Experimental investigation of photoluminescence spectra of Yb^{3+} sensitized Er^{3+}-doped glass samples in series

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Fabrication technology of the Yb^{3+}:Er^{3+} co-doped glass samples is introduced. Photoluminescence (PL) characteristics of a single sample were experimentally investigated. The PL peak intensities of two samples in series were measured and discussed. The results show that the PL peak intensities of two samples in series depend on pump manners and arrangement of the samples. The better amplification ability can be obtained by two samples in series doped with low-concentration ytterbium instead of a single sample doped with high-concentration ytterbium.

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Thin-film optical waveguides hold considerable potential in the field of integrated optics, and they are the foundation of development of all optical network (AON) communication. In particular, erbium-doped waveguide amplifiers (EDWA) have received world wide attention[1−4] because they can amplify light signal at $1.53 - 1.54$ μm based on the intense intra-$4f$ emission ($^4I_{13/2} \rightarrow ^4 I_{15/2}$) from Er^{3+} in Er-O clusters, one of the minimum transmission loss of standard silica wavelengths in optical telecommunications. Several types of waveguides have been fabricated[5−8]. The phosphate glass waveguide amplifiers co-doped with Er^{3+}/Yb^{3+} were theoretically studied[9] and the pump efficiency is ameliorated on account of sensitization effect of ytterbium. But it is still difficult to obtain higher photoluminescence (PL) intensity at certain pump power owing to ion-ion interaction mechanisms, such as co-operative upconversion, excited state absorption (ESA) and cross relaxation[10,11] when the samples are doped with high concentrations of trivalent erbium. So we think that a higher gain of optical signal can be achieved by using of two amplifiers with low-concentration dopant in series, which are used to take place of one amplifier with high-concentration dopant. PL characteristics of two Er-doped glass samples in series with different concentrations have been experimentally investigated[12]. In this letter, fabrication technology of the Yb^{3+}:Er^{3+} co-doped glass samples is introduced. PL characteristics of a single sample were experimentally investigated. The PL peak intensities of two samples in series were measured and discussed. The results show that the PL peak intensities of two samples in series depend on pump manners and arrangement of samples. The better amplification ability can be obtained by two samples in series doped low-concentration ytterbium instead of a single sample doped high-concentration ytterbium.

The compositions of Yb^{3+}:Er^{3+} co-doped glass samples were summarized in Table 1[13]. Total weights of Yb^{3+}:Er^{3+} co-doped samples are all 70.000 g. The powder was homogenized and compacted in 50-ml corundum crucible and heated in the high-temperature oven at 1450 °C for 30 minutes. While the glass stocks of Yb^{3+}:Er^{3+} co-doped took on molten state in high-temperature oven, they were poured into moulds and then moved into the thermostat oven. 10 minutes later, the samples were taken out of the moulds and put on asbestos web in the thermostat oven. Switched off the thermostat oven after 3 hours, and let its temperature decreased naturally down to room temperature. The pink transparent Yb^{3+}:Er^{3+} co-doped glass samples ($15 \times 15 \times 5$ mm^3) were obtained after incising and polishing. Erbium-doped concentration of the samples were all 0.5 at.-% while ytterbium-doped concentrations of the samples were 0.0, 1.5, 3.0, 4.5, and 6.0 at.-%, of which corresponding marks were No. 0, 1, 2, 3 and 4, respectively.

The absorption cross-section $\sigma_{\rm abs}(\lambda)$ of ytterbium and erbium at wavelength λ can be calculated by[14]

$$\sigma_{\rm abs}(\lambda) = \frac{2.303 \lg(I_0/I)}{Nl}, \tag{1}$$

where $\lg(I_0/I)$ is optical density, N is concentration of active ions at unit volume and l is thickness of the sample. According to the McCumber's formula, the stimulated emission cross-section $\sigma_{\rm emi}(\lambda)$ of erbium at wavelength λ can be derived from absorption cross-section $\sigma_{\rm abs}(\lambda)$

Table 1. The Composition and Weight of the Yb^{3+}:Er^{3+} Co-Doped Glass Samples (Unit: g)

Composition	SiO_2	$B(OH)_3$	Na_2CO_3	$Ba(OH)_2$	Er_2O_3	Yb_2O_3
No. 0 (0.0 at.-% Yb^{3+} Concentration)	22.7500	11.1911	11.7013	1.1734	1.7576	0.0
No. 1 (1.5 at.-% Yb^{3+} Concentration)	29.3349	14.4303	15.0882	1.5131	2.3558	7.2778
No. 2 (3.0 at.-% Yb^{3+} Concentration)	26.3361	12.9552	13.5458	1.3584	2.2019	13.6027
No. 3 (4.5 at.-% Yb^{3+} Concentration)	23.7036	11.6602	12.1918	1.2226	2.0667	19.1550
No. 4 (6.0 at.-% Yb^{3+} Concentration)	21.3764	10.5154	10.9948	1.1026	1.9472	24.0635

$$\sigma_{\rm emi}(\lambda) = \sigma_{\rm abs}(\lambda) \exp\left(\frac{\varepsilon - hc\lambda^{-1}}{kT}\right), \quad (2)$$

