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Fabrication and characterization of Er^{3+}-doped tellurite glass waveguide by Ag^+-Na^+ ion-exchange method

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Abstract. The planar waveguides of $12Na_2O \cdot 10NbO_{2.5} \cdot 25WO_3 \cdot 53TeO_2 + 1Er_2O_3$ ([NbWEr]) glasses were prepared by Ag^+-Na^+ ion-exchange at 320-380°C for 5-30 h. The optical properties of the waveguides were characterized. Waveguiding property was successfully confirmed under all the ion-exchange conditions in this study. The thickness of the waveguides increased with increasing ion-exchange temperature and time. The minimum propagation loss of the waveguides was approximately 0.8 dB/cm at 632.8 nm. Hence, the [NbWEr] glass waveguides were considered to be promising for broadband optical amplifiers.

1. Introduction

It is requested to enhance the speed and density of telecommunication with increasing in the demand for optical communication. As one of the solutions, the wavelength division multiplexing (WDM) method attracts attention. A wideband optical amplifier as one of optical devices is indispensable in order to amplify communication light that attenuates by transmission. An Er^{3+}-doped tellurite glass is an attractive material as a broadband amplifier at 1.5 μm in WDM network. An optical waveguide forms the basis for an integrated optical device applicable to an amplifier and laser for high-speed signal processing in telecommunication. The optical waveguides have been fabricated on substrate glasses by means of various techniques such as ion-exchange, sol-gel, plasma enhanced chemical vapor deposition (PECVD), physical vapor deposition (PVD), flame hydrolysis deposition (FHD), pulsed laser deposition (PLD), rf-sputtering and laser writing. Among these techniques, an ion-exchange method is effective to make an optical waveguide on a substrate glass owing to its simplicity, flexibility, reliability and low cost. So far, many studies about optical waveguides fabricated on silicate [1], soda-lime [2], borosilicate [3] and phosphate [4] substrate glasses by ion-exchange have been reported. However, studies about the fabrication and characterization of tellurite glass waveguides by ion-exchange are a few [5-9] although the waveguide amplifier in a tellurite glass is expected to exhibit high optical gain and to be low-cost and compact. Hence, the further information about the fabrication and characterization of tellurite glass waveguides by ion-exchange is necessary.

In this study, the planar waveguides of an Er^{3+}-doped niobium tungsten tellurite glass are prepared by Ag^+-Na^+ ion-exchange under various conditions. The optical properties of the waveguides are characterized.

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2. Experimental

$12Na_2O{\cdot}10NbO_{2.5}{\cdot}25WO_3{\cdot}53TeO_2{+}1Er_2O_3$ ([NbWEr]) glasses were prepared as a substrate glass. High purity reagents of Na_2CO_3, Nb_2O_5, WO_3, TeO_2, and Er_2O_3 powders were used as starting materials. A 20 g batch of well-mixed reagents were melted in a gold crucible covered with a rid of alumina using an electric furnace at 900°C for 30 min in air. The glasses prepared were annealed near the glass transition temperature for about 1.5 h. After annealing, all faces of the glasses were mirror-polished for optical measurements and waveguide fabrication.

In Ag^+-Na^+ ion-exchange process, each waveguide was prepared by immersing the glass samples in $1.0AgNO_3{\cdot}49.5NaNO_3{\cdot}49.5KNO_3$ (mol%) molten salt at 300-380°C for 5-30 h in air. Before ion-exchange, all samples were preheated in electric furnace at each ion-exchange temperature to prevent them from cracking due to high thermal expansion coefficient of tellurite glasses. After ion-exchange, the samples were pulled out of the reaction bath and were put in the electric furnace heated to the vicinity of the ion exchange temperature. Then, they slowly cooled up to the room temperature in the electric furnace.

T_g of the substrate glass was determined with a Rigaku TAS 300 TG 8110D TG-DTA. The measurement was carried out at a heating rate of 10 $K{\cdot}min^{-1}$ in air.

The refractive indices of the substrate glass and the effective mode indices and propagation losses of the waveguides at the wavelengths of 473, 632.8, 983.1, and 1548 nm were measured by means of a prism coupler technique (Metricon Model 2010 Prism Coupler). The optical properties of the [NbWEr] glass waveguides were compared with those of the following glass waveguides: $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ (mol%) ([WEr])[7, 8], $12Na_2O{\cdot}7ZrO_2{\cdot}25WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ (mol%) ([ZrWEr])[9], $12Na_2O{\cdot}10TiO_2{\cdot}25WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ (mol%) ([TiWEr])[9], and $12Na_2O{\cdot}10AlO_{1.5}{\cdot}25WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ (mol%) ([AlWEr])[9].

