Single-Mode Fiber-Type Polarizer

TOSHIHITO HOSAKA, KATSUNARI OKAMOTO, AND JUICHI NODA

Abstract—**The simple and novel fabrication technique of the fiber-type polarizer has been demonstrated and the polarization characteristics of the polarizer have been investigated. The polarizer structure consists of the eccentric core and the metal coat on the thin buffer layer whose thickness is controlled by chemical etching. The maximum extinction ratio of 41 dB (polarizer length $L = 40.8$ mm) was obtained at $\lambda = 1.15$ μm when the buffer layer thickness was about 0.3 μm. Although the insertion loss increases with decreasing the buffer layer thickness, the insertion loss of 0.66 dB was obtained with the extinction ratio of 22 dB (polarizer length $L = 21.4$ mm). An aluminum coat was superior to a gold coat for low propagation loss and a high extinction ratio.**

I. Introduction

RECENTLY, there has been growing interest in utilizing the state of polarization of a single-mode fiber [1]-[3]. A fiber-type polarizer is suitable for connecting it with optical fiber and is also important as a component in an optical isolator and fiber sensors. As for the fabrication technique of a fiber-type polarizer, two methods have been reported [4], [5]. Eickhoff [4] has fabricated the polarizer by polishing out the cladding on one side of the single-mode fiber and evaporating metal onto the polished surface. This fiber-type polarizer utilizes the attenuation difference between the two modes whose electric fields lie horizontally (pseudo-TE_0 mode) or perpendicularly (pseudo-TM_0 mode) to the metal surface. Bergh *et al.* [5] have made the polarizer by removing the cladding and replacing the removed portion by the birefringent crystal ($KB_5O_8 \cdot 4H_2O$). This type of polarizer is based on the principle that the refractive-index of the crystal is larger than the effective index of the waveguide for one polarization mode and thus, this mode radiates from the fiber. However, these polarizers are impractical because the polishing of the clad needs a high technique.

This paper presents a simple fabrication technique of a fiber-type polarizer using an eccentric core preform and describes the measured extinction ratio as well as the insertion loss as a function of the buffer layer thickness. A comparison of polarization characteristics on sputtered Au fiber and evaporated Al fiber has been discussed together with different etchants used for buffer layer thickness adjustments.

II. Experiments

A. Fabrication of a Fiber-Type Polarizer

A fiber-type polarizer was fabricated by the following process. An optical fiber preform prepared by the MCVD method was 0.6 mm in core diameter and 7.8 mm in outer diameter, and the refractive-index difference between the core and the cladding of 0.16 percent was jacketed with another quartz tube with an 8 mm inner diameter and 30 mm outer diameter. Core and cladding composition are GeO_2 doped silica and pure silica, respectively. The fiber preform was ground asymmetrically as shown in Fig. 1. Eccentric core preform dimensions are where the outer diameter is 16 mm and the buffer layer thickness which is minimum length between the core and the surface of the preform rod is 0.6 mm. The preform rod was drawn into a fiber and coated with polyurethane and silicone. Fig. 2 shows the SEM photograph of the fiber cross section. From this photograph, the core diameter and the outer diameter were found to be 9.4 and 240 μm.

Next, the coating in short section (3-5 cm) was stripped and etched with 49 percent HF or NH_4F-49 percent HF etching solution (NH_4F:49 percent HF = 9:1). The etching rate of 49 percent HF and that of NH_4F-49 percent HF was 220 Å/s and 12 Å/s. The buffer layer thickness was precisely controlled by varying the etching time.

Finally, Au film of about 700 Å was sputtered around the fiber and Al film was evaporated around another fiber.

B. Measurement Setup

The experimental setup for measuring the extinction ratio and the loss is shown in Fig. 3. Linearly polarized light emerging with a fixed plane of polarization from a He-Ne laser ($\lambda = 1.15$ μm) was passed through a setup consisting of a quarterwave platelet and rotatable Glan-Thomson polarizer. The output light was collimated by a lens and put into a Ge photodiode. The photodiode current was preamplified with a current amplifier and processed in a lock-in amplifier. A measured fiber consisted of a polarizer section with metal coating and following only an eccentric fiber without metal coating. In a measurement of extinction ratio, a light was coupled into a fiber polarizer section and was taken out from the eccentric core fiber end. Extinction ratio ER is defined as

$$ER = 10 \log_{10} (I_{max}/I_{min}) \tag{1}$$

where I_{max} and I_{min} are maximum and minimum output light intensity which are measured by rotating a Glan-Thomson polarizer.

