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Efficient ~2 μm Tm^{3+}-doped tellurite fiber laser

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Laser emission in the range of 1.88–1.99 μm from a Tm^{3+}-doped tellurite fiber is demonstrated when pumped with a diode-pumped Er^{3+}/Yb^{3+}-doped silica fiber laser operating at 1.57–1.61 μm. This pump source excites the Tm^{3+} ions directly into the $^3F_4$ upper laser level and yields an output power of 280 mW with a slope efficiency of 76% in a 99%–12% laser cavity arrangement and a 32 cm long fiber. This result is very close to the Stokes efficiency limit of ~80%. This is, to the authors' knowledge, the first demonstration of high efficiency lasing in a tellurite fiber at wavelengths longer than 1.56 μm. © 2008 Optical Society of America

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Tellurite (TeO_2) glass has several properties that overcome some of the drawbacks of other common fiber laser host glasses, such as silicates, fluorides, and germanates, making this material a potentially very promising candidate for new near- and mid-infrared fiber laser sources. Up until now, lasing at ~2 μm has been achieved in silicate, fluoride, and germanate fibers, but not in a tellurite fiber. We now demonstrate for the first time an efficient medium power ~2 μm tellurite fiber laser.

Tellurite glass has a high rare-earth ion solubility [1], a low phonon energy of 780 cm^{-1} compared to 1100 cm^{-1} in silica, and 880 cm^{-1} in germanate glasses, allowing transmission further into the infrared (up to ~5 μm), high refractive index (~1.95–2.05) and therefore high absorption and emission cross sections [2], and a long upper laser level lifetime in Tm^{3+}. Tellurite glass is also more chemically, environmentally, and thermally stable than fluoride glass, making it an attractive option for reliable fiber device manufacturing [3].

Lasing in a tellurite fiber was first reported in 1994 at 1.061 μm in an Nd^{3+}-doped fiber [4] and again in 1997 at 1.560 μm in an Er^{3+}-doped fiber [5]. Both of these tellurite fiber lasers were of a single-mode design constructed using a 12%–12% cavity from Fresnel reflections from the bare fiber ends. The output powers of these lasers were low (<10 mW), even when taking into account equal laser emission from each end of the fiber, and in the case of the Er^{3+}-doped fiber, the slope efficiency with respect to launched pump power was only 1.3%. Very little work has been reported in the area of tellurite fiber lasers at wavelengths beyond 1560 nm, where there is a high demand for new compact laser systems with medium power for applications, such as chemical and remote sensing, medicine, atmospheric monitoring, and eye-safe lidar. A 1.57 μm Er^{3+}-doped silica fiber laser was previously been used to pump Tm^{3+} ions in a silica fiber to produce lasing at 1.9 μm. In this case the 1.57 μm pump was very close to the absorption peak of the Tm^{3+}: $^3H_6 \rightarrow {}^3F_4$ transition, and a slope efficiency of 71% was achieved [6]. The low phonon energy of tellurite glass compared to silicate hosts is manifested by prolonged lifetimes of the $^3F_4$ level in tellurite, which is 2.4 ms compared with 630 μs in silicates, and suggests that a laser device based on a tellurite fiber should have a lower laser threshold and higher slope efficiency for a ~2 μm laser.

Laser experiments with this fiber initially used a 1088 nm Yb^{3+}-doped silica fiber laser to pump the Tm^{3+} ions into the $^3H_5$ level. Because of the small Tm^{3+} absorption at this wavelength, the fiber was codoped with Yb^{3+} to enhance the pump absorption and act as a sensitizer. Lasing was achieved with this arrangement, but the slope efficiency was limited to ~10% due to the strong pump excited-state absorption (ESA) generating intense upconversion emission at 480 and 800 nm [7]. This poor laser performance inspired the use of the ~1.6 μm pump, where there is virtually no pump ESA in Tm^{3+}, and despite the Yb^{3+} ions having no active role in this laser system except effectively acting as an impurity, the improvement in laser performance was dramatic.

