Nd^{3+}-doped ion-exchanged aluminum germanate glass waveguide for O-band amplification

Baojie Chen[1], Sai Tak Chu[2], and Edwin Yun Bun Pun[1]
[1]Department of Electronic Engineering,
[2] Department of Physics and Materials Science,
City University of Hong Kong,
Hong Kong, PR China,
eeeybpun@cityu.edu.hk

Hai Lin
School of Textile and Material Engineering,
Dalian Polytechnic University,
Dalian, PR China,
lhai8686@yahoo.com

***Abstract*—K^+–Na^+ ion-exchanged channel waveguide has been fabricated in Nd^{3+}-doped aluminum germanate (NMAG) glasses. The fabricated waveguide exhibits a loss of ~0.36dB/cm, is single mode at 1.3µm, and the maximum theoretical gain at 1.337µm is 16dB/cm. The ion-exchanged Nd^{3+}-doped NMAG glass waveguide show promises in the development of O-band waveguide amplifier, infrared UV-writing grating waveguide laser, and compact integrated optical device.**

Keywords-Rare earth ion; Germanate glasses; Ion-exchanged waveguide ;Optical Amplifier; Integrated optical devices

I. INTRODUCTION

1.55µm (C-band) optical fiber amplifiers have been extensively used in telecommunication systems, however, it is insufficient for the ever expansion in large-capability and high-speed communication systems [1]. Based on high fidelity and low polarization properties of the second telecommunication window, development on 1.3µm wavelength optical amplifiers becomes important for achieving all-optical amplification. Due to the small energy gaps between the emitting and the next lower energy levels of rare earth ions Pr^{3+}, Dy^{3+} and Ho^{3+}, efficient 1.3µm emission can only be obtained in low phonon energy chloride, sulfide and fluoride glasses. However, these glasses exhibit poor chemical durability and inferior thermal stability. As a result, practical application of 1.3µm emission from these rare earth ions is limited. Fortunately, Nd^{3+} possesses relatively wider energy gap (~5500cm^{-1}) for the $^4F_{3/2}$ emitting level, and even in high phonon energy glass systems it is possible to obtain efficient 1.3µm emission. Thus, practical devices can be obtained using Nd^{3+} ions [2].

In our previous works, high-quality aluminum germanate (NMAG) glasses have been successfully used in making Er^{3+} and Tm^{3+} singly doped ion-exchanged waveguides [3, 4]. In this work Nd^{3+}-doped ion-exchanged NMAG glass waveguide has been prepared and investigated for O-band amplification. Potential combination of the ion-exchanged waveguides and UV-direct writing gratings will give rise to attractive photonic devices such as O-band gain-flatten waveguide amplifiers, 1.3 µm waveguide lasers, and integrated optical waveguide devices and circuits.

II. EXPERIMENTS

Nd_2O_3 doped NMAG glasses were prepared using high-purity chemical powders according to the molar host composition $23Na_2O$-$3MgO$-$22Al_2O_3$-$52GeO_2$-5wt%Nd_2O_3, and the preparation procedure details is described in [3]. Using a Metricon 2010 prism coupler, the refractive indices of the sample were measured to be 1.57758 and 1.56078 at 632.8 and 1536nm wavelengths, respectively. The infrared fluorescence and excitation spectra were recorded using a Jobin Yvon Fluorolog-3 Spectrophotometer with a NIR PMT detector and a commercial CW Xe-lamp source. The emission decay curve was recorded under the same setup with a flash Xe-lamp source. All measurements were carried out at room temperature.

Before preparing ion-exchanged channel waveguides, a 150nm-thick high-quality aluminum film was deposited on the glass surface using an Edwards Auto 306 thermal evaporator, and then 8µm wide windows were opened by wet chemical etching method. The ion-exchange process was performed in pure KNO_3 molten bath at 390 °C. After cooling down to room temperature, the aluminum film was removed and the two end-facets of the waveguides were polished for further optical measurements. The near-field mode patterns at 1.3µm were examined using a video camera.

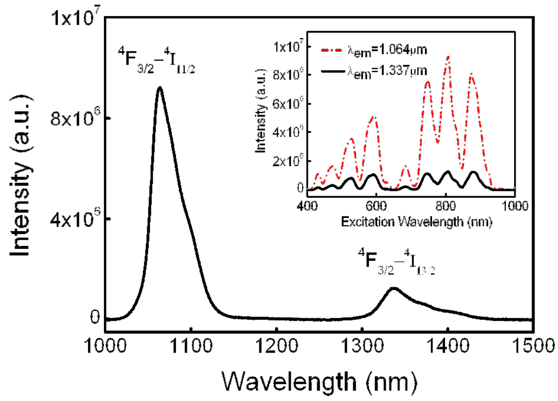

Figure 1. Infrared emission spectra in 5wt% Nd_2O_3 doped NMAG glasses. Inset: Excitation spectra for 1.064 and 1.337 µm emissions

III. Discussion

Figure 1 shows the infrared emissions in the 5wt% Nd_2O_3 doped NMAG glasses under 808nm excitation. The intense 1.064 and 1.337μm emissions can be attributed to the $^4F_{3/2}\rightarrow^4I_{11/2}$ and $^4I_{13/2}$ transitions. The full-width at half-maximum (FWHM) and the lifetime of the 1.337μm emission are ~43nm and 108μs, respectively. The inset shows the excitation spectra of the 1.064 and 1.337μm emissions, and there are eight excitation peaks at 432, 473, 530, 592, 684, 749, 808 and 874nm, respectively.