In a measurement of insertion loss of the pseudo-TE_0 mode whose electric field lies horizontally to the metal wall, the light was coupled into a eccentric core fiber end and taken out from the polarizer section. Intensities of output light (I_1, I_2) were measured by cutting a fiber at before and after the polarizer section fixing the input condition of light. It was easy to find out the pseudo-TE_0 mode because the pseudo-TM_0 mode perpendicular to the metal wall appeared as minimum trans-

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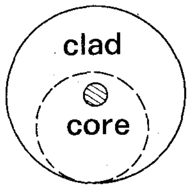

Fig. 1. Preparation of an eccentric mother rod.

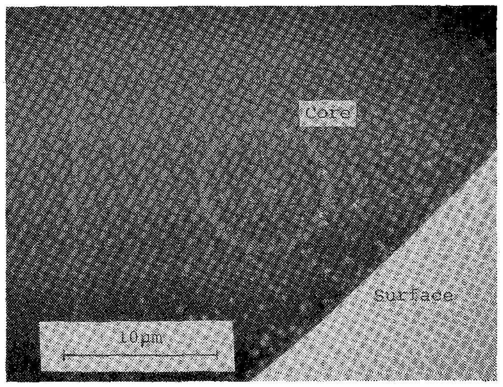

Fig. 2. SEM photograph of eccentric fiber cross section.

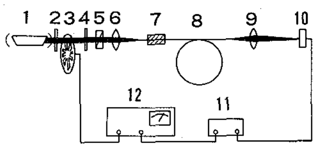

Fig. 3. Experimental setup for measuring the polarization characteristics. 1) He–Ne laser ($\lambda = 1.15$ μm), 2) filter, 3) chopper, 4) $\lambda/4$ platelet, 5) polarizer, 6), 9) microscope objective. 7) fiber-type polarizer, 8) single-mode fiber (eccentric fiber), 10) Ge detector, 11) current amplifier, 12) lock-in amplifier.

mitted light intensity when incident light polarization was rotated with the Glan–Thomson prism. These orthogonal modes were maintained in a whole fiber length of about 1 m.

III. Results and Discussions

A. Au Sputtered Fiber-Type Polarizer

Fig. 4 shows the intensity of the output beam detected by a Ge photodiode by varying the incident polarization angle θ for Au sputtered fiber-type polarizer. The length of the polarizer section was 3 cm which was followed by about 1 m fiber. The intensity of the output beam varies periodically against the incident polarization angle θ and the difference (θ_{max}-θ_{min}) between the incident polarization angle, which corresponds to the maximum and minimum intensity, is $\pi/2$. The attenuation of the pseudo-TM_0 mode is about two orders higher than that of the pseudo-TE_0 mode. Therefore, this fiber can act as a polarizer on this wavelength ($\lambda = 1.15$ μm).

The extinction ratio as a function of buffer layer thickness d is shown in Fig. 5. The buffer layer thickness was measured from the SEM photograph. The extinction ratios increase with decreasing the buffer layer thickness d. The maximum value of 29.4 dB was obtained when $d \simeq 0$. However, excess etching of the buffer layer caused extinction ratio degradation

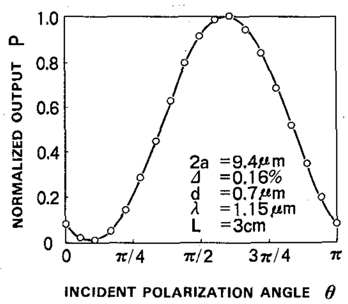

Fig. 4. Relation between the normalized output and the incident polarization angle.

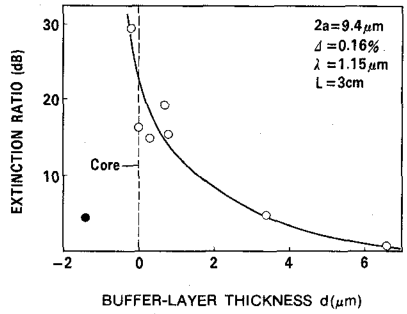

Fig. 5. Relation between the extinction ratio and the buffer layer thickness.

which was observed on the left side of the broken line as shown at the closed circle. This is due to the fact that when the core was etched off by HF, not only pseudo-TM_0 mode, but also pseudo-TE_0 mode, suffered large attenuation.