3. Results and discussion

3.1 Glass transition temperature and refractive indices

Table 1 lists T_g and refractive indices at the wavelengths of 473, 632.8, 983.1, and 1548 nm (n_{473}, $n_{632.8}$, $n_{983.1}$, and n_{1548}, respectively) of [NbWEr] substrate glass.

Table 1. Glass transition temperature (T_g) and refractive indices at wavelengths of 473, 632.8, 983.1, and 1548 nm (n_{473}, $n_{632.8}$, $n_{983.1}$, and n_{1548}, respectively) of [NbWEr] substrate glass.

	T_g[°C]	n_{473}	$n_{632.8}$	$n_{983.1}$	n_{1548}
[NbWEr]	379	2.141	2.076	2.034	2.015

3.2 Refractive-index profiles

In the prism coupling measurements, waveguide modes were observed for all the glasses ion-exchanged, indicating the successful fabrication of the planar waveguides in the glass under all the ion-exchange conditions in this study. Refractive-index profiles were obtained from the measured mode indices using an inverse Wentzel-Kramers-Brillouin (WKB) method.

Figure 1 shows refractive-index profiles at 632.8 nm for [NbWEr] glass waveguides by ion-exchange at 320-380°C for 5 h. The waveguide depths from glass surface increased with increasing ion-exchange temperature. The glass surface refractive indices were high at low ion-exchange temperatures. This is probably due to an error caused by a small number of waveguide modes. Figure 2 shows refractive-index profiles at 632.8 nm for [NbWEr] glass waveguides by ion-exchange at 360°C for 5-30 h. The waveguide depths from glass surface increased with increasing ion-exchange time. The glass surface refractive indices of the waveguides were independent of the ion-exchange time and waveguide depths.

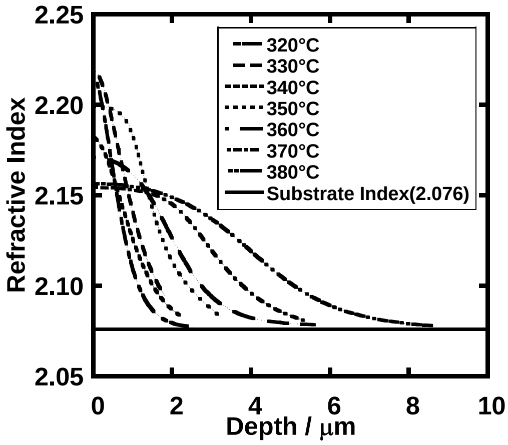

Figure 1. Refractive index profiles at 632.8 nm for [NbWEr] glass waveguides fabricated by ion-exchange at 320-380°C for 5 h.

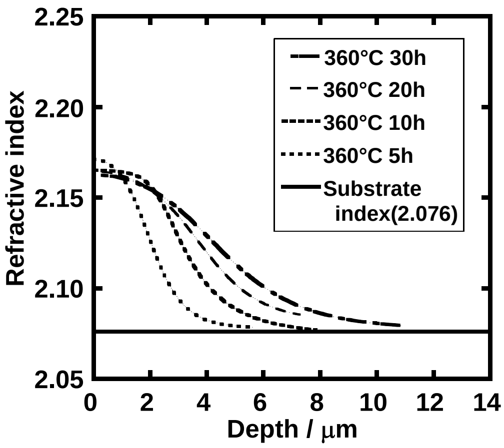

Figure 2. Refractive index profiles at 632.8 nm for [NbWEr] glass waveguides fabricated by ion-exchange at 360°C for 5-30 h.

3.3 Diffusion parameters

A refractive-index profile can be fitted using a Gaussian function,

$$n(x) = n_{sub} + (n_{surf} - n_{sub}) \exp(-x^2 / d^2)$$
$$= n_{sub} + \Delta n \exp(-x^2 / d^2) \qquad (1)$$

where x is the depth from the surface of glass substrate, n_{sub} is the refractive index of glass substrate, n_{surf} is the refractive index of glass surface, Δn is the maximum index change at the surface of the substrate, and d is the effective depth of the waveguide. When $x = d$, $n(d) = n_{sub} + \Delta n/\mathrm{e}$. d is used as a representative depth to calculate the diffusion parameters of Ag^+ ions in the waveguide, since the gradual refractive index change of the waveguide with the depth makes the determination of waveguide depth difficult.

d can be given by the following equation that describes the diffusion process:

$$d = (D_e t)^{1/2} \qquad (2)$$

where D_e is an effective diffusion coefficient, and t is the diffusion time. A d value can be obtained from a measured refractive-index profile and equation (1). A D_e value can be calculated by using d and t values and equation (2).

