Broadband 1.5-μm emission of erbium-doped TeO_2-WO_3-Nb_2O_5 glass for potential WDM amplifier

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Erbium-doped glass showing the wider 1.5-μm emission band is reported in a novel oxide system TeO_2-WO_3-Nb_2O_5 and their thermal stability and optical properties such as absorption, emission spectra, cross-sections and fluorescence lifetime were investigated. Compared with other glass hosts, the gain bandwidth properties of Er^{3+} in TWN glass is close to that of bismuth glasses, and larger than those of tellurite, germanate, silicate and phosphate glasses. The broad and flat $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission and the large stimulated emission cross-section of Er^{3+} ions around 1.5 μm can be used as host material for potential broadband optical amplifier in the wavelength-division-multiplexing (WDM) network system.

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The demand for increased transmission capacity of wavelength-division multiplexed telecommunication systems requires extension of the transmission window from the conventional C band (1530 – 1565 nm) to the L band (1570 – 1610 nm). It is of great importance to flatten the gain spectrum and broaden the amplification bandwidth of Er^{3+}-doped fiber amplifiers (EDFAs) because of their key function in the wavelength-division-multiplexing (WDM) network system[1−5]. However, the bandwidth of conventional SiO_2-based EDFA is limited, and an amplifier structure with a parallel configuration is complicated. So it is important to find other glass hosts for Er^{3+} doping to realize an intrinsically broader gain bandwidth. Because the stimulated emission cross-section of rare earth ions increases with the refractive indices of the glass hosts[6], and tellurite glasses have high refractive indices ($\sim$ 2.0 in most case). They are capable of providing large and broad stimulated emission cross-sections around 1.5-μm band. Furthermore, tellurite glasses have a wide infrared transmittance (extending up to 6 μm) and good chemical durability[6].

In this paper, the new tellurite glass of Er^{3+}-doped TeO_2-WO_3-Nb_2O_5 (hereafter called TWN) is prepared. The absorption spectrum, emission spectrum and fluorescence lifetime are investigated, and the gain bandwidth property of Er^{3+}in TWN glass is compared with that of glass hosts.

The glass sample studied has the following compositions in mol%: $80TeO_2$-$10WO_3$-$10Nb_2O_5$-$0.5Er_2O_3$. The reagent grade WO_3 and Nb_2O_5 and high purity TeO_2 (99.999%) were used as starting materials. Batched of 20 g were thoroughly mixed and melted in Pt crucible in a SiC resistance furnace at 700 – 800 °C for 15 min. The glass was subsequently annealed at the glass transition temperature. The glass sample was then cut and optically polished. The glass transition temperature (T_g), and crystallization onset temperature (T_x) were determined by differential thermal analysis (DTA) at a heating rate of 10 °C/min, using aluminum oxide ceramic pan. Density was measured according to the Archimedes' principle using distilled water as the medium. Refractive index of the sample was measured on prism by minimum deviation method. UV/VIS/NIR absorption spectrum was recorded between 400 and 1700 nm using a spectrophotometer. Emission spectrum measurement was carried out with a TRIAX550 spectrofluorimeter using a 980-nm laser diode (LD) as pumping source. The fluorescence lifetime of the $^4I_{13/2}$ level of Er^{3+} was measured with light pulses of the 980-nm LD and an HP546800B 100-MHz oscilloscope. All the measurements were made at room temperature.

Table 1 lists some basic properties for Er^{3+}-doped TWN glass. The TWN glass have high density and refractive index, which are 5.623 g/cm^3 and 2.035, respectively. The difference between T_x and T_g, $\Delta T = T_x - T_g$, has been frequently used as a rough estimate of the glass formation ability or glass stability. Since fiber drawing is a reheating process and any crystallization during the process will increase the scattering loss of the fiber and then degrade the optical properties[7,8]. To achieve a large working range of temperature during our sample fiber drawing, it is desirable for a glass host to have ΔT as large as possible[9]. The DTA curve of Er^{3+}-doped TWN glass is illustrated in Fig. 1. It can be seen from the figure that the ΔT value of the TWN glass is 148 °C, which is larger than those of the lead tellurite glasses and fluoride glasses[6,10], indicating the TWN glass is stable against devitrification.

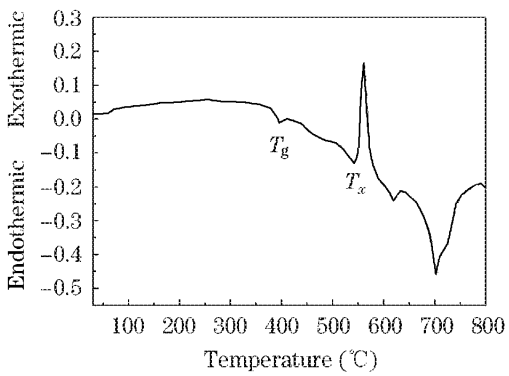

Fig. 1. The DTA curve of Er^{3+}-doped TWN glass.

