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Fabrication and blue upconversion characteristics of Tm-doped tellurite fiber for S-band amplifier

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Abstract

Tm^{3+}-doped tellurite glass fiber was fabricated and the optical properties, such as upconversion fluorescence were investigated by a single- and a dual-wavelength pumping scheme. From the blue upconversion characteristics of the fiber, the completely different pumping mechanisms of Tm^{3+} was shown between 1.05 and 1.4 μm pump as a main pump for the S^+, S-band amplification. The ESA to the $^1G_4$ level hardly occurs by the 1.4 μm pump, while intense blue upconversion was observed by the 1.05 μm pump.

Keywords: Tellurite glass; Thulium; Fiber fabrication; Luminescence; Blue upconversion

1. Introduction

Tm^{3+}-doped fiber amplifier (TDFA) has been attracting much attention due to the demand for the extension of the amplification band toward shorter side (S^+-band; 1450–1490 nm) than the C-band (1530–1560 nm) in the wavelength division multiplexing (WDM) optical telecommunication systems.

As a host material for Tm^{3+}, the fluoride glass with low phonon energy is put into practical use because the non-radiative loss from the $^3H_4$ to the next lower $^3H_5$ level is very small. In the previous studies [1,2], we reported that the quantum efficiency of Tm^{3+}. The $^3H_4$ level in a tellurite glass is 96% and full width at half maximum (FWHM) of the emission is broader than that in the fluoride glass. Therefore, the tellurite glass can be more suitable as a host material for broadband amplification than the fluoride glass.

In order to improve gain efficiently, a dual-wavelength pumping method for the Tm^{3+} excitation was suggested [3]. By using this method, the gain band can be shifted from usual S^+-band to the S-band (1490–1525 nm), which has higher transmittance than the S^+-band. We have been paying much attention to the dual-wavelength pumping scheme for the S-band amplification [4–6]. The pumping mechanism of a fluoride-based Tm-doped fiber in dual-wavelength pumping scheme was explained with spectroscopic data [7]. The pumping mechanism is affected by the change of wavelength of the pump lasers.

It can be considered that tellurite-based Tm-doped fibers in dual-wavelength pumping scheme would accomplish broadband gain in the S-band, which is a gap between the S^+-band and C-band that is covered by Er^{3+}-doped fiber amplifier (EDFA). In this study, a tellurite-based Tm-doped fiber (TeO_2–GeO_2–ZnO–Na_2O–Y_2O_3 system) was fabricated. Blue upconversion characteristics were also investigated by two dual-wavelength pumping schemes, 1.05/1.56 and 1.4/1.56 μm, in order to investigate the pumping mechanism of tellurite-based Tm-doped fiber.

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2. Experimental

2.1. Fiber fabrication

Fabrication of tellurite fiber is as follows by using high-purity (>99.99%) starting materials. Core and clad glass with composition of TeO_2–GeO_2–ZnO–Na_2O–Y_2O_3 system was prepared. The core glass was doped with 2000 ppm of Tm^{3+}. The mixed materials were melted and homogenized in a gold crucible at 850 °C. The glass melt was poured into a stainless mold for making a fiber preform. The preform was annealed at near the glass-transition temperature. A fiber was obtained by drawing the preform. The NA of fiber was 0.2 and a core diameter was 4 μm.

2.2. Optical measurements

2.2.1. Loss characteristics

Loss characteristic of the tellurite-based Tm-doped fiber (Te-TDF) was measured by cutback method [12,13]. A white light source (ANDO, AQ4303B) was introduced into the Te-TDF and the output spectra of the Te-TDF were monitored with an optical spectrum analyzer (Anritsu, MS9780A).

2.2.2. Blue upconversion characteristics

A fiber of 1 m length was used. Both ends of the Te-TDF were fusion-spliced to SiO_2 fibers with a FC/PC connecter. An Yb-fiber laser (IRE-Polus, 1051 nm) was used and a laser diode (FITEL, 1410 nm) was used as a main pump source. An L-band laser source (SANTEC, TSL210) used as an auxiliary pump source (1560 nm). Laser light from main pump (1051 nm or 1410 nm) and auxiliary pump are coupled into the Te-TDF with two WDM couplers in forward configuration. Upconversion luminescence of the Te-TDF was measured in the wavelength range of 300–900 nm with Shimadzu RF5000 fluorescence spectrophotometer, in which a photomultiplier tube is attached as a detector.

