A Novel Technique to Measure the Propagation Loss of Integrated Optical Waveguides

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***Abstract*—A novel method is presented to measure the propagation loss of integrated optical waveguides. The measurement system involves two 3-dB couplers, a charge coupled device camera, and a signal processing unit. The propagation loss measured from this technique is found to be independent of coupling conditions. The propagation properties of low to high loss waveguides prepared by annealed proton exchange (APE) in lithium niobate ($LiNbO_3$) and silver ion exchange in BK7 glass substrates are examined. The measurement system is found to be feasible over a broad range. This method offers a precision of 0.04 dB in case of a 25-mm-long waveguide prepared by APE.**

***Index Terms*—Annealed proton exchanged (APE) waveguide, coupling conditions, integrated optics, propagation loss.**

I. Introduction

OPTICAL waveguides based on lithium niobate and glass substrates have attracted great interest in the field of integrated optics for the devices to be used in high-speed optical communication and sensor technology. However, there are very few techniques available for the measurement of propagation loss of optical waveguides and they involve either a destructive (cutback) method [1] or a complex interferometric experimental setup [2]. Sliding prism loss measurement has been a popular technique, where the prism coupler is slid along the light streak of the waveguide and the light output from the prism is measured as a function of propagation length [3]. In another method known as fiber probe measurement, an optical fiber is scanned along the streak of the waveguide to collect the scattered light into the fiber [4]. Although these methods are widely used, their accuracy and reproducibility depend on the mechanical operation involved in the system. A method that overcomes the mechanical operation involves capturing the light streak in the waveguide and finding the optical power as a function of propagation length using computer analysis [5]. But this method suffers from the disadvantage of requiring significant surface scattering of the waveguide and cannot be applied to the buried waveguides.

Here, we discuss a new method for measuring the propagation loss that employs two 3-dB couplers and a detection system. In addition to the reproducibility, this method is free from the mechanical operation of the system and can also be applied to the buried waveguides. We have examined propagation loss of waveguides prepared by annealed proton exchange (APE) on $LiNbO_3$ and silver ion exchange on BK7 glass substrates and found that this method does offer a simple means to measure the propagation loss independent of coupling coefficients. Finally, we have studied the propagation properties of the APE waveguide by varying the annealing parameter.

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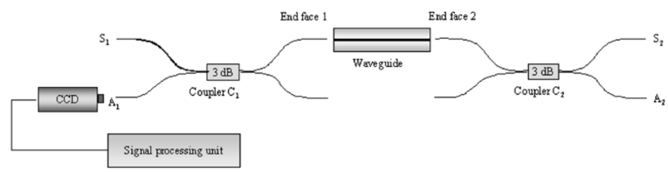

Fig. 1. Experimental setup for propagation loss measurement.

II. System Description

The experimental scheme for this technique is shown in Fig. 1 wherein two identical 3-dB couplers (C_1 and C_2) are aligned as shown. Coupling between the fiber and the waveguide is set to be equal at both the waveguide endfaces. This is ensured by aligning the fiber and waveguide in a way to get equal back-reflected power at A_1 and A_2 when light is launched from S_1 and S_2 separately. The distance between the fiber and waveguide is kept within the diffraction limit.

Light from a semiconductor laser (HP81654A) of wavelength 1.53 μm is launched into the waveguide Endface 2 using coupler C_2. The direct light output power P_1 from the coupler end A_1 is measured using photodetector (HP 81 633B). In all, the input light suffers from coupling loss, Fresnel reflection loss at end faces, and the propagation loss in the waveguide.

Considering the waveguide as a Fabry–Pérot cavity [6], for input power of P_0 at S_2, the output power P_1 at A_1 is given by

$$P_1 = \frac{P_0}{4} T_{\mathrm{fp}} C_{\mathrm{fw}} C_{\mathrm{wf}} (1 - R_f)^2 \tag{1}$$

where T_{fp} is the transmitivity of Fabry–Pérot cavity formed by waveguide ends, R_f is fresnel reflection at fiber-air interface, and C_{fw} and C_{wf} are coupling coefficients for fiber to waveguide and waveguide to fiber, respectively. T_{fp} is given by

