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Refractive-index profiles and propagation losses of Er^{3+}-doped tungsten tellurite glass waveguide by Ag^{+}–Na^{+} ion-exchange

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Abstract

The planar waveguide of $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ glass (in mol%) was prepared by Ag^{+}–Na^{+} ion-exchange at 330 °C for 5 h. The effective mode indices and propagation losses of the waveguide at the wavelengths of 473, 632.8, 983.1 and 1548 nm for TE and TM modes were measured by means of a prism coupler technique. The results were compared with those of a planar waveguide of the tungsten tellurite glass without Er^{3+} ions. Especially, the propagation losses of ion-exchanged tellurite glass waveguides were estimated for the first time to the best of our knowledge.

Keywords: Tellurite glasses; Ion-exchange; Optical waveguide; Optical materials and properties; Refractive-index profiles; Propagation losses

1. Introduction

Er^{3+}-doped tellurite glasses are good candidates as 1.5 μm broadband amplifier host materials for development of wavelength division multiplexing (WDM) telecommunication system. Planar waveguides allow the development of low-cost and compact devices to be used in metropolitan and local access networks. Ion-exchange method has been recognized as a powerful technique for planar waveguide fabrication in a glass due to its simplicity, flexibility, effectiveness, reliability and low-cost. So far, Ag^{+}–Na^{+} and K^{+}–Na^{+} ion-exchanges were carried out on various oxide glasses [1–6]. However, only a few papers report the fabrication of waveguides in tungsten tellurite glasses by Ag^{+}–Na^{+} ion-exchange [7,8] although the waveguide amplifier in a tellurite glass is expected to exhibit high optical gain and to be low-cost and compact. Hence, further study about tellurite glass waveguides by ion-exchange method is needed in order to obtain more detailed information.

In the present study, the effective mode indices and propagation losses of a planar waveguide of an Er^{3+}-doped tungsten tellurite glass by Ag^{+}–Na^{+} ion-exchange are examined. The results are compared with those of a planar waveguide of the tungsten tellurite glass without Er^{3+} ions.

2. Experimental

The composition of an Er^{3+}-doped tungsten tellurite glass prepared is $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ in mol%. The glass was prepared according to the following procedure: A 20 g batch of well-mixed reagents was melted in a gold crucible at 800 °C for 30 min. The melt was poured onto a brass plate and immediately pressed by a stainless plate. The prepared glass was annealed near the glass-transition temperature (374.2 °C) for 1 h. After annealing, the glass was cut into a plate of 50 × 15 × 2 mm in size and all faces mirror-polished for optical measurements and waveguide fabrication. The $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ glass without Er^{3+} ions was also prepared by the same procedures to examine an effect on optical properties by the addition of 1 mol% Er_2O_3.

Ion-exchange was performed by immersing the glass samples in $1.0AgNO_3{\cdot}49.5NaNO_3{\cdot}49.5KNO_3$ (mol%) molten salt at 330 °C for 5 h for waveguide fabrication.

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Table 1
Refractive indices (n) of $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass at the wavelengths of 473, 632.8, 983.1 and 1548 nm for TE and TM modes

Mode	n_{473}	$n_{632.8}$	$n_{983.1}$	n_{1548}
TE	2.1362	2.0720	2.0298	2.0103
TM	2.1360	2.0709	2.0300	2.0101

The refractive indices of the substrate glasses and the effective mode indices and propagation losses of the waveguides at the wavelengths of 473, 632.8, 983.1 and 1548 nm for TE and TM modes were measured by means of a prism coupler technique (Metricon Model 2010 Prism Coupler).

3. Results and discussion

The refractive indices of $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ substrate glass for TE and TM modes at the wavelengths of 473, 632.8, 983.1 and 1548 nm are listed in Table 1. In the table, n_{473}, $n_{632.8}$, $n_{983.1}$ and n_{1548} denote refractive indices at 473, 632.8, 983.1 and 1548 nm, respectively. The glass has high refractive indices more than two. The refractive indices for TE mode are almost the same as those for TM mode in the same wavelength, indicating that the glass is optically isotropic. The refractive indices of $12Na_2O·35WO_3·53TeO_2$ substrate glass for TE mode are 2.1463, 2.0801, 2.0368 and 2.0173 at 473, 632.8, 983.1 and 1548 nm, respectively, and larger than those of the $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass at the same wavelengths. This is probably due to the larger polarizability of Te^{4+} than that of Er^{3+}.