ε is calculated by

$$\frac{N_1}{N_2} = \exp\left(\frac{\varepsilon}{kT}\right), \quad (3)$$

where N_1, N_2 are populations of $^4I_{15/2}$ and $^4I_{13/2}$ at room temperature, respectively.

The lifetime of Er^{3+} at the first excited state of our Yb^{3+}:Er^{3+} co-doped glass sample is 7.8 ms. The absorption cross-section of ytterbium at 980-nm wavelength is 0.62×10^{-20} cm^2 and the emission cross-section of erbium at 1530 nm is 0.73×10^{-20} cm^2. Yb^{3+} sensitized Er^{3+}-doped glass samples can enhance the pump efficiency because ytterbium ions absorb most of the pump power and subsequently transfer the absorbed energy to the adjacent erbium ions through a cross relaxation mechanism. Figure 1 shows Yb^{3+} and Er^{3+} energy level transitions diagram. The pump light at 980-nm wavelength excites Yb^{3+} ions in the ground state $^2F_{7/2}$ to the $^2F_{5/2}$ state. The excited Yb^{3+} (donors) transfer energy to the nearby Er^{3+} (acceptors) in ground state $^4I_{15/2}$ and transit them to the pump level $^4I_{11/2}$, the resonant energy levels. Er^{3+} ions in the $^4I_{11/2}$ then decay to the metastable state $^4I_{13/2}$ energy level through non-radiative relaxation transitions. At about 1.54 μm fluorescent emission is produced by transitions from $^4I_{13/2}$ to $^4I_{15/2}$, subsequently.

PL characteristics of Yb^{3+}:Er^{3+} co-doped glass samples were measured at room temperature, as shown in Fig. 2[15]. Two semiconductor lasers emitting 980-nm light were used to pump ytterbium and erbium ions of the samples from ground state to excited state. The pump beams were aligned to the face of the samples through a convergent lens and a concave mirror, respectively. The signal light (about 1.54 μm) was chopped by optical chopper with 425 Hz and focused into entrance of a monochromator. The analyzed light was detected with a semiconductor-cooled InGaAs detector and the signals were amplified by using of a look-in amplifier. Experimental data were treated with a computer and the PL spectra were displayed on the screen.

The spectrum of the LED with peak wavelength 1.232 μm was firstly measured without any samples, as shown in Fig. 3. Then the absorption spectrum of the Er^{3+}:Yb^{3+} co-doped sample was measured with the output of the LED as signal and through sample, for example No. 3. We know from Fig. 3 that the spectrum of the LED is absorbed by sample and leads to the decrease

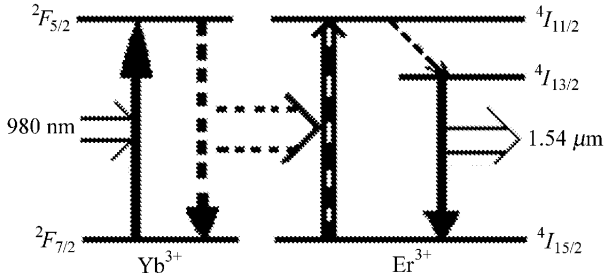

Fig. 1. Energy level transitions for Yb^{3+} and Er^{3+}.

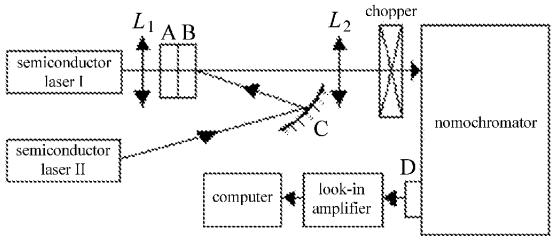

Fig. 2. Measurement of PL intensity. L_1 and L_2: convergent lenses; A and B: samples; C: concave mirror; D: detector.

of intensity. The wavelength at center of valley in the curve of absorption spectrum is about 1.544 μm.