Figure 3 shows relationship between D_e and ion-exchange temperatures for [NbWEr], [TiWEr], [AlWEr], and [ZrWEr] glass waveguides. For D_e of tellurite glass waveguides at the same temperature the following order is obtained; [NbWEr] > [TiWEr] > [AlWEr] and [ZrWEr]. Hence, Ag^+ ions in [NbWEr] glass diffuse faster than those of other glasses.

3.4 Propagation losses

The propagation losses of [NbWEr] glass waveguides were obtained by fitting an exponential curve to an experimental curve, where a loss was defined by the next equation:

$$\text{Loss (dB)} = 10 \log_{10}(I_{in} / I_{out}) \qquad (3)$$

Since the absorption by Er^{3+} ion was not observed at 632.8 nm, the propagation losses at 632.8 nm were used for the evaluation. Figure 4 shows relationship between propagation losses at the wavelength of 632.8 nm and ion-exchange temperatures for [NbWEr], [TiWEr], [AlWEr], [ZrWEr], and [WEr] glass waveguides. The propagation losses in this figure are about 1-5 dB/cm and are not very dependent on ion-exchange temperature.

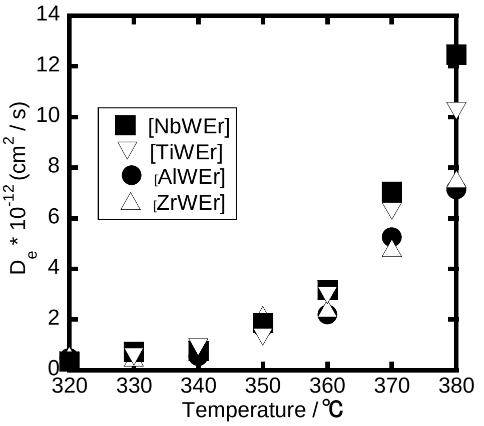

Figure 3. Effective diffusion coefficient (D_e) of tellurite glass waveguides by ion-exchange at 320-380℃ for 5 h.

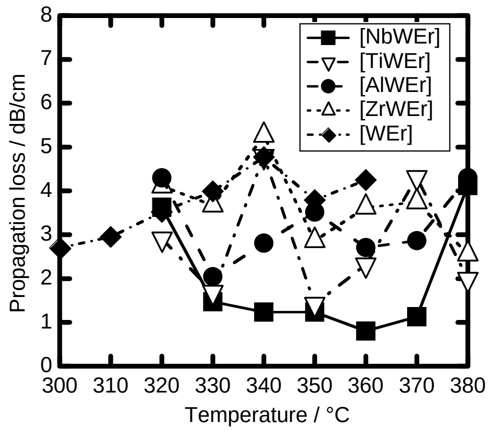

Figure 4. Relationship between propagation losses at the wavelength of 632.8nm and ion-exchange temperatures for [NbWEr], [TiWEr], [AlWEr], [ZrWEr] and [WEr] glass waveguides.

It was considered that the lowest loss was obtained at the best measurement conditions such as optical contact between prism and specimen, and hence the comparison of the lowest loss was chosen. The order of the lowest loss for [NbWEr], [TiWEr], [AlWEr], [ZrWEr] and [WEr] glass waveguides was as follows; [NbWEr] (0.80 dB/cm) < [TiWEr] (1.41 dB/cm) < [AlWEr] (2.04 dB/cm) < [ZrWEr] (2.55 dB/cm) < [WEr] (2.70 dB/cm). From the viewpoint of loss, [NbWEr] and [TiWEr] glasses seem to be suitable for optical waveguides. Therefore, [NbWEr] and [TiWEr] glasses are appropriate host materials for the application to a small wideband optical amplifier.

4. Conclusion

The planar waveguides have been successfully fabricated on [NbWEr] glass substrate by Ag^+-Na^+ ion-exchange. The waveguide depths from glass surface increased with increasing ion-exchange temperature and time. [NbWEr] glass waveguides indicated lower propagation losses than other glasses developed by the authors' research group before. It was concluded that [NbWEr] and [TiWEr] glasses were appropriate host materials for the application to a small wideband optical amplifier.

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