$$T_{\mathrm{fp}} = \frac{(1-R)^2 L}{(1-RL)^2} \left(\frac{1}{1 + F \sin^2\left(\frac{\delta}{2}\right)} \right) \tag{2}$$

where $F = 4RL/(1-RL)^2$ is finesse of the cavity, $R = (n - 1/n + 1)^2$ is the reflection coefficient at waveguide-air interface, $L = \exp(-\alpha l)$ is the loss with α being loss coefficient per unit length, l is length of waveguide, and $\delta = (2\pi)/(\lambda) 2nl$ is the phase shift inside the cavity for wavelength of light λ and n is the surface refractive index of the waveguide.

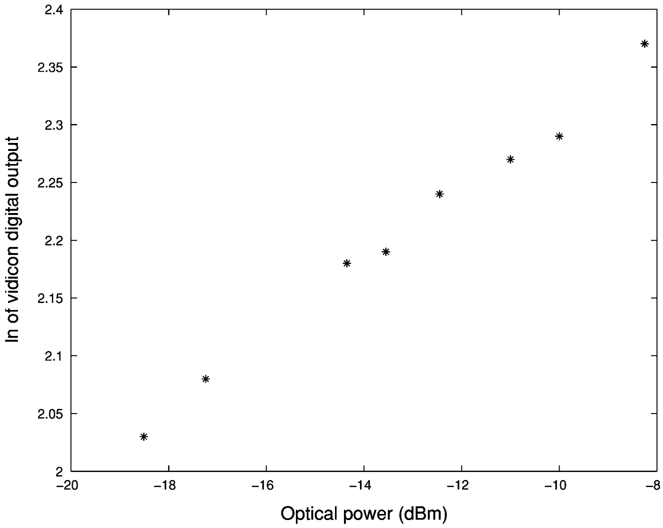

Fig. 2. Transfer characteristics of infrared vidicon.

Now, the coupler C_2 is removed and light (P_0) is launched into waveguide Endface 1 using coupler C_1. The back-reflected light P_2 is measured at the same point (A_1). P_2 is given by

$$P_2 = \frac{P_0}{4} R_{\text{fp}} C_{\text{fw}} C_{\text{wf}} (1 - R_f)^2 \tag{3}$$

where R_{fp} is the reflectivity of Fabry–Pérot cavity formed by waveguide ends given by

$$R_{\text{fp}} = \frac{R}{(1 - RL)^2} \left(\frac{(1 - L)^2 + 4L \sin^2\left(\frac{\delta}{2}\right)}{1 + F \sin^2\left(\frac{\delta}{2}\right)} \right). \tag{4}$$

Dividing (3) by (1) and solving, the propagation loss coefficient is obtained as

$$\alpha = \frac{1}{l} \ln \left(\frac{(k + 2) + \sqrt{(k + 2)^2 - 4}}{2} \right) \tag{5}$$

where

$$k = \frac{P_2}{P_1} \frac{(1 - R)^2}{R} - 4 \sin^2 \left(\frac{\delta}{2} \right).$$

To minimize uncertainity in measurements, the loss coefficient α is found again by interchanging the position of detector and source without disturbing the waveguide. The mean value of loss coefficient α is obtained from the above measurements.

In order to calculate the Fresnel reflection coefficient, the refractive index of the waveguide is to be obtained. In our case, we have used the propagation mode near-field method [7], wherein the refractive index profile of the optical waveguide is computed from the propagation mode near-field data captured by an infrared vidicon (FIND-R-Scope 85 400A). Since the transfer characteristics of the vidicon is nonlinear, one plots (see Fig. 2) the optical intensity I and the digital output V from the vidicon to obtain γ as $I = DV^{1/\gamma}$, where D is a constant, I is optical intensity, and γ is obtained from the gradient of transfer characterisitcs of infrared vidicon.

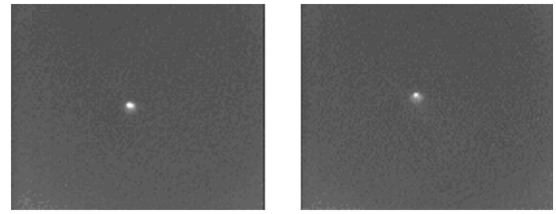

Fig. 3. Photographs of fiber modes at the coupler end A_1 of (a) direct and (b) back-reflected light.

