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Refractive index change of multicomponent glass films for bismuthate erbium-doped waveguide amplifiers prepared by radio-frequency magnetron sputtering under different magnetic fields of cathode

Junichi Kageyama [a,b,*], Mamoru Yoshimoto [b], Akifumi Matsuda [b], Yuki Kondo [a], Motoshi Ono [a], Naoki Sugimoto [a]

[a] Asahi Glass Co., Ltd., 1150 Hazawa-cho, Kanagawa-ku, Yokohama 221-8755, Japan
[b] Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta, J3-16, Midori-ku, Yokohama 226-8502, Japan

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ABSTRACT

Bismuthate erbium (Er)-doped waveguide amplifiers consist of an Er-doped core surrounded by an Er-free cladding film with lower refractive index. The propagation loss of a waveguide critically depends on both the thickness and the refractive index of its core and cladding films; hence, these two properties of such films must be controlled. We studied the influence of magnetic fields on a batch-to-batch variation of the refractive index of Er-free multicomponent cladding glass films deposited by radio-frequency magnetron sputtering. We successfully controlled the variation in the refractive indices of the films to within 0.001 throughout the lifetime of the target by applying the design techniques of a weak magnetic field and flat magnetic field lines to a magnetic array for sputtering. We also found that the self-bias voltage maintained a high value irrespective of target consumption. This phenomenon is thought to be related to stabilization of the deposition rate and the refractive index of the films under the experimental sputtering conditions.

1. Introduction

Worldwide Internet traffic has been continuing to grow for more than a decade. To satisfy the huge demand for Internet connectivity, the capacity of optical communication systems must be increased [1]. Wavelength division multiplexing (WDM) technology when applied to a traditional optical fiber enables a significant and cost-effective increase in the amount of transmitted data [1,2]. Optical signals are attenuated during their transmission over a fiber. Consequently, optical amplifiers must be positioned throughout the optical network. An optical amplifier for WDM systems is desired to broaden amplifier bandwidth and to yield a higher output signal power. Because the erbium (Er)-doped waveguide amplifier (EDWA) is compact and cost-effective, it is an attractive amplifier for a WDM system in a metropolitan network [3,4].

Bismuthate glass is highly capable of being doped with Er-ions; in addition, it emits a wide-band emission spectrum, its refractive index is easily adjusted, and its performance is highly reliable. Therefore, multicomponent bismuthate glass is considered a promising host material for EDWAs [5]. The above-mentioned remarkable features contribute to the compactness and high performance of the device, as we have already reported for bismuthate Er-doped fibers [6–8] and waveguides [5,9–11].

Sputtering is considered the most suitable technique for the deposition of multicomponent glass films, such as those of bismuthate glass, for the fabrication of bismuthate EDWAs (Bi-EDWAs) because of the ease with which the composition is adjusted and the simplicity of the deposition system [12]. However, achieving precise control of the refractive index of an optical film throughout the lifetime of the sputtering target and precise control of the film thickness is difficult. Some authors have described the relationship between deposition rate and magnetic field [13–15] or between film composition and magnetic field [16]. However, few studies have considered the ultra-precise technology for controlling the refractive index of a film, even for a simple component film. The light propagation loss in a waveguide critically depends on both the thickness and the refractive index of the core and cladding films; hence, these two properties must be controlled.

To minimize the bending loss of a waveguide circuit, the appropriate refractive index difference between the core and the cladding film of Bi-EDWA is approximately 0.03 [refractive indices at a wavelength of 1310 nm: 1.952 (core), 1.922 (cladding film)] [5]. Thus the batch-to-batch reproducibility of the refractive indices of the mentioned optical films needs to be controlled within 0.001 throughout the target life. The purpose of this study is to investigate the influence of the magnetic fields on the refractive index of radio-frequency (RF) magnetron sputtered multicomponent bismuthate glass films for the Bi-EDWA

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* Corresponding author at: Asahi Glass Co., Ltd., 1150 Hazawa-cho, Kanagawa-ku, Yokohama 221-8755, Japan. Tel.: +81 45 374 7142; fax: +81 45 374 8874.
E-mail address: junichi.kageyama@agc.com (J. Kageyama).

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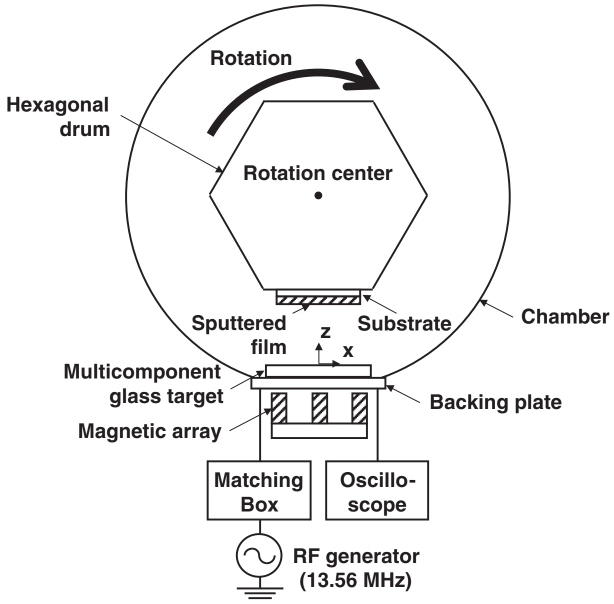

Fig. 1. Top view of the RF magnetron sputtering system.

cladding layer. As a result, we report a magnetron sputtering technique in which the batch-to-batch refractive index variations are controlled to within 0.001 throughout the target life under the application of an appropriate magnetic field setup.