3. Results

3.1. Loss characteristics

Fig. 1 shows the loss characteristics of the Te-TDF. The attenuation loss of the Te-TDF was 1.92 dB/m at 1.31 μm.

3.2. Blue upconversion characteristics

Figs. 2 and 3 show the visible emission spectra of the Te-TDF by using single (1.05 μm)- and dual (1.05/1.56 μm)-wavelength pumping scheme, respectively. Three emission bands at around 480, 650 and 800 nm were observed in the range of 300–900 nm, which were assigned to the $^1G_4 \rightarrow {}^3H_6$, the $^1G_4 \rightarrow {}^3F_4$ and the $^3H_4 \rightarrow {}^3H_6$ transitions, respectively.

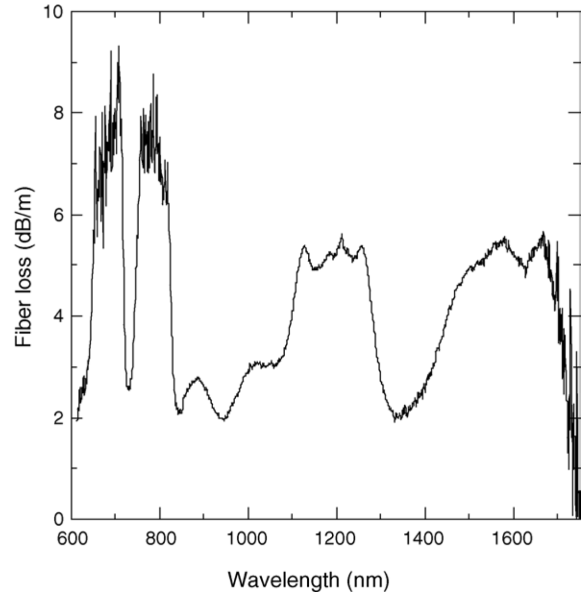

Fig. 1. Loss spectrum of tellurite-based TDF.

Figs. 4 and 5 show the visible emission spectra of the Te-TDF by using single (1.4 μm)- and dual (1.4/1.56 μm)-wavelength pumping scheme, respectively. Only one emission band at around 800 nm was observed in the 300–900 nm by using 1.4 μm as a main pumping wavelength.

Fig. 6 shows log–log plot of the main pumping power dependence of the 800 nm emission intensity of the Te-TDF by single- and dual-wavelength pumping scheme. Emission intensity increased with increasing main pumping power. By single-wavelength pumping scheme, the slope of the main pumping power dependence of the 800 nm emission was smaller than two. By dual-wavelength pumping scheme, the slope of the main pumping power dependence of the 800 nm emission was smaller than unity.

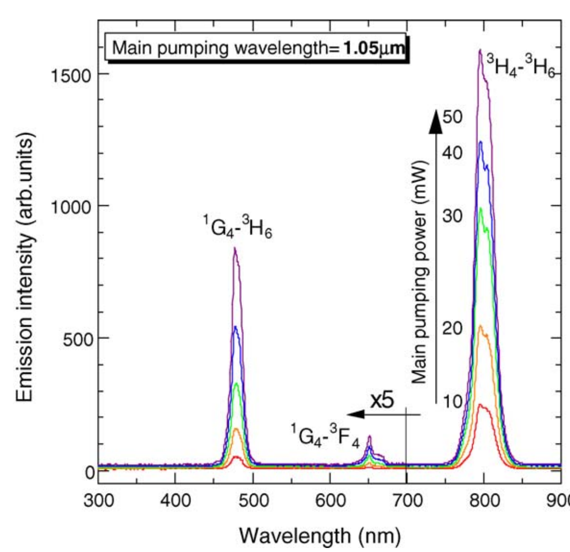

Fig. 2. Visible emission spectra of Te-TDF using 1.05 μm pumping.