Fig. 6 shows the extinction ratio dependence of the polarizer length by shortening the polarizer section. The core diameter, the outer diameter, the buffer layer thickness, and refractive-index difference was 9.4 μm, 240 μm, 0.3 μm, and 0.16 percent, respectively. The extinction ratio was not improved linearly with the length, although the extinction ratio from 0–15 mm shows the linear change. The measured insertion losses of the pseudo-TE_0 mode are shown in Fig. 7, taking as a function of the buffer layer thickness. Parameters of a fiber-type polarizer are identical with those shown in Fig. 5. The insertion losses were measured by cutting the fiber just before and after the polarizer section maintaining the incident polarization coincident with the pseudo-TE_0 mode. As can be seen from the solid line in Fig. 7, the insertion losses rapidly increase with decreasing the buffer layer thickness, which was thinner than 1 μm. Maximum insertion loss was 9.4 dB at $d \simeq 0$, whose value was not desirable as a polarizer. However, since propagation losses for the TE_0 mode in the metal coat waveguide are small [6] it is believed that these relatively high insertion losses are not intrinsic. Therefore, it is necessary to estimate the absorption losses due to the metal clad coat on the buffer layer in order to make the cause of the insertion losses clear.

Calculating the absorption losses, attenuation constant α for the TE_0 mode in the four-layer metal-clad planar optical waveguide as shown in Fig. 8 was investigated. The TE_0 mode characteristic curve is determined by applying the usual

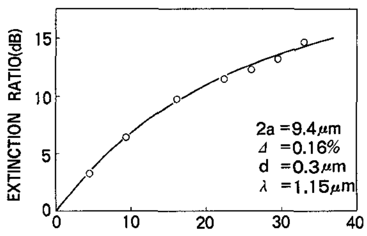

Fig. 6. Relation between the extinction ratio and the length of polarizer (Au sputtered).

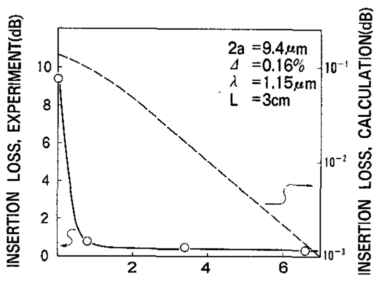

Fig. 7. Relation between the measured or calculated insertion loss and the buffer layer thickness.

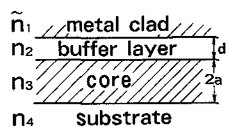

Fig. 8. Four layer metal-clad planar optical waveguide with dielectric buffer layer.

boundary-value technique, and the complex propagation constant $k_z = \beta - j\alpha$ is expressed as solutions of the eigenvalue equations as [7]

$$2aU_3 = \tan^{-1}\left(\frac{U_4}{-jU_3}\right) + \tan^{-1}\left[\frac{U_2}{U_3}\tan \cdot \left\{\tan^{-1}\left(\frac{U_1}{-jU_2}\right) - U_2 d\right\}\right] \quad (2)$$

where

$$U_l = \sqrt{k_0^2 n_l^2 - (\beta - j\alpha)^2}, \quad l = 1 \sim 4 \quad (3)$$

$$k_0 = 2\pi/\lambda \quad (4)$$

$2a$: thickness of core layer
d: thickness of buffer layer
β: phase constant
α: attenuation constant
λ: wavelength in vacuum.

A broken line in Fig. 7 shows the absorption losses obtained by the numerical analysis of the eigenvalue (2). The absorption losses κ are determined by using the attenuation constant α and the length L of the polarizer as

$$\kappa = (10 \log_{10} e^{2\alpha}) \cdot L.$$

The numerical parameters used in the calculation were $2a$ = 9.4 μm, $\lambda = 1.15$ μm, $L = 3$ cm, $\tilde{n}_1 = 0.2\text{-}j7.0$, $n_3 = 1.4603$, and $n_2 = n_4 = 1.458$, respectively. The calculated insertion loss (absorption loss of polarizer length $L = 3$ cm) of the TE_0 mode was 0.13 dB even at $d = 0$ μm like the broken line shown in Fig. 7. Large differences in the experimental insertion loss and the calculated ones must be due to causes such as fiber structural imperfections. Main origin to produce the large insertion loss is considered to be the light scattering yielded by the buffer layer surface roughness. Especially, in order to improve the extinction ratio, the buffer layer thickness must be set within 1 μm, where surface roughness severely affects the insertion loss.

Comparing the etchant characteristics, NH_4F-49 percent HF etchant which consists of NH_4F:49 percent HF = 9:1 was applied instead of 49 percent HF. It was found that the smooth surface was maintained after etching the flat quartz plate for 5 h with NH_4F-49 percent HF, while the roughness of the etched surface became large after 5 min with 49 percent HF as shown in Fig. 9. This surface roughness difference appears in the relation between the insertion losses and the extinction ratios as shown in Fig. 10. When the extinction ratio was from 0 to 15 dB, the insertion loss was always less than 1 dB independently to the etchant. An extinction ratio of about 15 dB corresponds to the buffer layer thickness of about 1 μm, NH_4F-49 percent HF etchant is superior to 49 percent HF etchant for achieving the low insertion loss. Typical measured characteristics for a fiber-type polarizer were 9.4 dB insertion loss at 22 dB extinction ratio for 49 percent HF etchant and 7 dB insertion loss at 30 dB extinction ratio for NH_4F-49 percent HF etchant.

