm³⁺/Ho³⁺ codoped silica fiber laser has been previously reported [6]. However, in that case, only lasing at 1.9 μm from the ³F₄ → ³H₆ transition in Tm³⁺ was observed; no lasing transition was detected from the Ho³⁺ ions. Here we report both efficient cw and *Q*-switched emission from a Tm³⁺/Ho³⁺ codoped tellurite fiber laser pumped in-band at 1.6 μm . Emission is at 2.1 μm and is from the ⁵I₇ → ⁵I₈ transition in Ho³⁺. To our knowledge, this is the longest wavelength operation of a tellurite fiber laser yet reported and the first demonstration of pulsed operation.

The Tm³⁺/Ho³⁺ codoped tellurite fiber was fabricated using the same techniques as for the Tm³⁺-doped tellurite fiber described in [2]. The core composition was 80 TeO₂–10 ZnO–10 Na₂O

(mol %) doped with 1.5 wt. % Yb₂O₃, 1.0 wt. % Tm₂O₃, 1.0 wt. % Ho₂O₃, and the cladding had a 75 TeO₂–15 ZnO–10 Na₂O (mol. %) composition. (The Yb³⁺ ions were added with other experiments in mind, similar to those reported in [7]; they have no absorption at wavelengths longer than 1.1 μm and therefore are not thought to play an active role here.) The core and cladding diameters were 7.5 ± 1 and 125 μm , respectively, and the NA was 0.28. The background loss of the fiber was measured using the cut-back technique to be 1.2 dB m⁻¹ at 1476 nm. Figure 1 shows the absorption spectrum of a bulk sample of Yb³⁺/Tm³⁺/Ho³⁺-doped tellurite glass. The Tm³⁺ ion concentration of the bulk sample used is the same as in the doped fiber and is expected to have the same absorption coefficient as in the doped fiber around the pump wavelength.

Figure 1 shows that the pump wavelength of $\sim 1.6 \mu\text{m}$ is on the short wavelength tail of the Tm³⁺: ³H₆ → ³F₄ absorption band and has an absorption coefficient of 0.068 cm⁻¹. Despite this small pump absorption, the long path length in the fiber enables the pump light to be adequately absorbed by

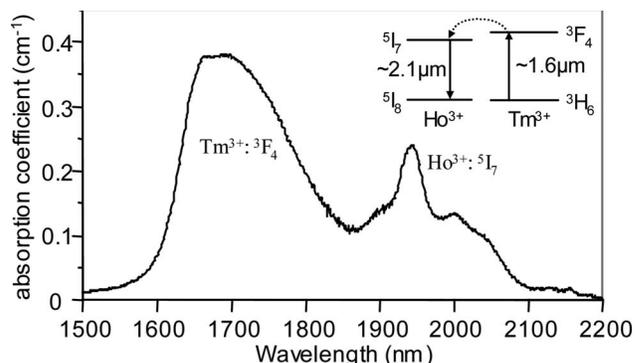


Fig. 1. Absorption coefficient spectrum for an Yb³⁺ (2.0 wt. %)/Tm³⁺ (1.0 wt. %)/Ho³⁺ (0.5 wt. %)-doped TZN bulk glass. The inset is the partial energy level diagram of Tm³⁺ and Ho³⁺ showing the bottom two energy levels and the associated pump and lasing transitions.

the ${}^3H_6 \rightarrow {}^3F_4$ transition in Tm^{3+} . Energy is then transferred to the 5I_7 level of Ho^{3+} , as shown in the inset in Fig. 1. The emission spectrum FWHM of a 0.2 wt. % Tm^{3+} -1.0 wt. % Ho^{3+} codoped bulk tellurite glass sample is ~ 140 nm [8], which provides the opportunity for a wide tuning range. Moreover, since it is a transition to the ground level, the wavelength can be tuned by altering the amount of ground-state reabsorption; for instance, increased fiber length and output coupler reflectivity can be used to produce longer lasing wavelengths [9].

Continuous-wave lasing was achieved with the same experimental arrangement as shown in Fig. 1 of [3], with the Tm^{3+}/Ho^{3+} codoped tellurite fiber used instead of the Tm^{3+} singly doped tellurite fiber. The pump source for the tellurite fiber laser was a Er^{3+}/Yb^{3+} -doped silica fiber (INO, Canada) laser operating at multiple lasing peaks within the range of ~ 1570 – 1610 nm; the silica fiber laser was pumped by a 970 nm laser diode. The $1.6 \mu m$ output was collimated and focused into the tellurite fiber. The launched pump power was estimated by measuring the power launched into a transmission fiber with a core diameter and NA similar to the doped tellurite fiber. A high-reflectance pump-end mirror and either Fresnel reflection from the cleaved fiber end or a partially reflecting mirror comprised the optical cavity for light at a wavelength of $2.1 \mu m$. The output power of the tellurite fiber laser was measured using a Moletron PM30 thermopile power meter; a germanium filter was used between the fiber and the power meter to eliminate residual pump light. The spectrum was measured using an extended infrared laser spectrometer (APE, Germany). The lasing wavelength for this fiber laser was observed to range from 2051 to 2096 nm for fiber lengths in the range of 9.5–92 cm and output end reflectances from 11% (Fresnel reflection) to 80%.