Table 1. Density d, Refractive Index n_d, and Er^{3+} Concentration N of Er^{3+}-Doped TWN Glass

Glass Sample	d (g/cm^3)	n_d	N (10^{21}/cm^3)
TWN	5.623	2.035	0.19

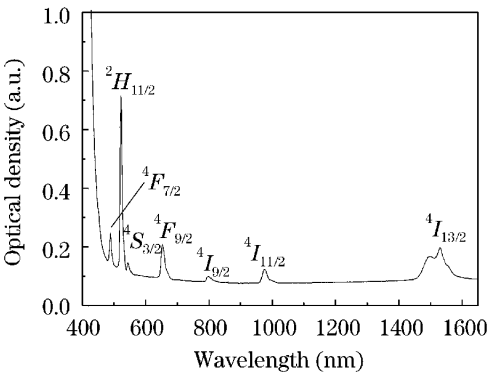

Fig. 2. Absorption spectrum of Er^{3+}-doped TWN glass.

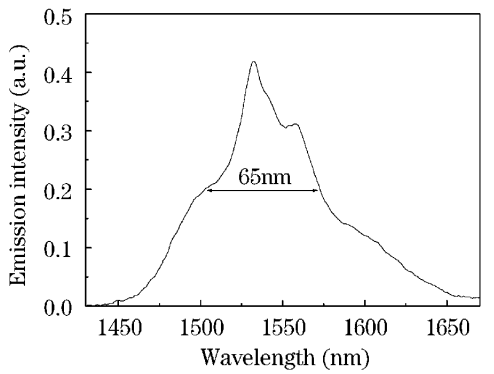

Fig. 3. Emission spectrum of Er^{3+}-doped TWN glass.

Figure 2 shows absorption spectrum of Er^{3+}-doped TWN glass. The absorption spectrum consists of seven absorption bands peaks at 1530, 977, 798, 653, 544, 522, and 489 nm, corresponding to the absorptions from the ground state $^4I_{15/2}$ to the excited states $^4I_{13/2}$, $^4I_{11/2}$, $^4I_{9/2}$, $^4F_{9/2}$, $^4S_{3/2}$, $^2H_{11/2}$, and $^4F_{7/2}$, respectively.

The emission spectrum of the TWN glass is shown in Fig. 3. Because of the differences of the emission spectra in various glass hosts, FWHM is often used as a semi-quantitative indication of the bandwidth. From Fig. 3 it can be seen that FWHM is 65 nm from 1508 to 1573 nm, which is smaller than that for the bismuth glasses, ~ 79 nm, but is wider than those for the phosphate (~ 37 nm), the silicate glass (~ 40 nm) and the germante glass (~ 42 nm)[11–14].

The absorption cross-section of $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition of Er^{3+} was determined from the absorption spectrum

$$\sigma_{\mathrm{a}}(\lambda) = \frac{2.303}{Nl}\mathrm{OD}(\lambda), \tag{1}$$

where σ_{a} is absorption cross-section, $\mathrm{OD}(\lambda)$ is optical density, l is the sample thickness, and N is concentration of Er^{3+} (ions/cm^3). The stimulated emission cross-section is calculated from McCumber theory[15]. According to the McCumber theory, the absorption and stimulated emission cross-sections are related by

$$\sigma_{\mathrm{e}}(\lambda) = \sigma_{\mathrm{a}}(\lambda)\exp[(\varepsilon - h\nu)/kT], \tag{2}$$

where σ_{e} is stimulated emission cross-section, h is the Planck constant, k is the Boltzmann constant, ν is the photon frequency, and ε is the net free energy required to excite one Er^{3+} from the $^4I_{15/2}$ state to $^4I_{13/2}$ at temperature T. ε was determined using the procedure provided in Ref. [16]. Figure 4 illustrates the calculated absorption and stimulated emission cross-sections for the $^4I_{15/2} \leftrightarrow {}^4I_{13/2}$ transition of Er^{3+} in TWN glass. The peak absorption ($\sigma_{\mathrm{a}}^{\mathrm{p}}$) and stimulated emission ($\sigma_{\mathrm{e}}^{\mathrm{p}}$) cross-sections are 7.1×10^{-21} and 7.8×10^{-21} cm^2, respectively.

The peak stimulated emission cross-section and FWHM are very important parameters in optical amplifiers to realize broadband and the gain amplification. The gain bandwidth properties of optical amplifiers can be evaluated by FWHM $\times$ $\sigma_{\mathrm{e}}^{\mathrm{p}}$ product. The bigger the product, the better the property. Table 2 lists FWHM, $\sigma_{\mathrm{e}}^{\mathrm{p}}$ and FWHM $\times$ $\sigma_{\mathrm{e}}^{\mathrm{p}}$ of Er^{3+} in various glass hosts for comparison of the gain bandwidth properties. It is clear that FWHM$\times\sigma_{\mathrm{e}}^{\mathrm{p}}$ of Er^{3+} in TWN glass is close to that of bismuth glasses, and larger than those of tellurite, germanate, silicate and phosphate glasses. Consequently, the TWN glass can be used as potential host material for developing broadband optical amplifiers in WDM.