2. Experimental procedures

Fig. 1 shows the top view of the RF magnetron sputtering system (ANELVA Corp., SPC-350), in which a multicomponent glass target composed of the oxides of Bi_2O_3, SiO_2, Ga_2O_3, Al_2O_3, and La_2O_3 with a diameter of 4 in. (101.6 mm) and a thickness of 3 mm was placed on the backing plate. Using the sputtering system shown in Fig. 1, we deposited a multicomponent bismuthate glass film as a Bi-EDWA cladding layer onto a soda–lime glass substrate [Asahi Glass Co., Ltd.; 3-inch diameter (76.2 mm)] under Ar and O_2 gas at flow rates of 30 and 0.5 sccm, respectively. The substrate was mounted to a rotary hexagonal drum centered in a chamber. Sputtering was conducted as a power of 120 W using a 13.56-MHz RF power supply with the substrate under a pressure of 0.3 Pa at room temperature. Because the drum was rotated at 6 rpm, the sputtered target material was iteratively deposited onto the substrate while the substrate was facing the target. A magnetic array was allocated behind the target to produce high-density plasma above the target. In this paper, we compared the refractive-index stability of RF magnetron-sputtered multicomponent glass films under the four different types of magnetic arrays, i.e., arrays A to D. As shown in Fig. 2, these magnetic arrays were built using several permanent magnets (neodymium sintered magnets and ferrite magnets).

We repeated the deposition of approximately 6.5-μm-thick films under identical conditions until a given target was consumed. The substrate was exchanged after the deposition of each 6.5-μm-thick film. Each magnetic array was used until a target was consumed. The refractive index at a wavelength of 1310 nm and the film thickness were simultaneously measured with a prism coupling apparatus (Metricon, Model 2010) using two different propagation modes, i.e., transverse electric (TE) and transverse magnetic (TM) modes. The accuracies of refractive index and film thickness are ± 0.0005 and $\pm(0.5\% + 5\ \text{nm})$, respectively. The composition ratios of the sputtered films were analyzed by an electron probe microanalyzer (EPMA; JEOL JXA-8900M). The repeatability of the EPMA measurement results is less than 1%. The deposition rate of the film was obtained by dividing film thickness by deposition time. Each time a few 6.5-μm-thickness depositions were performed, the radial erosion profile of the target was measured with a depth gauge (Teclock DM-224). The volume sputtered (eroded) from the target was estimated from the radial erosion profile of the target. The error of estimated volume is thought to be less than 3%. The stability of the sputtering rate was estimated from the relationship between the sputtered (eroded) volume and the total deposited film thickness from one target. The self-bias voltage at the backing plate was measured with a high-voltage passive probe and a digital oscilloscope (Tektronix P6009 and TDS-520).

3. Results and discussion

3.1. Refractive index control

Fig. 3 shows the simulated results of the horizontal and vertical elements of magnetic flux density (B_x and B_z) of each magnetic array, which are defined at the target surface. The simulation was carried out by using the commercialized software (ELF/MAGIC, ELF Corp.) based

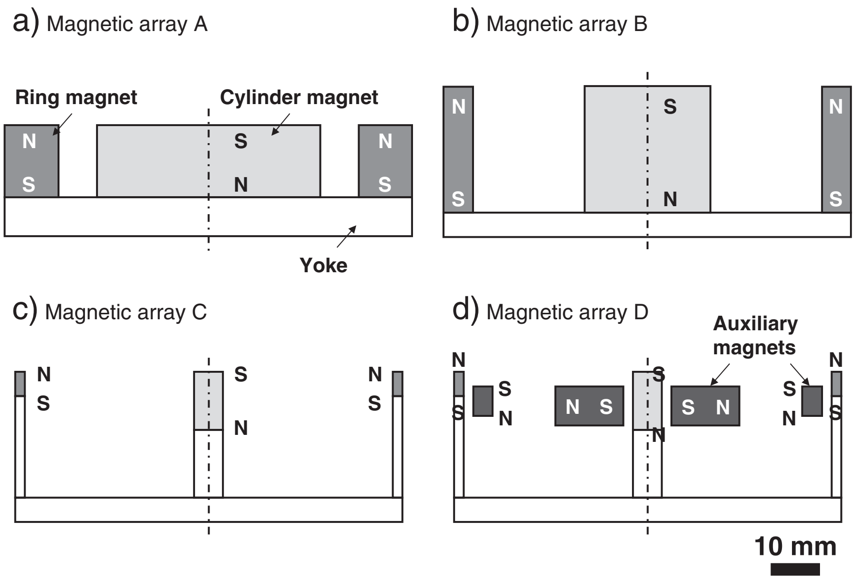

Fig. 2. Cross-sections of magnetic arrays A to D.