Compact broadband amplified spontaneous emission in Tm^{3+}-doped tungsten tellurite glass double-cladding single-mode fiber

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Abstract: We reported the ~2 μm amplified spontaneous emission (ASE) performance of highly Tm^{3+}-doped (3.76×10^{20} ions/cm^3) tungsten tellurite single-mode fibers. The double-cladding fiber was pumped by a commercial 792 nm laser diode without any reflectors. Broadband ASE spectra with the bandwidth (FWHM) varying from ~45 nm to ~140 nm were achieved in a fiber length of 34 cm. The maximum output power was ~34 mW, with a slope efficiency of 4.8%. The ASE beam quality factor (M^2) was 1.8. The dependence of output power, ASE mean wavelength, and bandwidth on the launched pump power and fiber length were discussed in detail.

OCIS codes: (140.6630) Superradiance, superfluorescence; (140.3070) Infrared and far-infrared lasers; (160.3380) Laser materials; (060.2430) Fibers, single-mode; (140.3480) Lasers, diode-pumped.

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#181964 - $15.00 USD Received 19 Dec 2012; revised 20 Mar 2013; accepted 29 Mar 2013; published 3 May 2013

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1. Introduction

Superfluorescent fiber sources (SFS's) from the process of amplified spontaneous emission (ASE) in rare-earth-doped fibers characterized by high power, high brightness, excellent spatial coherence, short coherence length, and broadband spectral emission have attracted a great deal of attention [1–6]. Superfluorescence at ~1.5 μm and ~1 μm has been widely studied due to its important telecommunication window and the high pump conversion efficiency, respectively [1–4]. Moreover, ~2 μm fiber source plays an important role in environmental and biomedical field, and the wideband ~2 μm SFS is of interest for many applications such as spectroscopy, fiber-optic gyroscopes, fiber sensors [7], high-resolution optical coherence tomographic imaging [8] and optical component testing [9] (e.g. fiber gratings and wavelength-division multiplexing systems).

Up to now, the broadband two-micron fiber source has been achieved in Tm^{3+}-doped and Tm^{3+}-Ho^{3+} co-doped fibers [10]. A superfluorescent source in a Tm-doped fiber near 2 μm was first demonstrated in 1994 with a full width at half-maximum (FWHM) of 77 nm at output power of ~1.2 mW and a slope efficiency of ~0.3% when pumped with a Ti:sapphire laser at 815 nm [11]. A broad ASE FWHM of ~92 nm was reported with an average power of 80 mW in a 5-m-long Tm^{3+}-doped silicate fiber pumped with a 798 nm laser diode [12]. So far, the published highest output power of ~2 μm ASE is about 11 W with a FWHM of 36 nm and a slope efficiency of 38% from a 790 nm laser diode pumped Tm^{3+}-doped silica fiber [5]. ASE broadband light around 2 μm has also been demonstrated in Tm-doped and Tm-Ho co-doped fluoride fibers with fiber length of 6 m and 4.5m and with output power of 2.3 mW and 20 mW respectively [6,10]. To date, superfluorescent sources near 2 μm have been achieved in silica, silicate, and fluoride fibers with a commercial 0.8 μm laser diode or in-band pumped at 1.6 μm [5,6,10,11], but there is no investigation on 2 μm ASE in tellurite glass fiber. It is widely acknowledged that tellurite glass is a promising ~2 μm fiber laser host material [13–15]. In contrast to the common fiber host glasses, multiple component tellurite (TeO_2) glass exhibits significant advantages such as a low phonon energy of 780 cm^{-1} that results in low non-radiative rates, high radiative rates, and wide transmission window (0.4-5 μm); high rare-earth solubility enables very compact fiber component to be realized [14,15]; high nonlinearity provides nonlinear optical applications like supercontinuum generation [16]. Tellurite glass also has a large refractive index (~2.1) which enhances both the absorption and emission cross sections, and with its broad emission spectra it is good for obtaining efficient signal amplification [17]. Thus far, tellurite has been applied to fiber laser, fiber amplifier, nonlinear fiber material etc.

In this paper, we reported for the first time, to the best of our knowledge, a broadband ~2 μm ASE from thulium-doped tellurite glass fiber pumped by a 792 nm laser diode. With a

#181964 - $15.00 USD Received 19 Dec 2012; revised 20 Mar 2013; accepted 29 Mar 2013; published 3 May 2013

fiber length of 34 cm and single-ended operating configuration, the FWHM of ASE spectrum was ~140 nm at low output power of 3 mW and 45 nm at the highest output power of ~34 mW. The slope efficiency was 4.8%, and the beam quality factor (M^2) was 1.8. The wavelength range of ASE can be tuned from ~1800 to ~1925 nm by modifying the fiber length. The dependence of output power, ASE mean wavelength, and bandwidth (FWHM) on pump power and fiber length were presented in detail.