Figure 2 shows the laser output power with respect to the launched pump power for a ~ 78 cm long fiber with output end reflectances of 11%, 40%, and 80%. The highest slope efficiency, 62%, and lowest threshold, 0.1 W, were achieved for an output end reflectance of 11%, i.e., Fresnel reflection from the fiber end; the inset in Fig. 2 shows a typical output spectrum for this cavity. The maximum output power achieved was 0.16 W. Increasing the reflectance of the output end of the cavity reduced the slope efficiency. The threshold increased to 0.15 W when output coupling was via a mirror rather than by Fresnel reflection at the fiber end; this effect was attributed to losses at the fiber-mirror interface. A slope efficiency of 62% is very close to the Stokes efficiency limit of 76% for this system, and demonstrates the efficiency of this in-band pumping scheme. The fraction of the Stokes limit achieved here, 82%, is only slightly lower than the 90% obtained for the in-band pumped Tm^{3+} -doped tellurite laser [3], indicating that the energy transfer process from Tm^{3+} to Ho^{3+} ions is efficient.

Figure 3 shows the effect of fiber length on the slope efficiency and threshold (both with respect to

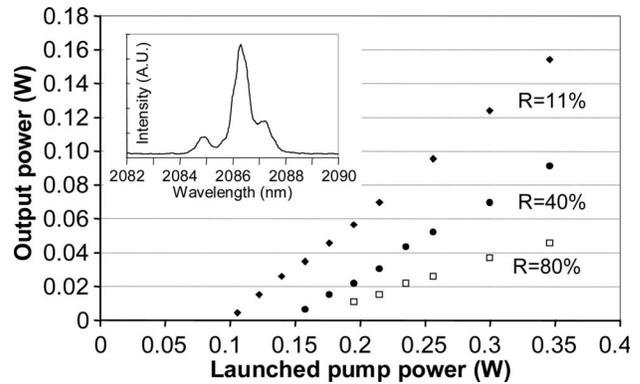


Fig. 2. Output power of the $2.1 \mu m$ laser with respect to launched pump power for a 76 cm long fiber and output end reflectances of 11%, 40%, and 80%. The inset shows a typical laser spectrum obtained with output end reflectance of 11%.

the launched pump power) for the cavity with 11% output end reflectance. As can be seen from Fig. 3, the laser performance was largely unchanged for the fiber lengths between 40 and 76 cm. Lasing was also achieved without any external mirrors, i.e., in an optical cavity formed only from 11% Fresnel reflectance from each fiber end. In this case, a slope efficiency of 30% and a threshold of 0.11 W were measured for a 35 cm long fiber. However, output power was measured from only one end; thus if equal emission from both ends is assumed, then the actual slope efficiency is similar to that seen with the highly reflecting pump end mirror in place.

The Tm^{3+}/Ho^{3+} -doped tellurite fiber was actively Q switched by a mechanical chopper as shown in Fig. 4. The chopping disk was placed close to the surface of the highly reflecting end mirror, where the minimum beam waist exists, to reduce the rise and fall times of the Q switching. The maximum chopping frequency was 19.4 kHz.

Q -switched emission was observed at the same rate as the cavity modulation as shown in Fig. 5. However, observation on a shorter time scale revealed that each cavity opening resulted in three Q -switched pulses (see the inset in Fig. 5). For a launched pump power of 170 mW, an average output power of 26 mW was measured, which corresponds to a total pulse energy per cavity opening of $1.3 \mu J$. The

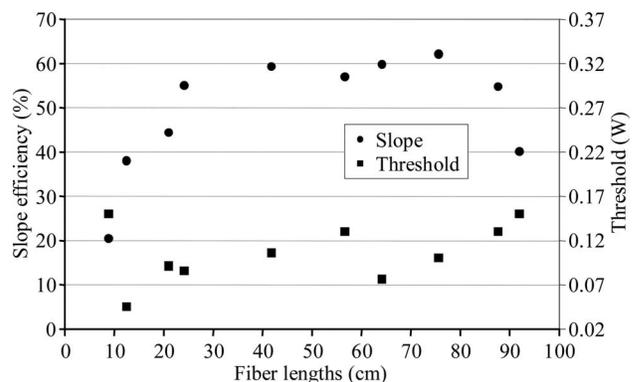


Fig. 3. Effect of fiber length on slope efficiency and threshold for an output end reflectance of 11%.