Figure 4 depicts how the peak intensities and the FWHM of PL spectra of the Yb^{3+}:Er^{3+} co-doped glass samples vary with different Ytterbium dopant concentrations while input pump power was kept constant. Gradual increase of the PL peak intensity and FWHM can be seen from 0.0 at.-% up to their maximum values at 4.5 at.-%. But the PL peak intensity and FWHM were of decrescent tendency as Yb^{3+}-doped concentrations are higher than 4.5 at.-%. It means that the Yb-doped concentration of the Yb^{3+}:Er^{3+} co-doped glass sample has an optimum value of 4.5 at.-%, about 9 times over Er^{3+}-doped concentration.

Two Yb^{3+}:Er^{3+}co-doped glass samples in series (see A and B in Fig. 2) can be thought as a two-stage amplification system, that is, sample A is preamplifier and B is

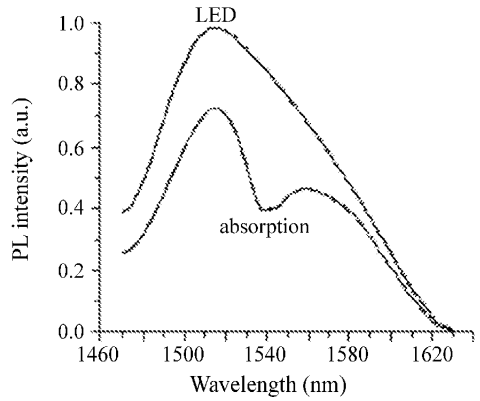

Fig. 3. Absorption spectrum of the Er^{3+}:Yb^{3+} co-doped sample.

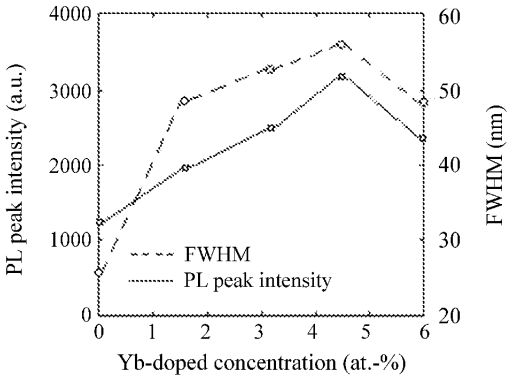

Fig. 4. Peak intensities and FWHMs of the samples with different Yb-doped concentrations.

post-amplifier. The relationship between the peak intensity and pump power or pump manner (equi-directional pump: only laser I is working; bidirectional pump: lasers I and II are both working) was investigated as two samples were arranged in different fashions.

Figure 5 is the comparison of the PL spectra between two measurements, one was two glass samples doped with only erbium ions (No. 0, both concentrations of 0.5 at.-%) in series and another was a single Er^{3+}-doped glass sample (No. 0, concentration of 0.5 at.-%). Laser I was used to pump samples at 1.2 W all along. As we can see from the figure, PL peak intensity of the two samples in series is about 1.5 times more than that of a single Er^{3+}-doped glass sample. So we can say that the gain of the two-stage amplification system is better than that of the one-stage amplifier. This result is in accordance with Ref. [15].

Figure 6 shows spectra of two samples (No. 0: Er = 0.5 at.-%, No. 2: Yb = 3.0 at.-%, Er = 0.5 at.-%) in series with different arrangements and under different pump conditions. Curve a is the PL spectrum of the system in which sample No. 0 is preamplifier (facing the laser I) and sample No. 2 is post-amplifier (facing the detector). Curve b is just of the right opposite arrangement to the previous one: that is, the sample No. 2 is preamplifier while sample No. 0 is post-amplifier. On the above measuring, pump manner was equi-directional. The intensity of curve b is obviously lower than that of curve a. The probable reason is that the absorption cross-section of Ytterbium for 980-nm wavelength is very large, and ytterbium ions in sample No. 2 absorb vast majority of pump power in the second arrangement. When the signal of 1.54 μm emitted from preamplifier is transmitting through sample No. 0, the absorptive loss in the post-amplifier is larger than its gain because it is not pumped by sufficient power. So the curve b in Fig. 6 is similar to the absorption curve in Fig. 3. But we must say that the intensity is enhanced, as shown by the curve c in Fig. 6, even in the second arrangement when two lasers are working in bidirectional pump at the same time. In this case, the post-amplifier is also pumped abundantly by laser II and its gain is larger than the loss.

Figure 7 represents the comparison of spectra between a single glass sample No. 1 (Er: 0.5 at.-%, Yb: 1.5 at.-%) and two glass samples (both No. 1) in series pumped with different conditions. Curve a is the spectrum of

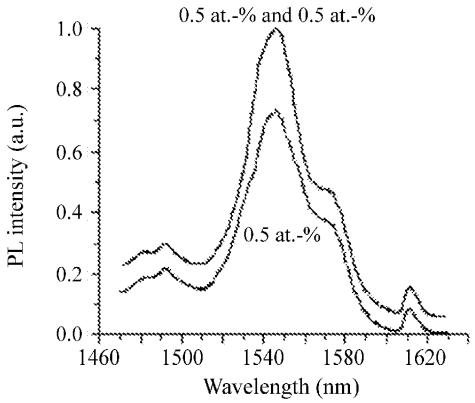

Fig. 5. Comparison between the two samples in series and a single sample. All samples are erbium-doped only.