2. Experiments and results

The experimental setup is shown in Fig. 1. A modified single-ended output configuration is used for our fiber ASE source. The Tm^{3+}-doped tungsten tellurite single-mode fiber was prepared by the rod-in-tube method. The fiber had a ~8 µm core diameter with a numerical aperture (NA) of 0.14, and a ~60 µm inner cladding diameter with a NA of 0.29. The diameter of the fiber was ~250 µm. The single-mode fiber with a small V parameter can provide good beam quality [15]. The core of the fiber was uniformly doped with 1 mol. % Tm_2O_3 (Tm^{3+}: 3.76×10^{20} ions/cm^3). The high doping concentration of thulium ions provides sufficient gain in a short active fiber length, and a short fiber length can be favorable for avoiding optical nonlinearity. Its propagation loss at 1310 nm was ~2.5 dB/m measured by using the cutback method. A multimode laser diode operating at 792 nm was collimated and then focused into the inner cladding of double-cladding fiber efficiently by a 10x microscope objective lens. Considering the system complexity, the single-ended output configuration is a preferred choice. In the cavity arrangement of our Tm^{3+}-doped fiber, the pumping end of the fiber was perpendicularly cleaved and the output end was angle-cleaved at about 8° to suppress resonant oscillations as a result of Fresnel back reflections from a high index difference between the interfaces. With low feedback reflectivities at both ends of the fiber while the reflectivity of output end is much less than pumping end, most of ASE power can be emitted from one end [4,5], and the lasing threshold is higher than that of standard single-ended output configuration (i.e. a fiber with a high reflectivity of one end and a low feedback of the other end). The side view of the angle-cleaved tungsten tellurite fiber tip was also captured. A long-pass filter was placed before the power meter and spectrometer to attenuate unabsorbed pump light from the angle-cleaved fiber end in spectral and power measurements. The ~2 µm ASE spectrum of the fiber was measured using a StellarNet RED-Wave NIRx spectrometer with an optical resolution (RES) of 1 nm. The beam quality factor was measured by using Thorlabs BP109-IR2 beam profiler.

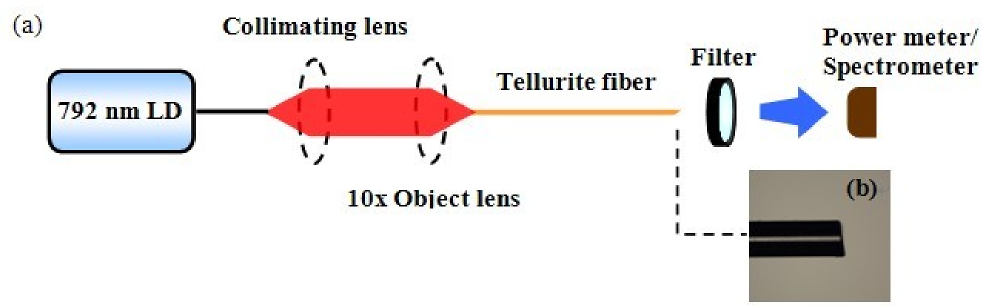

Fig. 1. (a) Schematic diagram of the Tm^{3+}-doped tungsten tellurite fiber ASE source using the pump excitation at 792 nm. (b) The side view of angle-cleaved tungsten tellurite fiber end with a cleaved angle of ~8°. LD: laser diode.

Figure 2(a) shows the fluorescence of Tm^{3+}-doped tungsten tellurite fiber, which has a FWHM of more than 220 nm spanning from ~1650 nm to ~2050 nm, and the central wavelength is around 1840 nm. Below the laser threshold, when the pump power is strong enough to stimulate the population inversion in fiber medium, the fluorescence (spontaneous emission) can be amplified to be ASE propagating along the fiber axis, but there is no

#181964 - $15.00 USD Received 19 Dec 2012; revised 20 Mar 2013; accepted 29 Mar 2013; published 3 May 2013

significant "threshold" between the fluorescence and ASE processes. It can be clearly observed that the bandwidth of ASE spectra is much smaller than that of fluorescence, and with increase of the output power, it is obviously reduced owing to the spectral narrowing effect especially in this high gain fiber [18]. The intensity of ASE is exponentially related to the power amplification coefficient with gain unsaturation [19], and the power amplification coefficient is proportional to frequency so that the amplification at the center of ASE will be much higher than the wings [17,18]. With fiber length of 34 cm, at high output power of 26 mW, ASE has a FWHM of 58 nm, which is smaller than the results reported by Jiang et al in silicate fiber and Sheng et al. in silica fiber [5,12], but at low output power of 5 mW, the FWHM is about 80 nm, which is comparable to them, and better than that of fluoride fiber [6,10].