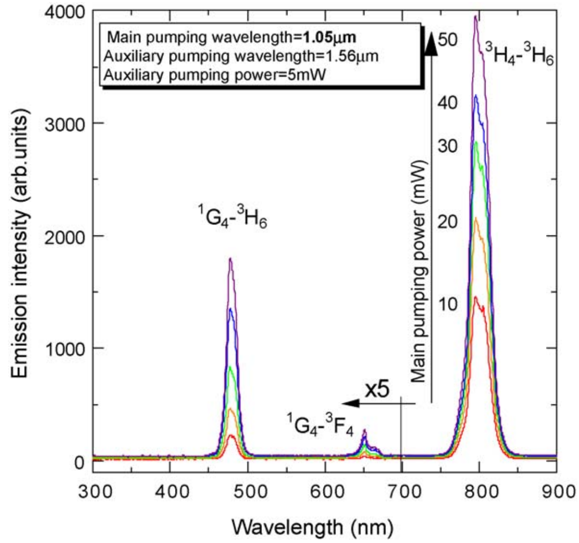

Fig. 3. Visible emission spectra of Te-TDF using 1.05 and 1.56 μm pumping.

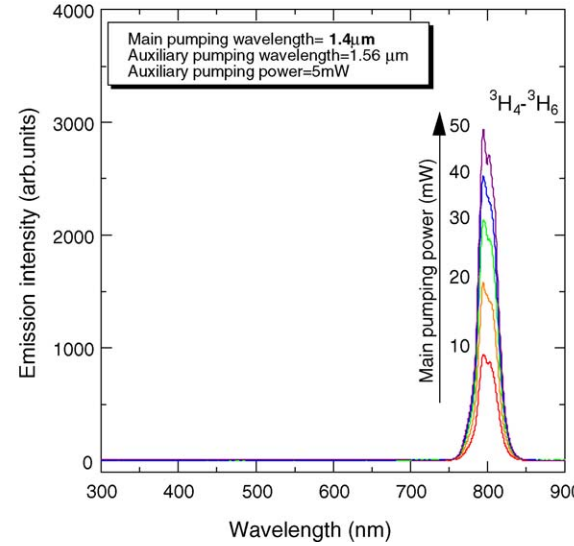

Fig. 5. Visible emission spectra of Te-TDF using 1.4 and 1.56 μm pumping.

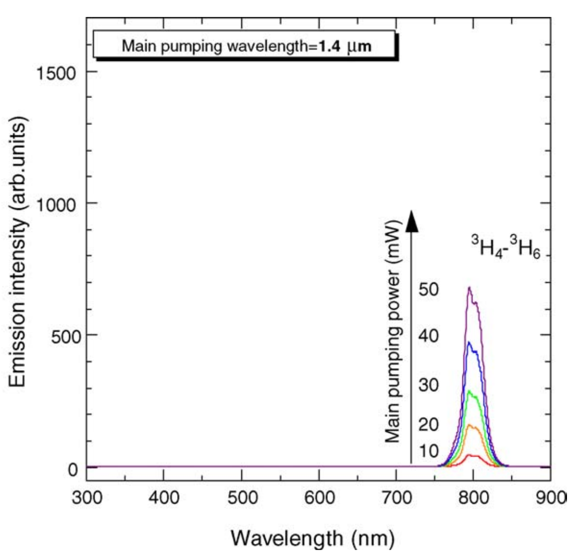

Fig. 4. Visible emission spectra of Te-TDF using 1.4 μm pumping.

4. Discussion

4.1. Pumping mechanism of Tm^{3+} by dual-wavelength pumping scheme

The visible emission spectra were completely different between the 1.05 and the 1.4 μm pump as a main pump. This result indicates the different pumping mechanisms in the Tm^{3+} energy level. The slope of the main pumping power dependence of the 800 nm emission varied from approximately two to unity by introducing the auxiliary pump. It is deduced that the role of an auxiliary pump is to increase only the population of the $^3F_4$ level by the ground state absorption (GSA) from the $^3H_6$ to the $^3F_4$ level and pumping efficiency to the $^3H_4$ level is improved. Also, both main pumping laser sources at 1.05 and 1.4 μm are used for ESA from the $^3F_4$ level. The ESA to the higher levels than the $^3H_4$ level exist because of the emission from the $^1G_4$ level by using 1.05 μm pump. From the above results, the pumping mechanisms of Tm^{3+} by 1.05 and 1.4 μm pumping as a main pump are shown in Fig. 7. By using 1.05 μm pumping as a main pump, since the population of the $^3F_4$ level is increased by introducing the auxiliary pump, the ESA efficiency from the $^3F_4$ level to higher levels than the $^3H_4$ level is increased more. The roles of the 1.05 μm pump are the first ESA from the $^3F_4$ to the $^3H_4$ level and the second ESA from the $^3H_4$ to the $^1G_4$ level. The