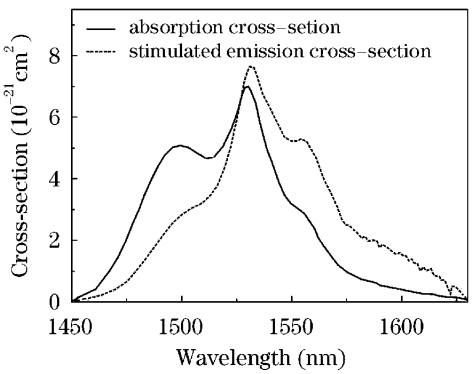

Fig. 4. Absorption and stimulated emission cross-section of Er^{3+} in TWN glass.

Table 2. The Emission Parameters FWHM, $\sigma_{\mathrm{e}}^{\mathrm{p}}$ and FWHM $\times$ $\sigma_{\mathrm{e}}^{\mathrm{p}}$ of Er^{3+} in Different Glass Hosts

Glass	TWN	Tellurite[14]	Bismuth[11]	Phosphate[12]	Germante[13]	Silicate[14]
FWHM (nm)	65	65	79	37	42	40
σ_e^p(10^{-21} cm^2)	7.8	7.5	7.0	6.4	5.7	5.5
FWHM$\times\sigma_e^p$	507	487.5	554	236.8	239.4	220

The lifetime of $^4I_{13/2}$ level of Er^{3+} is also an important parameter for optical amplifier. A critical factor in the success of Er^{3+}-doped fiber amplifier in optical communications is the long lifetime of the metastable state that permits the required high population inversions to be obtained under steady-state conditions using modest pump powers[7]. The measured fluorescence lifetime τ_{meas} of $^4I_{13/2}$ level of Er^{3+} in TWN glass is 3.9 ms, which is more than that of bismuth glasses[11].

In conclusion, Er^{3+}-doped TWN glass has a good thermal stability, high refractive index, high absorption and stimulated emission cross-sections, and a very broad-width for 1.5 μm emission. Compared with other glass hosts, the gain bandwidth properties of Er^{3+} in TWN glass is close to that of bismuth glasses, and larger than those of tellurite, germanate, silicate and phosphate glasses. Furthermore, the lifetime of $^4I_{13/2}$ level of Er^{3+} in TWN glass is longer than that of Er^{3+} in bismuth glasses. Consequently, the TWN glass can be used as potential host material for developing broadband optical amplifiers in WDM.

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References

1. S. Tanabe, N. Sugimoto, S. Ito, and T. Hanada, J. Lumin. **87&89,** 670 (2000).
2. M. Yamada, A. Mori, K. Kobayashi, and H. Ono, IEEE Photon. Technol. Lett. **10,** 1244 (1998).
3. S. Tanabe, J. Non-Cryst. Solids **259,** 1 (1999).
4. S. Q. Xu, Z. M. Yang, S. X. Dai, J. H. Yang, N. L. Dai, A. X. Lin, L. L. Hu, and Z. H. Jiang, Chin. Phys. **12,** 997 (2003).
5. J. H. Yang, S. X. Dai, L. Wen, N. L. Dai, L. L. Hu, and Z. H. Jiang, Chin. Opt. Lett. **1,** 294 (2003).
6. D. Yong, S. B. Jiang, B. C. Hwang, T. Luo, N. Peyghambarian, Y. Himei, T. Ito, and Y. Miura, Optical Materials **15,** 123 (2000).
7. S. Q. Xu, Z. M. Yang, S. X. Dai, J. H. Yang, W. Lei, L. L. Hu, and Z. H. Jiang, Chin. Phys. Lett. **20,** 905 (2003).
8. S. Q. Xu, Z. M. Yang, S. X. Dai, J. H. Yang, L. L. Hu, and Z. H. Jiang, J. Chin. Rare Earth Soc. **21,** 137 (2003).
9. L. L. Neindre, S. B. Jiang, B. C. Hwang, T. Luo, J. Watson, and N. Peyghambarian, J. Non-Cryst. Solids **255,** 97 (1999).
10. D. R. Macfarlane, J. S. Javorniczky, P. J. Newman, D. J. Booth, and V. Bogdanov, J. Non-Cryst. Solids **184,** 249 (1995).
11. J. H. Yang, S. X. Dai, Y. F. Zhou, L. Wen, L. L. Hu, and Z. H. Jiang, J. Appl. Phys. **93,** 977 (2003).
12. S. Jiang, T. Luo, B. C. Hwang, F. Smekatala, K. Seneschal, J. Lucas, and N. Peyghambarian, J. Non-Cryst. Solids **263&264,** 364 (2000).
13. H. Lin, E. Y. B. Pun, S. Q. Man, and X. R. Liu, J. Opt. Soc. Am. B **18,** 602 (2001).
14. X. Zou and T. Izumitani, J. Non-Cryst. Solids **162,** 68 (1993).
15. D. E. McCuber, Phys. Rev. A **134,** 299 (1964).
16. W. J. Miniscalo and R. S. Quimby, Opt. Lett. **16,** 258 (1992).