Fig. 1 shows waveguide modes of ion-exchanged $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass at 473, 983.1 and 1548 nm for TE mode and at 632.8 nm for TE and TM modes. Downward peaks and a numeral in parentheses in the figure denote modes and the number of mode, respectively. One–five modes were clearly detected at all the measured wavelengths, indicating that the waveguide of the glass was able to be fabricated under this ion-exchange condition. The number of mode increased with decreasing wavelength. The number of TE and TM modes at 632.8 nm was three and almost the same values of the effective mode indices for TE and TM modes were observed. The number of modes of ion-exchanged $12Na_2O·35WO_3·53TeO_2$ glass was the same as that of the ion-exchanged $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass at 473, 983.1 and 1548 nm whereas that of the ion-exchanged $12Na_2O·35WO_3·53TeO_2$ glass at 632.8 nm increased by one to four compared with that of the ion-exchanged $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass. This is probably due to the larger polarizability of Te^{4+} than that of Er^{3+}.

Fig. 2 shows refractive-index profiles of $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass waveguide for TE and TM modes (top) and of $12Na_2O·35WO_3·53TeO_2$ glass waveguide for TE mode (bottom) at 632.8 nm. The closed circles and solid curve in the figure denote TE mode, and the open squares and dotted curve TM mode. The horizontal broken lines in the figure exhibit the glass substrate indices. These profiles were calculated from the measured mode indices by use of an inverse Wentzel–Kramers–Brillouin (WKB) method [9]. The number of modes for the $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ waveguide was three for TE and TM modes, and the differences in the refractive index and depth from the glass surface corresponding to each mode for the waveguide between TE and TM modes were hardly observed. Consequently, the shapes of the index profiles for the waveguide were almost the same between TE and TM modes. This indicates that the ion-exchanged layer in the waveguide is optically isotropic. The ion-exchanged layer was about 3 μm thick. The number of mode for the $12Na_2O·35WO_3·53TeO_2$ waveguide was four for TE mode and the ion-

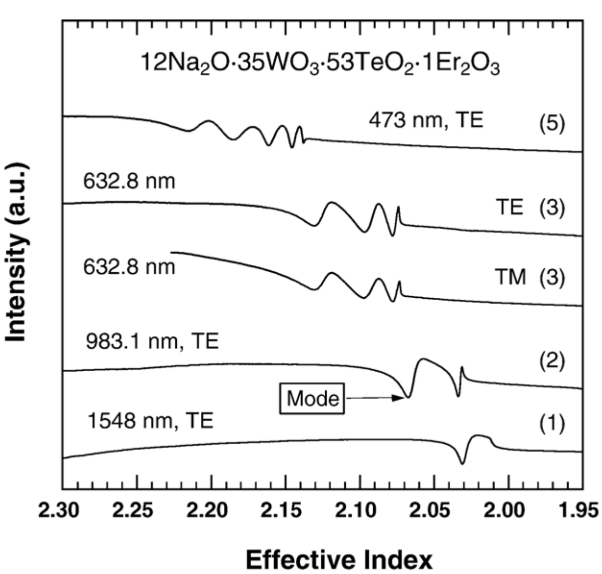

Fig. 1. Waveguide modes of ion-exchanged $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass at 473, 983.1 and 1548 nm for TE mode and at 632.8 nm for TE and TM modes.