III. Results and Discussion

In order to verify the effectiveness of the present technique, the propagation loss is found for different waveguides fabricated by APE on $LiNbO_3$ and silver exchange on BK7 glass substrates. A low-loss three-dimensional (3-D) channel waveguide single mode at 1.53-μm operating wavelength is fabricated by thermal ion exchange technique by immersing a x-cut $LiNbO_3$ substrate in molten dilute benzoic acid (proton source) at 224 °C for 90 min. To reduce the surface scattering and redistribute the H^+ ions, the substrate is annealed for 2 h at 400 °C and a single-mode waveguide is obtained. Fig. 3 shows the photographs of fiber mode at the coupler end A_1 of the direct and back-reflected light. In the case of BK7 glass substrate, a two-step ion exchange process has been carried out to fabricate a 3-D channel waveguide. In the first step, the waveguide is formed by the field-assisted $Ag^+ - Na^+$ ion exchange technique using a diluted molten silver ion source and in the second step a reverse ion exchange is carried out to burry the waveguide inside the substrate. Since the waveguide is burried in the second step, the surface scattering loss and the fiber waveguide mode mismatch loss are minimized.

A. Proton Exchanged Waveguides

The APE single-mode waveguide was tested using the present technique and the propagation loss for this waveguide has been found for different coupling coefficients and plotted, as shown in Fig. 4. To achieve maximum coupling between the fiber and the waveguide, the fiber is scanned along horizontal and vertical directions to get the maximum back-reflected optical power. To attain different coupling conditions, the fiber has been misaligned equally in horizontal direction at both the waveguide endfaces and the coupling coefficient has been normalized with respect to the maximum obtained output power. The results show that the value of α does not depend on the coupling conditions. The average propagation loss for this waveguide is found to be 0.55 dB/cm.

The propagation loss of proton-exchanged waveguide is examined for different annealing durations at 400 °C using the present technique. The result in Fig. 5 shows a steep decline in the loss for small annealing time and this decline is less significant as the annealing time is increased. This indicates that for small annealing durations, $LiNbO_3$ crystal does not attain single phase and the decrease in propagation loss shows that the crystal approaches the single-phase condition as annealing duration increases.

With the help of a high precision (submicron) XYZ translators, we obtained repeatable values with 0.04-dB precision.

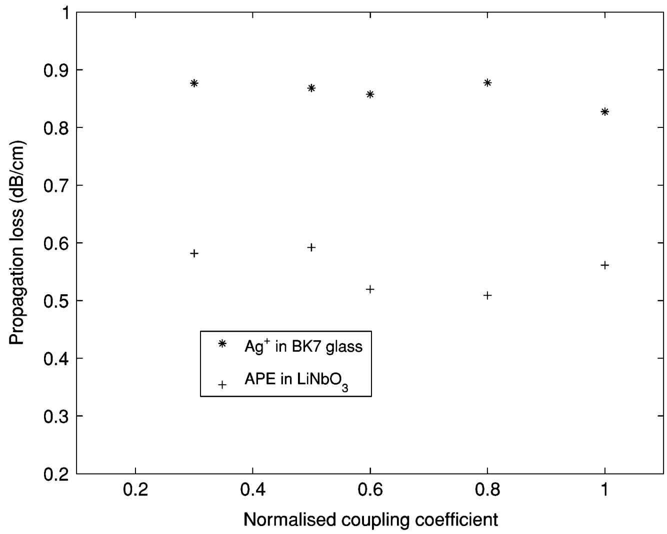

Fig. 4. Propagation loss of APE waveguide in $LiNbO_3$ and Ag^+ ion exchanged waveguide in BK7 glass for various coupling conditions.

