Physica B 403 (2008) 3470–3472

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

High Er^{3+} concentration low refractive index fluorophosphate glass for evanescent wave optical amplifiers

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ARTICLE INFO

Article history:
Received 8 October 2007
Received in revised form
28 January 2008
Accepted 12 May 2008

PACS:
78.20.−e
42.70.Ce
32.70.Cs
42.70.Hj

Keywords:
High Er^{3+} concentration
Low refractive index
Evanescent wave optical amplifiers (EWOA)

ABSTRACT

This is about the first reported laser glass with very low n_D, high Er^{3+} concentration and no quenching. In this work, a series of high Er^{3+} concentration ($10.6–12.2\times10^{20}$ ions/cm^3), low refractive index ($n_{1550}<1.47$) and relatively high fluorescence lifetime (6.8–12.6 ms) fluorophosphate glasses were made. A cw-pumping evanescent wave optical amplifier experiment was performed with it, and a relative gain of around 2 dB at 1550 nm wavelength was achieved while the noise level was almost unchanged. To our knowledge, this is the first successful relative gain in evanescent wave optical amplifiers (EWOA) demonstrated with cw pumping. It is a valuable study of specially designed fluorophosphate glass suitable for EWOA communication experiment.

1. Introduction

Gain robbing and noise raising caused by guided amplified spontaneous emission (ASE) are unavoidable problems in erbium-doped fiber amplifiers (EDFA). Hence evanescent wave optical amplifiers (EWOA) featured with naturally depressed ASE were studied [1,2], and a 22 dB gain based on a pulse-pumped laser had been demonstrated [3]. Generally, in the evanescent pumping process, the interaction length of the signal and pump light along the gain medium is only 1–2 mm. In order to achieve sufficient gain, gain medium must possess very high Er^{3+} concentration. RE ions in high RE-doped silica glasses cluster heavily and are not suitable for use as EWOA gain media. It is well known that fluorophosphate glass, which possesses large inhomogeneous broadening and better broadband and flatness properties, is a promising candidate for Er^{3+}-doped lasers and amplifiers [4–6], and it also features high Er^{3+} doping ability and low refractive index.

2. Experiments

Glasses were prepared by mixing appropriate quantities of reagent grade phosphates, alkaline-earth fluorides, ErF_3 and/or YbF_3 according to the corresponding glass compositions. The mixtures were melted at 1000–1100 °C in platinum crucible. After refining, melts were cast into mould and annealed to room temperature with a cooling rate of 1 °C/10 min. After that, samples were cut and polished for property measurements.

Absorption spectra were recorded with a Perkin-Elmer Lambda 900 UV/vis/IR spectro-photometer over the range of 300–2000 nm. Fluorescence spectra were obtained with a Triax 550 spectrofluorimeter under 980 nm LD excitation. The fluorescence lifetime of $^4I_{13/2}$ level of Er^{3+} was detected by an HP546800B100-MHz oscilloscope. Refractive indices and densities were obtained through the V-prism method and Archimedes method, respectively. The EWOA experiment was performed in Taiwan National Chiao Tung University. All the measurements were taken at room temperature.

3. Results and discussion

Table 1 shows the compositions of the glass samples, and Table 2 shows some of their properties. Er^{3+} concentration is over

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doi:10.1016/j.physb.2008.05.015

Table 1
Compositions of the glass

Glass no.	Compositions
1♯	$35AlF_3$–$38RF_2$–$9YF_3$–$5Al(PO_3)_3$–$7KF$–$6ErF_3$
2♯	$30AlF_346RF_2$–$9YF_3$–$5Al(PO_3)_3$–$4KF$–$6ErF_3$
3♯	$30AlF_3$–$46RF_2$–$11YF_3$–$5Al(PO_3)_3$–$2KF$–$6ErF_3$
4♯	$30AlF_3$–$46RF_2$–$11YF_3$–$5Al(PO_3)_3$–$2KF$–$5ErF_3$–$1YbF_3$

$RF_2 = MgF_2, CaF_2, SrF_2, BaF_2$.

Table 2
Some properties of the samples

Glass no.	n_{1550}	d (g/cm^3)	l (mm)	$N_{Er} \times 10^{20}$ ions/cm^3
1	1.4635	3.8253	1.78	11.9
2	1.4656	3.9815	1.65	12.0
3	1.4646	4.0195	1.80	12.2
4	1.4647	3.9796	1.83	10.6