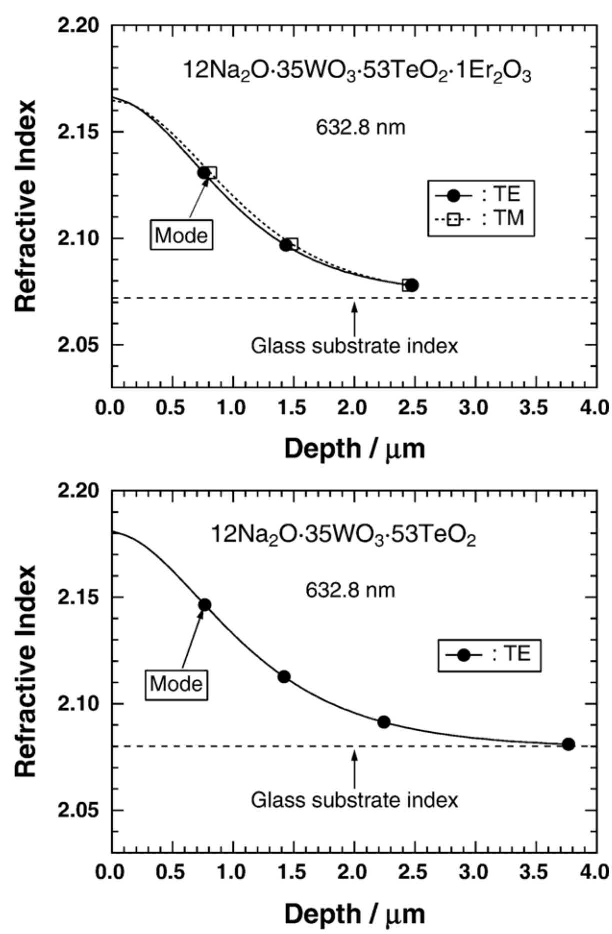

Fig. 2. Refractive-index profiles of $12Na_2O·35WO_3·53TeO_2·1Er_2O_3$ glass waveguide for TE and TM modes (top) and of $12Na_2O·35WO_3·53TeO_2$ glass waveguide for TE mode (bottom) at 632.8 nm.

Table 2
Propagation losses (dB/cm) at 473, 632.8, 983.1 and 1548 nm and TE and TM modes for $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ glass waveguide by ion-exchange

Mode	473 nm	632.8 nm	983.1 nm	1548 nm
TE	6.46	3.99	6.67	7.90
TM	6.04	3.67	6.48	7.42

exchanged layer was about 4 μm thick. Thus, the addition of Er_2O_3 leads to the decrease in the thickness of the ion-exchanged layer. Therefore, it can be said that the thickness of ion-exchanged layer depends on glass composition. The surface refractive indices n_{surf} obtained by the refractive-index profiles were 2.1663 and 2.1810 for $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ and $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ waveguides, respectively (TE mode). The refractive-index changes Δn from the substrate indices were 0.0943 and 0.1009 for $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ and $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ waveguides, respectively (TE mode). These Δn values are very similar. This is probably due to almost the same Na_2O content ion-exchanged by Ag^+ ions.

Table 2 summarizes the propagation losses (dB/cm) at 473, 632.8, 983.1 and 1548 nm and TE and TM modes for $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ glass waveguide by ion-exchange. The propagation losses of the $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ waveguide at each wavelength gave similar values for both modes. The propagation losses were about 6, 3–4, 6 and 7–8 dB/cm at 473, 632.8, 983.1 and 1548 nm, respectively. The magnitude of the losses was of the following order: $1548 > 983.1 \approx 473 > 632.8$ nm. On the other hand, the propagation losses of the $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ glass waveguide for TE mode were 6.16, 3.10 2.52 and 2.19 dB/cm at 473, 632.8, 983.1 and 1548 nm, respectively. The losses of the $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ waveguide at 473 and 632.8 nm were similar to those of $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ waveguide whereas the losses of the $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ waveguide at 983.1 and 1548 nm were much smaller than those of $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ waveguide. The large losses at 983.1 and 1548 nm for $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ waveguide are due to the absorption of Er^{3+} ions.

4. Conclusions

In conclusion, the planar waveguide of $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ glass in mol% was fabricated by Ag^+–Na^+ ion-exchange at 330 °C for 5 h. The optical properties of the waveguide were characterized. The planar waveguide has been fabricated by the ion-exchange condition. The ion-exchanged layer in the waveguide was about 3 μm thick. The substrate glass and the ion-exchanged layer in the waveguide were optically isotropic. The propagation losses at each wavelength gave similar values for TE and TM modes. The propagation losses were about 6, 3–4, 6 and 7–8 dB/cm at 473, 632.8, 983.1 and 1548 nm, respectively. For comparison the $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ glass waveguide was also fabricated by the same condition. The ion-exchanged layer in the waveguide was about 4 μm thick. The thickness of ion-exchanged layer depends on the diffusion rate of Ag^+ under the same condition. The addition of Er_2O_3 is considered to make the diffusion rate of Ag^+ slow. Therefore, it can be said that the thickness of an ion-exchanged layer depends on glass composition. The propagation losses of the $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2$ waveguide were 6.16, 3.10 2.52 and 2.19 dB/cm at 473, 632.8, 983.1 and 1548 nm, respectively, indicating that the large losses at 983.1 and 1548 nm for $12Na_2O{\cdot}35WO_3{\cdot}53TeO_2{\cdot}1Er_2O_3$ glass waveguide are due to the absorption of Er^{3+} ions. Studies of the detailed optical properties with respect to planar waveguides of tungsten tellurite glasses under various ion-exchange conditions are now in progress and the results will be reported later.

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