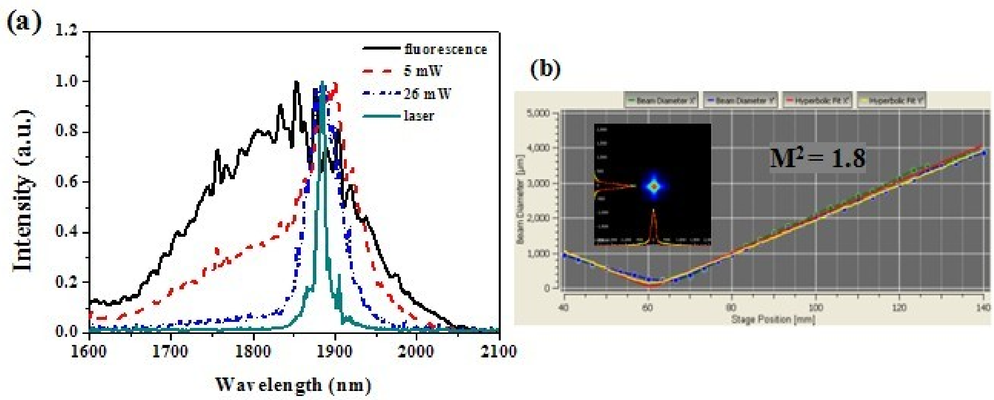

Fig. 2. (a) The normalized fluorescence, ASE (power at 5 and 26 mW), and laser spectra of Tm^{3+}-doped tungsten tellurite fiber with fiber length of 34 cm pumped by a 792 nm diode laser. (b) The beam quality measurement of ASE output beam; the inset is the beam profile.

The ASE output power was recorded as a function of absorbed pump power, and the results at different fiber lengths were also investigated, as shown in Fig. 3(a). There is no obvious difference in power thresholds of ~2 μm ASE among different fiber lengths except the 55-cm-length fiber. The output power increases almost linearly with absorbed pump power. The slope efficiencies for ASE output with fiber length of 55, 34, 15, 10 cm are about 3.3, 4.8, 2.8, 1.0%, respectively. As the fiber length increases, the slope efficiency increases because of more pump absorption in longer fiber. However, the slope efficiency in 55-cm-length fiber is smaller than that in 34 cm which is attributed to high background loss and re-absorption in longer fiber [20]. Figure 3(b) shows the bandwidth (FWHM) of ~2 μm ASE spectra of Tm^{3+}-doped tellurite fibers at various power levels. For longer fiber length the high slope efficiency promises a high output power, but the long interaction path length results in the narrowing of the ASE spectrum. On the other hand, in shorter fiber length, higher pump power is required for higher output. In the fiber length of 10 cm, the output power increases slowly with increasing pump power, and the curve in Fig. 3(a) indicates it is close to the saturated value. By comparison, the ASE from the fiber length of 34 cm is optimum in obtaining high power and broadband spectrum simultaneously. The maximum ASE output power reaches ~34 mW with a FWHM of 45 nm, and at low output power of ~3 mW, the FWHM is ~140 nm. Its ASE output power of 5, 7.8, 14.7 and 26 mW corresponds to the emission bandwidth (FWHM) of 78, 66, 61 and 58 nm, respectively. The beam propagation factor (M^2) for the ASE output beam is 1.8, the beam quality and beam profile are shown in Fig. 2(b). The efficiency of ~2 μm ASE could be further ameliorated by improving the fiber end facets to reduce the effective back reflection and using the non-circular inner cladding geometries to enhance the absorption of pump light.

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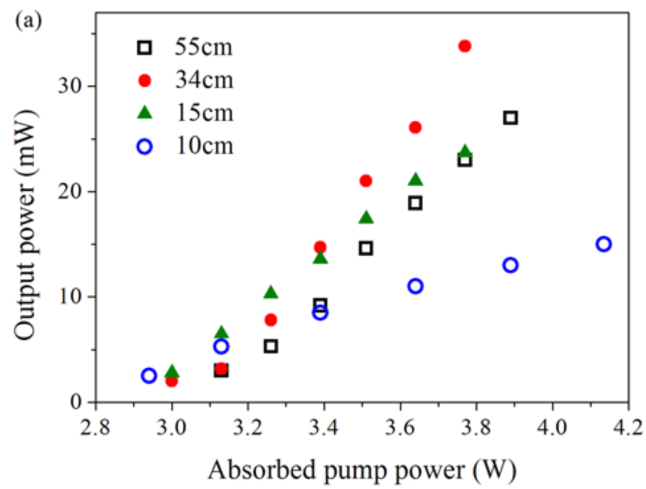