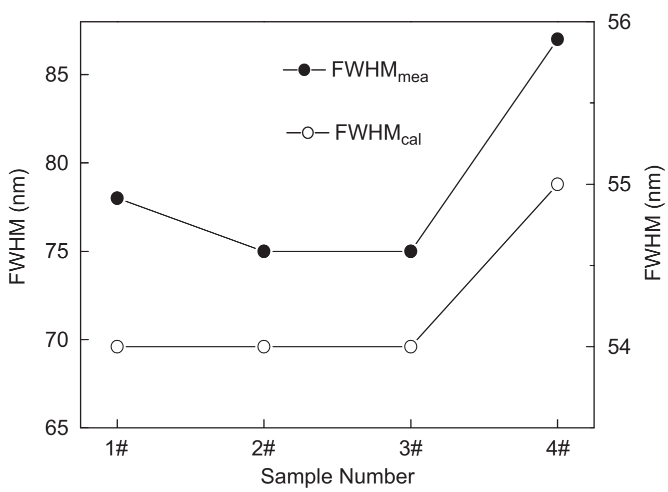

Fig. 1. Measured and calculated FWHM value of the samples.

10^{21} ions/cm^3 in this series of glasses with the refractive index at 1550 nm below 1.47. Another phenomenon is that the measured and calculated fluorescence widths at half maximum (FWHM) of these samples have large differences in this research, as shown in Fig. 1. In this figure, the measured FWHM values are about 20 nm wider than the calculated values, especially for Yb:Er codoped sample 4♯, for which $FWHM_{mea} = 87$ nm and $FWHM_{cal} = 55$ nm. Fig. 2 shows some reasons for this phenomenon. It is a normalized fluorescence spectra of sample 3♯ and a common Er^{3+}-doped fluorophosphate glass. In this figure, the fluorescence spectrum of sample 3♯ is flatter and wider than that of the common Er^{3+}-doped glass. This is induced by fluorescence re-absorption effect (radiation trapping effect), and it also prolongs the fluorescence lifetime value.

Fig. 3 shows the emission cross-section σ_{emi} and fluorescence lifetime τ_f values of these four samples. Although all the samples have similar glass composition, their σ_{emi} and τ_f values show large differences. Samples 1♯ to 3♯ have almost the same Er^{3+} concentration, but with the relatively changing content of AlF_3, RF_2, YF_3 and KF, their σ_{emi} decreases from 0.63 to 0.52 pm^2 and τ_f increases from 6.8 to 9 ms. For the Yb^{3+}:Er^{3+} codoped sample 4♯, τ_f reaches even as high as 12.6 ms. In all the samples, no concentration quenching is detected. All the optical and spectroscopic properties indicate that this glass system is quite suitable

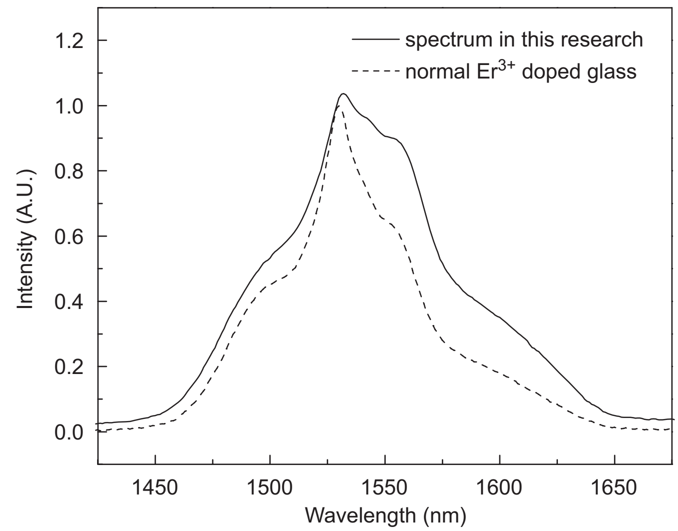

Fig. 2. Fluorescence spectra of sample 3# and a common Er^{3+}-doped fluorophosphate glass.

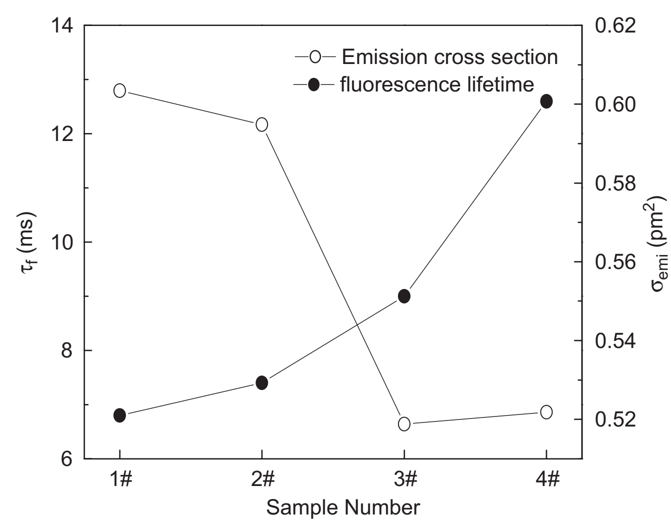

Fig. 3. Emission cross-section and fluorescence lifetime of the samples.

for those situations which need the media glass having low refractive index, high Er^{3+} concentration and relatively high fluorescence lifetime.