In this Letter we report what is to our knowledge the first high efficiency Tm^{3+}-doped tellurite fiber laser operating at close to 2 μm from the Tm^{3+}: $^3F_4 \rightarrow {}^3H_6$ transition, pumped with an Er^{3+}/Yb^{3+}-doped double-clad silica fiber laser operating at 1.57–1.61 μm. Combined with the bandwidth of emission and long lifetime of the metastable state, the Tm^{3+}-doped tellurite fibers are genuine contenders for efficient, tunable, relatively high output power (>1 W) in near and mid-infrared lasers.

The tellurite fiber was fabricated in house using the suction method to produce the preform, which was then extruded into a rod and drawn into the fiber using the rod-in-tube method. The core of the fiber had an 80 TeO_2–10 ZnO–10 Na_2O mol.% composition and was doped with 1.0 wt.% Tm_2O_3 and 1.5 wt.% Yb_2O_3, and the cladding had a 75 TeO_2–15 ZnO–10 Na_2O mol.% composition. The core and cladding di-

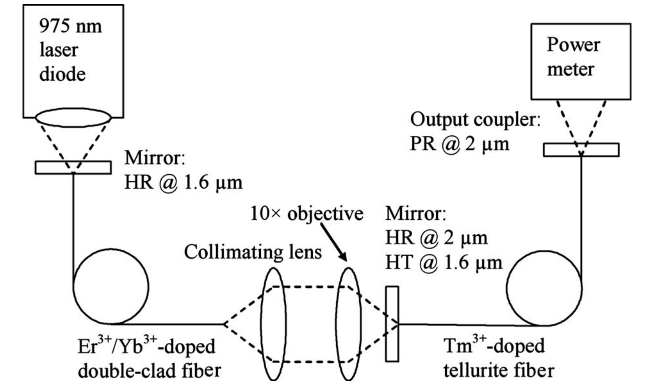

Fig. 1. Schematic diagram of the experimental setup used for the Tm^{3+}-doped tellurite fiber laser.

ameters were 13 and 125 μm, respectively, the NA was 0.29, and the fiber was uncoated. The background loss of the fiber was measured to be 2.6 dB/m at 633 nm using the cut-back method, and $\sim$1 and 2 dB/m at 1.4 and 1.7 μm, respectively, using Fourier transform infrared (FTIR) spectroscopy.

The tellurite fiber laser was pumped using an Er^{3+}/Yb^{3+}-doped silica fiber (INO, Canada) operating at 1568–1610 nm, which was in turn pumped with a high power 975 nm laser diode (Fisba Optik, Switzerland). The Er^{3+}/Yb^{3+}-doped silica fiber was of a double-clad design with a 16 μm core diameter and a 200 μm inner cladding between parallel planes of a hexagonal geometry. The Er^{3+}/Yb^{3+} fiber laser cavity was constructed using a high reflectance mirror at the pump end and $\sim$4% Fresnel reflection at the output end, and the output was collimated and focused into the tellurite fiber with a launch efficiency of $\sim$28%. A high reflectance pump-end mirror and output couplers of varying reflectivity made up the $\sim$2 μm tellurite fiber laser cavity (Fig. 1). The output power of the tellurite fiber laser was measured using a power meter, and the spectrum was measured using an extended-IR laser spectrometer (APE, Germany). A germanium filter was used between the fiber and the power meter, which attenuates virtually all of the $\sim$1.6 μm pump light.

Figure 2 shows the absorption and emission cross sections of Tm^{3+} doped into tellurite glass. The absorption spectrum was measured using a Perkin–Elmer Lambda 19 spectrometer, and the emission cross section spectrum was determined using the McCumber theory. The absorption cross section at the pump wavelength of 1.61 μm is 8×10^{-22} cm^2, which is on the tail of the Tm^{3+}: $^3H_6\rightarrow{}^3H_6$ absorption band. Despite this small pump absorption, the nature of a fiber laser provides a long path length, which enables the pump light to be adequately absorbed to produce sufficient population inversion for lasing. The inset in Fig. 2 shows the partial energy level diagram of Tm^{3+} showing the 1.61 μm pumping scheme.