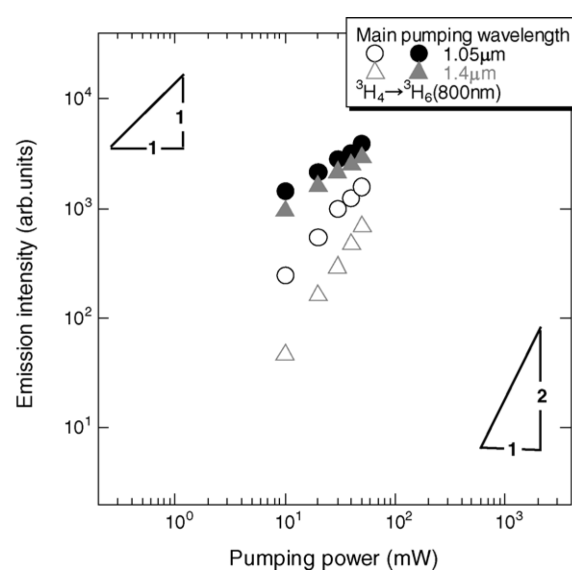

Fig. 6. Pumping power dependence of 800 nm emission intensity of Te-TDF by single- (open plot) and dual- (solid plot) wavelength pumping scheme.

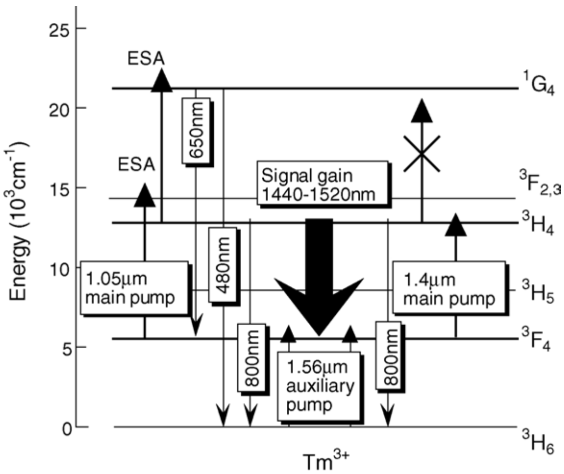

Fig. 7. Energy level diagram and upconversion pumping mechanism of Tm^{3+} ions.

ESA to the higher levels than the $^3H_4$ level decrease the population of the $^3H_4$ level. Therefore, this pumping scheme is disadvantage for forming the population inversion more efficiently between the $^3H_4$ and the $^3F_4$ level. On the other hand, by using 1.4 μm pump as a main pump, the $^3H_4$ level can be populated more efficiently because of the absence of the ESA from the $^3H_4$ level. It is clear that the pumping mechanism depends strongly on the main pumping wavelength (1.05 or 1.4 μm).

5. Conclusions

A Tm-doped tellurite fiber was fabricated and the blue upconversion characteristics of the fiber were also investigated. From the spectra, the different pumping mechanisms of Tm^{3+} were shown between 1.05 and 1.4 μm pump as a main pump. The role of an auxiliary pump is to increase only the population of the $^3F_4$ level by the GSA from the $^3H_6$ to the $^3F_4$ level and pumping efficiency to the $^3H_4$ level is improved. The roles of the 1.05 μm pump are the first ESA from the $^3F_4$ to the $^3H_4$ level and the second ESA from the $^3H_4$ to the $^1G_4$ level. On the other hand, the role of the 1.4 μm pump is the ESA from the $^3F_4$ level and not the ESA from the $^3H_4$ level.

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