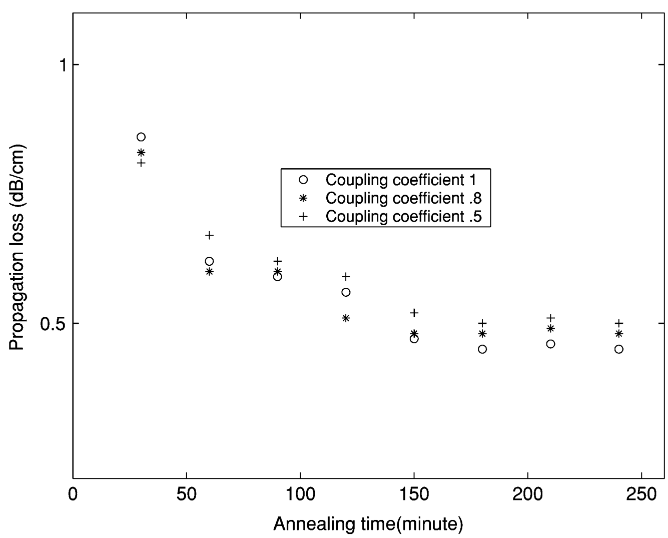

Fig. 5. Variation of propagation loss with different annealing time of APE waveguides in $LiNbO_3$ at different coupling conditions.

The accuracy of the present scheme is dependent on the refractive index computed as discussed in Section II. For example, if the error in the refractive index calculation is 5%, then the error in the value of propagation loss is 7%.

B. Silver Ion Exchanged Waveguide

The propagation loss of the silver ion exchanged waveguide is measured using the present technique for different coupling conditions, as explained above. The average propagation loss for this waveguide after the second step ion exchange is found to be 0.85 dB/cm and the result is shown in Fig. 4. The same device is characterized before the second step ion exchange and the mean propagation loss is found to be 2.09 dB/cm, which can be attributed to the presence of scattering centers. The abrupt change in the value of α tells that the waveguide is buried under substrate after the second step.

In order to examine the effect of coupling conditions on the measured value of α, different coupling conditions are deliberately introduced at the end faces of waveguide. With coupler C_1 fixed, a transverse movement of coupler C_2 through 1 μm causes 6% increase in the value of α. When coupler C_2 is fixed and C_1 is varied, a transverse movement of 1 μm causes 8% decrease in the value of α. An offset beyond 1 μm introduces a large variation in the value of α. An offset of 1 μm corresponds to 0.85 of normalized coupling constant.

IV. CONCLUSION

We have demonstrated a novel technique to measure the mode propagation loss of 3-D optical waveguides, which is simple and reproducible over the existing methods. Propagation loss of single-mode 3-D straight channel waveguides prepared by APE in $LiNbO_3$ and $Ag^+ - Na_+$ ion exchange in BK7 glass substrates has been calculated. The accuracy of this technique is limited by the calculation of Fresnel reflection coefficient. The novel feature of this method is the use of ratio of the two measured optical powers P_1 and P_2 to eliminate the effect of coupling conditions.

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REFERENCES

[1] J. Werner *et al.*, "Reduced optical waveguide losses of a periodically distributed GaAs/AlGaAs single quantum well laser structure for photonic integrated circuits," *Appl. Phys. Lett.*, vol. 53, pp. 1693–1695, 1988.

[2] R. G. Walker, "Simple and accurate loss measurement technique for semiconductor optical waveguides," *Electron. Lett.*, vol. 21, pp. 581–583, 1985.

[3] P. K. Tien, "Light waves in thin films and integrated optics," *Appl. Opt.*, vol. 10, no. 11, pp. 2395–2413, 1971.

[4] M. D. Himel and U. J. Gibson, "Measurement of planner waveguide losses using a coherent fiber bundle," *Appl. Opt.*, vol. 25, no. 23, pp. 4413–4416, 1986.

[5] Y. Okamura *et al.*, "Measuring mode propagation losses of integrated optical waveguides: A simple method," *Appl. Opt.*, vol. 22, no. 23, pp. 3892–3894, 1983.

[6] T. Saito *et al.*, "Raman gain and optical loss in GaP-AlGaP waveguides," *J. Appl. Phys.*, vol. 87, no. 7, pp. 3399–3403, 2000.

[7] K. Morishita, "Index profiling of three-dimensional optical waveguide by the propagation-mode-near-field method," *J. Lightw. Technol.*, vol. LT-4, no. 8, pp. 1120–1124, Aug. 1986.