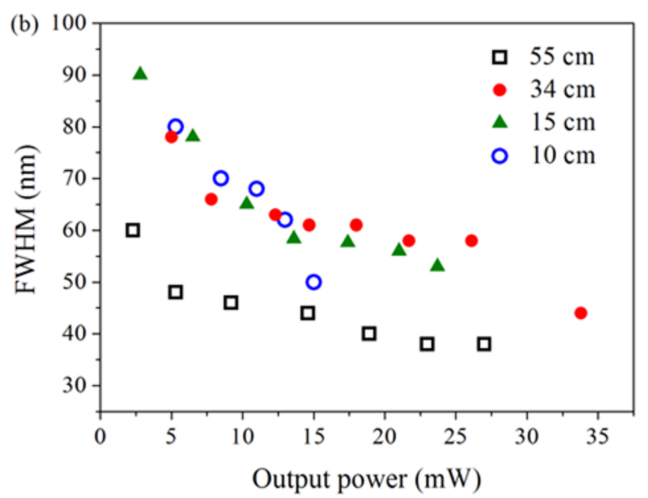

Fig. 3. (a) ASE output power versus absorbed pump power and (b) FWHM of ASE spectra with various output power for fiber lengths of 55, 34, 15, 10 cm, respectively.

Figure 4 shows the ASE spectra of the Tm^{3+}-doped tungsten tellurite fiber at varying lengths with bandwidth (FWHM) of ~50 nm to ~60 nm. The pump power are 3.5W for fibers with length of 55, 34 and 15 cm, and 3.65 W for 10 cm length fiber. As the length of the fiber increases, the peak shifts to longer wavelengths due to radiation trapping where light is absorbed from the ground state to the $^3F_4$ level and then re-emitted [21]. Accordingly, the central wavelength of ASE spectra shifts to a longer wavelength, and the ASE wavelength range can be chosen by modifying the fiber length. In addition, the ASE spectra from our fiber are close to a Gaussian distribution shape, and the presence of sidelobes in the coherence envelope can be solved by spectral filter or shaping technique into a smoother form which is ideal for applications [22].

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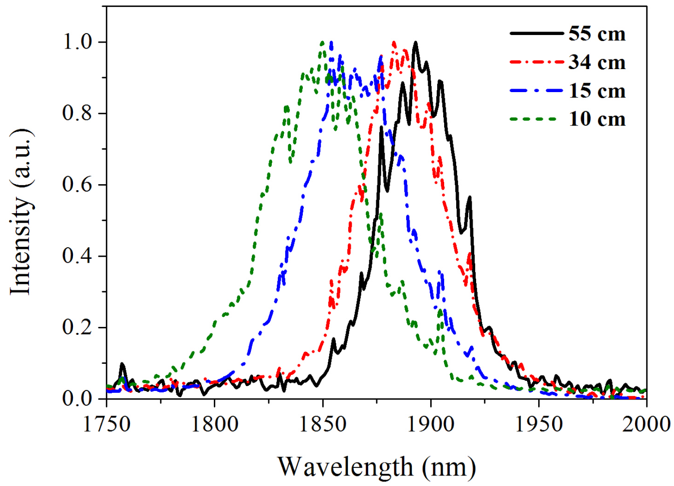

Fig. 4. Spectra of the ASE with various active fiber lengths when excited with a 792 nm laser source.

3. Conclusion

In conclusion, we have demonstrated the broadband ASE at ~2 μm in a 3.76×10^{20} ions/cm^3 Tm^{3+}-doped tungsten tellurite single-mode fiber pumped by a commercial multimode 792 nm laser diode, with a simple ~8° angle-cleaved one-ended configuration. In a fiber length of 34 cm, the maximum ASE output power reached ~34 mW with a FWHM of 45 nm, and at low output power about 3 mW, the FWHM was ~140 nm. The slope efficiency was 4.8%. The ASE beam quality factor M^2 was 1.8. The wavelength range of ASE can be tuned from ~1800 to ~1925 nm by modifying the fiber length. Broader bandwidth can be achieved by sacrificing the output power scaling.

Acknowledgments

This research is financially supported by the Chinese National Natural Science Foundation (Grant No. 60937003) and Natural Science Foundation of Shanghai, China (Grant No. 12ZR1451600).