B. Al Evaporated Fiber-Type Polarizer

For the practical use of the polarizer the insertion loss is required to be less than 1 dB, so that Au coat fiber-type polarizer is still insufficient for this purpose. Further high extinction ratio may be realized by changing coated metal. Among several metals, Al is the most available to serve high TM_0 mode absorption [4], [6], [7], considering the refractive index ($n_{Al} \simeq 1.48\text{-}j9.0$ and $n_{Au} \simeq 0.2\text{-}j7.0$ at $\lambda = 1.15$ μm [8]. In addition, the absorption for the TE_0 mode measured in $LiNbO_3$ waveguide is not so high [6].

Fig. 11 shows the relation between the extinction ratio and the polarizer length in the case of the Al coat. Contrary to the Au coated fiber-type polarizer, the extinction ratio for the Al coat varies linearly with the polarizer length and the extinction ratio more than 40 dB could be easily obtained. The insertion loss of the pseudo-TE_0 mode was very low as expected using NH_4F-49 percent HF. Assuming that the insertion loss is proportional to the length, the insertion loss is 0.31 dB/cm for the 0.3 μm buffer layer thickness and 1.0 dB/cm for the -0.6 μm buffer layer thickness. Here, a minus sign means that the fiber was excessively etched until the core. The appropriate buffer layer thickness for low insertion loss and high extinction ratio was found to be 0.2-0.3 μm. Typical fiber-type polarizer characteristics was that the extinction ratio was 22 dB and the insertion loss was 0.66 dB for 0.3 μm buffer

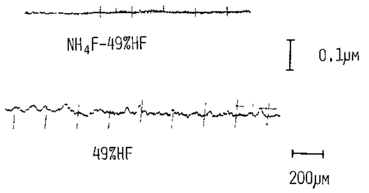

Fig. 9. Surface of the quartz plates after etched with 49 percent HF or NH_4F–49 percent HF.

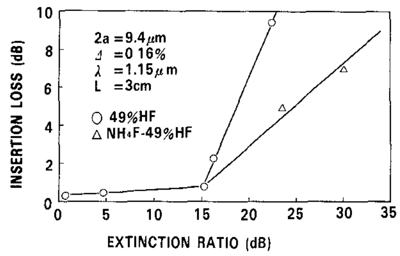

Fig. 10. Relation between the insertion loss and the extinction ratio.

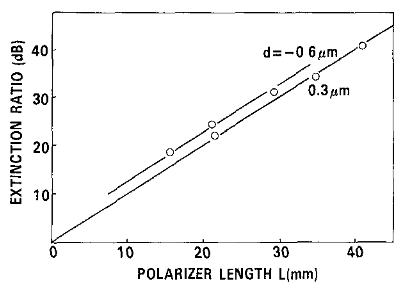

Fig. 11. Relation between the extinction ratio and the length of polarizer (Al evaporated).

layer thickness and 20.1 mm polarizer length. This value is applicable to the optical isolator or the fiber sensor.

IV. Conclusion

A new and simple fabrication technique of a fiber-type polarizer coated metal film onto the fiber surface, which was drawn from the eccentric mother rod, has been demonstrated and polarization characteristics of this polarizer have been investigated concerning the buffer layer thickness, coated metals, and etchants. Al coated fiber-type polarizer was available to serve high extinction ratio compared with the Au coated one. Also, NH_4F–49 percent HF etchant was superior to 49 percent HF etchant for achieving the low insertion loss. Maximum extinction ratio of 41 dB (polarizer length $L = 40.8$ mm) and the insertion loss of 0.31 dB/cm were obtained on Al coated and NH_4F–49 percent HF etched fiber-type polarizer. The appropriate buffer layer thickness for low insertion loss and high extinction ratio was found to be 0.2–0.3 μm.

Further investigation is necessary to determine the appropriate parameters of the fiber-type polarizer for applying to the other wavelength, although the polarizer has high potential to perform in the optical transmission systems or fiber sensors.

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Toshihito Hosaka, for a photograph and a biography, see p. 349 of the April 1982 issue of this Transactions.

Katsunari Okamoto, for a photograph and a biography, see p. 349 of the April 1982 issue of this Transactions.

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