Thermal K^+–Na^+ ion-exchange process was carried out at 390°C. The refractive index of a slab waveguide as a function of diffusion depth at 632.8nm was derived from the measured mode indices using IWKB method and shown in Figure 2. The surface refractive index is estimated to be 1.5926, and the maximum refractive index change is 0.015. Here, one guided mode at 1536 nm is demonstrated as shown in Figure 2 upper inset, indicating that it is feasible to fabricate single mode waveguide in the wavelength range 1300-1800nm using the ion-exchange process.

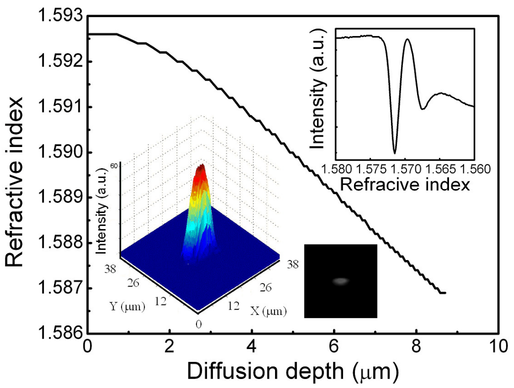

Figure 2. Index profile of a slab waveguide measured at 632.8nm. Upper inset: Prism coupler result measured at 1536nm. Bottom inset: Near-field mode pattern and a 3D representation of the channel waveguide at 1.3μm.

Based on the parameters of slab waveguides, the condition of K^+–Na^+ ion-exchanged process for single mode channel waveguide was selected to be 4h at 390°C. As shown in Figure 2 bottom inset the mode profile confirms that the channel waveguide is single mode at 1.3μm, and the measured mode field diameters were 10.1μm (horizontal, X) and 5.3μm (vertical, Y), respectively, indicating an excellent overlap with those of a standard single-mode fiber. Using cut-back method the loss is ~ 0.36dB/cm at 1.3μm wavelength.

Figure 3 shows the calculated emission cross-sections based upon the Fuchtbauer-Ladenburg formula. The maximum emission cross-sections for the $^4F_{3/2}\rightarrow^4I_{11/2}$ and $^4F_{3/2}\rightarrow^4I_{13/2}$ transitions are estimated to be $33.66\times10^{-21}cm^2$ and $14.32\times10^{-21}cm^2$, respectively. The gain properties of the Nd^{3+} ions can be derived using the emission cross-section parameters. Assuming that the Nd^{3+} ions are partially or totally located at the $^4F_{3/2}$ level, the gain $G(\lambda,P)$ can be expressed by the following expression [5]:

$$G(\lambda,P)=10\log_{10}\exp(PN\beta\sigma_{em}(\lambda)) \tag{1}$$

where P is the fractional factor, N is the total dopant concentration, and β is the branching ratio. Figure 3 inset shows the calculated gain spectra of the 1.337 μm emission. The theoretical gain increases as the population density increases. When P reaches 0.8 and 1.0, the signal gains at 1.337μm wavelength are evaluated to be 13dB/cm and 16dB/cm, respectively, indicating that the Nd^{3+}-doped NMAG glass waveguide amplifier is a potential O-band gain medium.

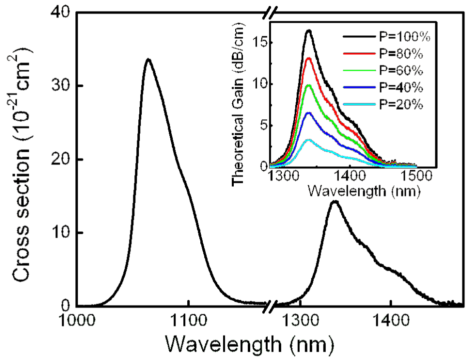

Figure 3. Stimulated emission cross-section profiles for the $^4F_{3/2}\rightarrow^4I_{11/2}$ and $^4F_{3/2}\rightarrow^4I_{13/2}$ transitions in 5wt% Nd^{3+} doped NMAG glasses. Inset: Calculated theoretical gain spectra of the $^4F_{3/2}\rightarrow^4I_{13/2}$ transition.

IV. Conclusion

5wt% Nd^{3+} doped NMAG ion-exchanged glass waveguide has been fabricated, and the emission spectra were investigated. Single mode waveguide at 1.3μm was prepared, and the mode field diameters and losses were measured. The maximum theoretical gain at 1.337μm wavelength is calculated to be ~16dB/cm. The results indicate that the Nd^{3+}-doped NMAG glass ion-exchanged waveguide amplifier has potential applications as O-band optical amplifier and laser.

V. Acknowledgment

This work is supported by a City University of Hong Kong Strategic Grant No. 7008099.

VI. References

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