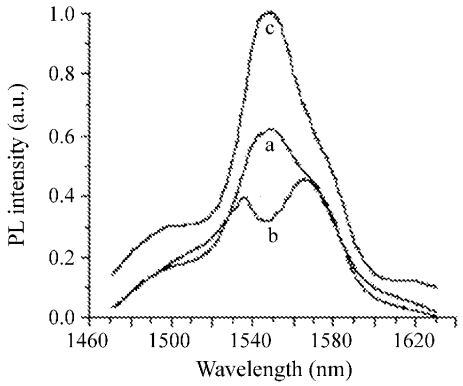

Fig. 6. Spectra of two samples (No. 0 and 2) in series. a: No. 2 and No. 0; b: No. 0 and No. 2; c: No. 0 and No. 2, bidirectional pump.

a single amplifier of one sample and curve b is spectrum of a two-stage amplifier constituted by two samples in series. The measurement was under equi-directional pump by laser I. We can see from the figure that the peak intensity of curve b is lower than that of curve a, but it is not an absorptive spectrum. The main reason is the preamplifier does not exhaust pump power because it only has low Yb^{3+}-doped concentration and post-amplifier also can receive some pump power and has definite gain to compensate absorption loss when the 1.54-μm signal emitted by the preamplifier is passing through the post-amplifier. So curve b does not take on clearly sinking. The post-amplifier, however, also can get hold of enough pump power while laser II is working too (bidirectional pump). The signal is amplified ulteriorly and peak intensity is enhanced, as shown by curve c.

In Fig. 8, curves a and b are the spectra of two single samples No. 3 (Er: 0.5 at.-%, Yb: 4.5 at.-%) and No. 4 (Er: 0.5 at.-%, Yb: 6.0 at.-%), respectively. Curves c and d are the spectra of the two samples in series in different arrangement. In the former, the preamplifier and the post-amplifier are constituted by sample No. 3 and 4, respectively. The arrangement of the latter is in the other way round. We can know that the peak intensity of curve c is lower than that of curve d. The reason can be explained qualitatively as follows. When the post-amplifier is sample No. 4, its amplification ability

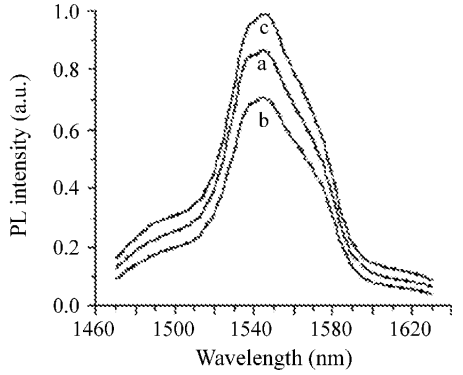

Fig. 7. Comparison between the two samples in series and a single sample. All samples are No. 1. a: a single sample; b: two samples in series pumped by laser I; c: two samples in series pumped by two lasers.

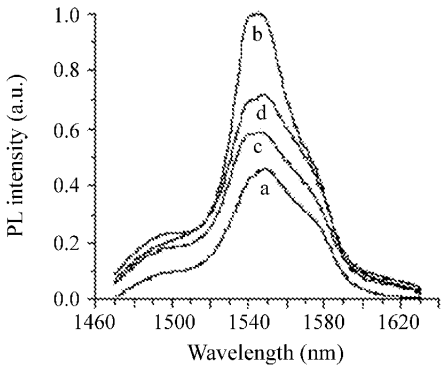

Fig. 8. Spectra of two samples (No. 3 and 4) in series. a: sample No. 5 only; b: sample No. 4 only; c: No. 4 and 5 in series; d: No. 5 and 4 in series.

is limited because the output power of laser II is finite and Yb^{3+}-doped concentration of the sample is high. But when sample No. 3 is post-amplifier, its amplification ability is better than that of sample No. 4 at the same pump power because Yb^{3+}-doped concentration of the sample is lower. The results are coincident with Fig. 4. At the same time, we find that the peak intensity of the two-stage amplifier is lower than that of single sample, though two lasers are working in bidirectional pump. The possible reason is that the samples both have high concentration of Yb^{3+}-doped and need stronger pump power, but we do not have such a powerful laser.

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