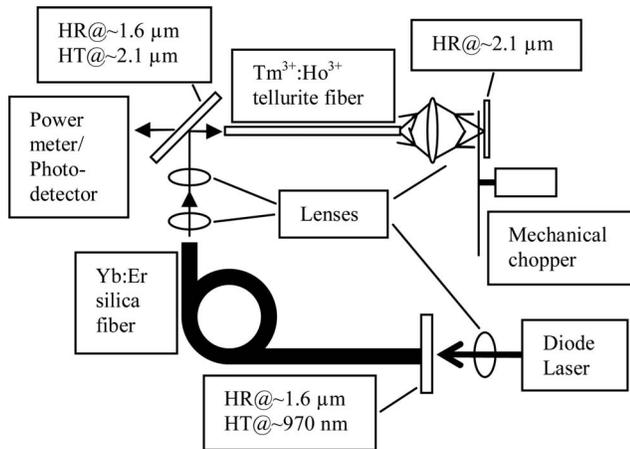


Fig. 4. Schematic of the experimental setup used for the Q -switched $\text{Tm}^{3+}/\text{Ho}^{3+}$ -doped tellurite fiber laser. Tellurite fiber length is equal to 79 cm (HR, high reflectance; HT, high transmittance).

main pulse energy was calculated to be $0.65 \mu\text{J}$ with a measured duration of ~ 160 ns. This multiple pulse operation is attributed to the slow Q switching of the mechanical chopper [10].

Until now most of the work on fiber lasers emitting at $2.1 \mu\text{m}$ has been based on Ho^{3+} -doped silica glass and was described in a recent review [11]. Of particular note is the demonstration by Jackson *et al.* [11] of 83 W of output power from a diode-pumped $\text{Tm}^{3+}/\text{Ho}^{3+}$ co-doped silica fiber [12]. However, even though good slope efficiencies have been realized, up

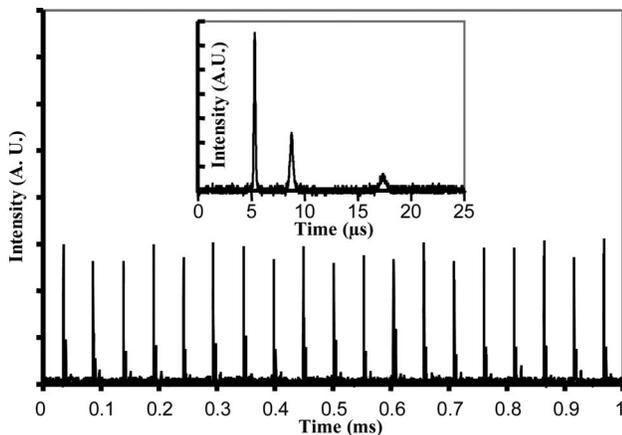


Fig. 5. Photodetector output showing Q -switched emission at the same rate as the mechanical modulation. Inset, close-up of the typical emission from a single cavity opening.

to 42% [12], the pump power required to reach threshold for Ho^{3+} -silica fiber lasers, whether singly doped or codoped with Yb^{3+} or Tm^{3+} , has typically been a few watts [11]. These high threshold levels have been attributed to significant background losses in silica at $2.1 \mu\text{m}$, which are exacerbated by the long fiber lengths necessitated by the weak pump absorption of the dopants in silica. In contrast, the $\text{Tm}^{3+}/\text{Ho}^{3+}$ codoped tellurite fiber laser demonstrated here has a threshold that is an order of magnitude smaller as well as a slope efficiency that is 50% greater. Codoping with Tm^{3+} enables direct pumping by diodes emitting at $0.8 \mu\text{m}$, as has been demonstrated in silica [11]. Hence, the low threshold demonstrated here means that a compact and efficient source of $2.1 \mu\text{m}$ laser radiation based on a $\text{Tm}^{3+}/\text{Ho}^{3+}$ codoped tellurite fiber laser pumped by a single low-power diode may be anticipated.

In summary, we have demonstrated efficient $2.1 \mu\text{m}$ emission from an in-band pumped $\text{Tm}^{3+}/\text{Ho}^{3+}$ codoped tellurite fiber laser, in both cw and Q -switched modes. We believe this is the longest output wavelength yet achieved with a tellurite fiber laser. The highest slope efficiency observed is more than 80% of the Stokes limit, showing that energy transfer from Tm^{3+} to Ho^{3+} can be efficient in fiber lasers.

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