Since the crystallization stability of glass is very important for practical applications, a DTA test of 3♯ is conducted. The result is that $T_g = 436.5$ °C, $T_x = 582.3$ °C, T_x–$T_g = 145.8$ °C. This means that this glass system has good crystallization stability. The IR transmission spectrum shown in Fig. 4 has a tiny peak around 3150 cm^{-1} with an absorption coefficient 0.2755 cm^{-1}, which indicates that OH^- absorption has tiny influence on the fluorescence lifetime.

Fig. 5 is the cw-pumping EWOA gain experiment with sample 3# as the gain media. The low refractive index of the FP glass induces low loss and good coupling with the fiber. In this figure, the black part (Si substrate) with pink Er^{3+} glass on it is a real picture taken in the experiment. Relative gains at 1530, 1550 and 1570 nm were obtained and a 2 dB relative gain at 1530 nm was acquired. Further improvement in optical homogeneity of the glass and the coupling efficiency of pumping light will increase the gain largely. Previous works were not successful in cw pumping with Er^{3+}-doped silicate glass [3,7]. Hence this is the

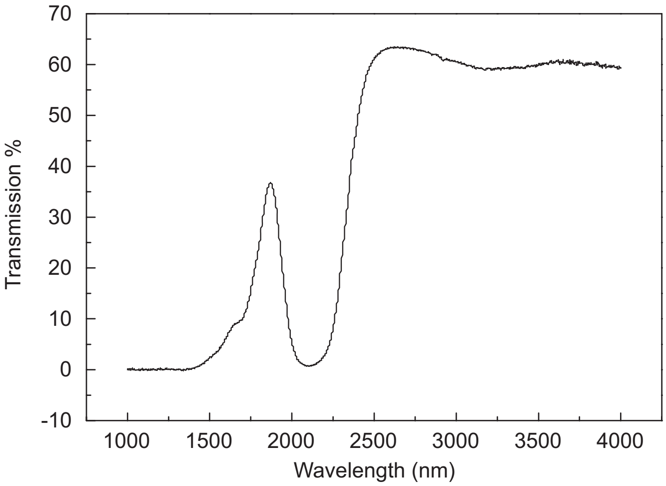

Fig. 4. IR spectrum of the sample.

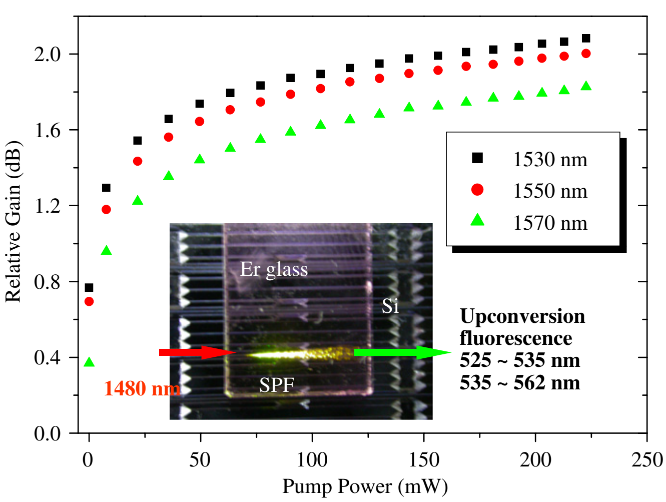

Fig. 5. EWOA gain experiment with sample 3♯.

first time a cw-pumping gain was obtained. The obvious green upconversion luminescence induced by the high Er^{3+} concentration was also detected around 525–562 nm, which is a sign that this series glass can also be used as an upconversion gain medium.

4. Conclusion

A series of high Er^{3+} concentration, low refractive index and relatively long fluorescence lifetime Er^{3+} or Er^{3+}:Yb^{3+}-doped fluorophosphate glasses were prepared. Changes in the relative content of AlF_3, RF_2, YF_3 and KF can induce relatively large changes of σ_{emi} and τ_f value. Also, Yb^{3+}:Er^{3+} codoped sample has a very high τ_f value of 12.6 ms. No concentration quenching is detected in the test. DTA test shows that this glass system possesses good crystallization stability with $T_g = 436.5\,^{\circ}C$, $T_x = 582.3\,^{\circ}C$, $T_x - T_g = 145.8\,^{\circ}C$. The IR transmission spectrum indicates that there is a tiny OH^- peak around 3150 cm^{-1} with an absorption coefficient 0.2755 cm^{-1}. EWOA gain experiment with cw pumping showed a relative gain of 2 dB at 1530 nm. Further improvement can be obtained when the glass and lasing experiment system is enhanced.

Acknowledgment

This work is financially supported by the Chinese National Natural Science Foundation (50502030).

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