The $^3F_4\rightarrow{}^3H_6$ transition of Tm^{3+} has one of the broadest emission peaks of the rare-earth ions and is $\sim$200 nm FWHM in this glass composition [7]. This provides the opportunity for a wide tuning range, and due to the fact that this is a bottom level transition,

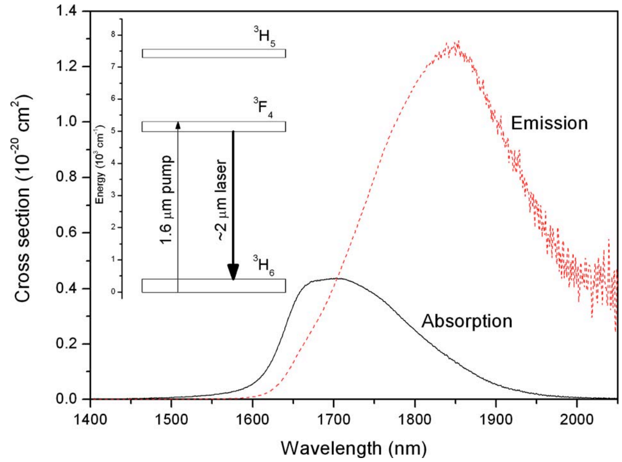

Fig. 2. (Color online) Absorption and emission cross sections of the Tm^{3+}: $^3H_6\rightarrow{}^3F_4$ transition when doped into tellurite glass. The inset is the partial energy level diagram of Tm^{3+} showing the bottom three energy levels and the pumping scheme.

the wavelength can be tuned by altering the amount of ground state reabsorption, with increased fiber length and output coupler reflectivity resulting in longer lasing wavelengths [8]. The lasing wavelength for this fiber laser was observed to range from 1879 to 1994 nm with lengths in the range of 9–60 cm, and output coupler reflectivity from 12% (Fresnel reflection) to 90%.

Figure 3 shows the $\sim$2 μm laser output power with respect to the launched pump power for a 32 cm long fiber with 99%–12% and 99%–50% cavities. The highest achieved slope efficiency of 76% was for the 99%–12% cavity, with a reduced slope efficiency of 60% for the 99%–50% cavity, and a laser threshold of $\sim$0.16 W of launched pump power. The inset in Fig. 3 shows a typical laser spectrum from the 32 cm Tm^{3+}-doped tellurite fiber with a 99%–12% cavity. The maximum slope efficiency of 76% is very close to the Stokes efficiency limit of $\sim$82% due to the very efficient nature of this in-band pumping scheme. An

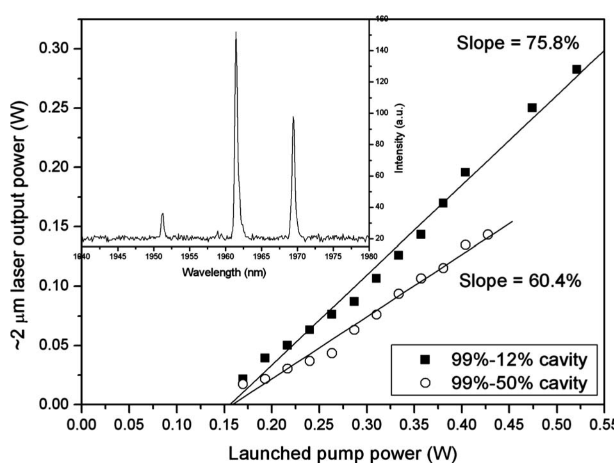

Fig. 3. Output power of $\sim$2 μm laser with respect to launched pump power for a 32 cm long fiber with 99%–12% and 99%–50% cavities. The inset graph shows a typical laser spectrum from a 32 cm long fiber and a 99%–12% cavity.

output power of 280 mW was achieved, which is the highest so far for a tellurite fiber laser.

Figure 4 shows the effect of the fiber length on the slope efficiency and threshold with respect to the launched pump power. The graph shows that the optimum fiber length for this system is ~32 cm with the slope efficiency reaching a maximum of 76%, and that the laser threshold generally increases in longer fibers owing to increasing reabsorption loss. For these measurements, 12% Fresnel reflection at the output end was used because higher reflectivity output couplers caused a reduction in the slope efficiency. However, the increasing output coupler reflectivity does cause a reduction in the threshold, because with the greater feedback of signal light lower pump powers are required to reach the lasing condition.

It was possible to achieve lasing without using any mirrors to construct the cavity and therefore relying on just 12%–12% Fresnel reflection from both bare fiber faces. This arrangement has the advantage of being more stable and easier to optimize, and if equal laser emission is assumed from each end of the fiber, then doubling the power measured from the output end should give a similar slope efficiency as from the output end of a 99%–12% cavity. This comparison was made and has been included in Fig. 4. The hollow squares are for the 99%–12% cavity, the solid dots are for the 12%–12% cavity with equal laser emission assumed from each end of the fiber, and there is a good agreement between these two sets of data. The inclusion of mirrors in the laser setup can make finding the optimum alignment difficult and unstable due to the fact that the fiber end is in contact with the mirror. The fact that the data with and without the mirror match well suggests that the 99%–12% results were well optimized. The threshold values are for the 99%–12% cavity lasers, as the threshold was generally slightly lower than for the 12%–12% cavity.

The shortest fiber tested during this experiment was 9 cm, in which lasing readily occurred. The amount of unabsorbed pump light was quite high for short fibers, but the large rare-earth ion solubility of tellurite glass would allow very short fibers to have a high pump absorption. This opens up the possibility of ultracompact fiber lasers, which are of great interest for such areas as photonic integration. Ultra compact Tm^{3+}-doped fiber lasers (2–4 cm) have recently been demonstrated in a highly doped germanate fiber with output powers up to 20 mW under 808 nm pumping [9]; however, the lower phonon energy of tellurite glass compared to germanates [2] could potentially lead to improved performance.

In conclusion, we have demonstrated for the first time, to our knowledge, a highly efficient Tm^{3+}-doped tellurite fiber laser pumped with a 1.61 μm Er^{3+}/Yb^{3+}-doped silica fiber laser. The tellurite fiber laser had a wide tuning range of 1.88–1.99 μm, which was achieved by altering the fiber length and output coupler reflectivity. The maximum slope efficiency achieved for this laser was 76% with respect to the launched pump power from a 32 cm long fiber and a laser cavity constructed using a high reflectivity mirror at the pump end and 12% Fresnel reflection at the output end. We have also demonstrated the highest output power for a tellurite fiber laser of 280 mW.

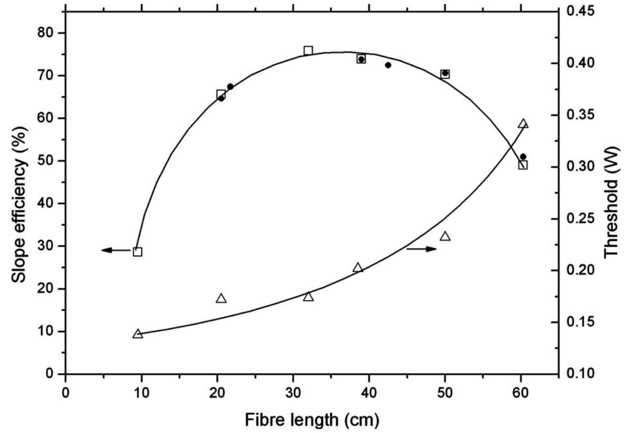

Fig. 4. Effect of the fiber length on the slope efficiency and threshold with respect to the launched pump power. The hollow squares are measured using a 99%–12% cavity, and the solid dots are measured from one end of a 12%–12% cavity and doubled to assume equal emission from both fiber ends.

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