

In-line Variable Attenuator Based on the Evanescent Wave Coupling Between a Side-polished Single-mode Fiber and an Index Matched Dielectric Plate

Kwang Taek Kim* and Hyo Kyeom Kim

Department of Optoelectronics, Honam University, Gwangju, 506-714, KOREA

(Received October 9, 2003)

An in-line variable attenuator has been proposed and demonstrated exploiting a side-polished single-mode (SM) fiber evanescently coupled with an index matched dielectric plate. The attenuation can be controlled by fine mechanical sliding of the index matched dielectric plate. We have achieved 49 dB dynamic range and very low excess loss of 0.2 dB at 1550 nm wavelength. The measured polarization dependent losses (PDL) were 0.1, 0.2, and 0.4 dB at 10, 20, and 30 dB attenuation, respectively. Wavelength sensitivity was measured to be $-0.017/\text{nm}$ dB at 20 dB attenuation.

OCIS codes : 060.2330, 060.3240, 060.2370

I. INTRODUCTION

The variable attenuator is a key device used to adjust the power level of optical signals in several important optical communication systems, including optical amplifiers, add-drop modules, multiplexers/de-multiplexers, optical transmitters/receivers, and other components. A variable attenuator can also be applied to simulate cable loss in the research and development of the optical communication link power budget. Robustness, small size, high resolution, wide attenuation range and polarization, and wavelength insensitivity are basically required in the variable attenuators. Intensive investigation on the variable attenuators using integrated waveguides [1,2] and an MEMS (micro electronic mechanical system) [3,4] have been reported. Recently, in-line fiber optic solutions have attracted a lot of attention, because they provide a low insertion loss, low back reflection, and good mechanical reliability due to elimination of the interfacing problem to single mode fibers. The fused and tapered fibers have been often used for implementation of the in-line variable attenuators [5-6]. The side-polished fiber can also be applied to realize an in-line variable attenuator because its guiding mechanism varies with change of the optical characteristics of the external overlay placing on top of the polished fiber [7,8].

In this paper, we have proposed and demonstrated an in-line variable attenuator that exploits the evanescent wave coupling between a side-polished SM fiber and an index matched dielectric plate. The precise control of

attenuation is achieved by fine-tuning the coupling overlap length between the side-polished fiber and the high index dielectric. The design and fabrication technology of the device are described.

II. DEVICE STRUCTURE AND OPERATIONAL PRINCIPLE

Fig. 1 shows the schematic structure of the proposed variable attenuator based on evanescent wave coupling between the side-polished fiber and the high index dielectric plate. The sliding block (upper block) composed of fused silica and a dielectric plate is in contact with the side-polished fiber block (lower block). The

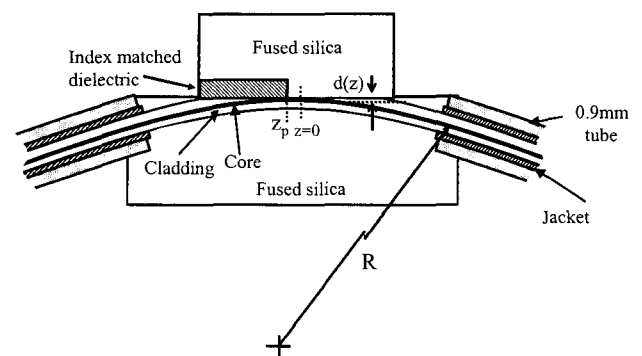


FIG. 1. Schematical structure of proposed variable attenuator.

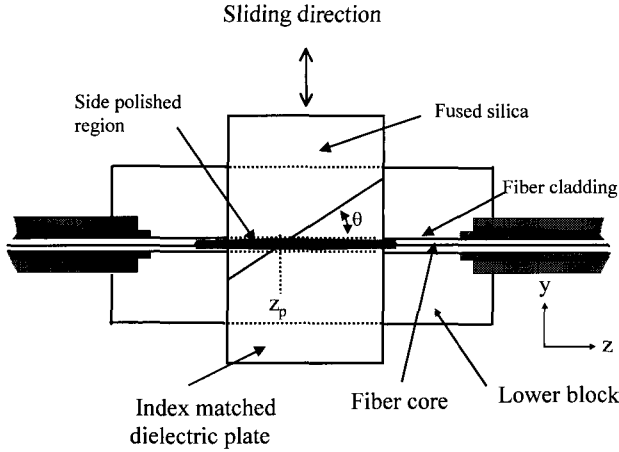


FIG. 2. Top view of the variable attenuator explaining the operation principle.

refractive index of the fused silica equals that of the fiber cladding. Therefore, the side-polished fiber covered with the index matched dielectric can not guide an optical wave into its core and some portion of optical power leaks into the dielectric plate.

In this work, a Pyrex plate is chosen as the index matched dielectric plate whose refractive index is adequate to induce high coupling loss when it contacts the side-polished fiber. The attenuation is a function of how much the side-polished area is covered by the Pyrex plate, that is, it depends on the coupling point denoted as z_p . In the proposed device, the sliding of the upper block along the vertical direction (y direction) results in variation of the coupling point, z_p because the Pyrex plate is tilted by θ with respect to fiber direction shown in Fig. 2. The z_p accords to relation, $z=y/\tan\theta$. The resolution, change of attenuation per unit moving distance of upper block can be controlled through appropriate design of the angle, θ .

The fiber core radius, bending radius, and minimal remaining cladding thickness are denoted as a , R , and d_0 , respectively, as shown in Fig. 1, while n_{co} , n_{cl} , and n_p refer to the refractive index of the fiber core, fiber cladding, and Pyrex plate, respectively. Since the fiber is curved, the attenuation coefficient of the fiber mode and remaining cladding thickness expressed as $d(z) \cong d_0 + z^2/2R$ vary along the z direction.

The attenuation of side-polished fiber covered with high index Pyrex plate can be derived through the integration of the attenuation coefficient with respect to z [9].

$$\alpha(z_p)[dB] = 10 \cdot (\log_{10} e) \cdot \sqrt{\pi R a} \cdot \left[1 + \operatorname{erf} \left(\frac{z_p}{\sqrt{2 R a}} \right) \right] \cdot \frac{2 \beta_0}{n_{cl}^2 k_0^2} \cdot \left[\frac{u}{a V K_1^2(w)} \right]^2 \cdot \frac{V_p^2 - w^2}{V_p^2} \int \frac{\sqrt{1 - \xi^2}}{\left[\sqrt{(V_p^2 - w^2) \xi^2 + w^2} \right]^{1/4}} \exp \left[- \frac{(d_0 + a)}{a} \sqrt{(V_p^2 - w^2) \xi^2 + w^2} \right] d\xi \quad (1)$$

Where K_1 , k_0 , β_0 , u , w , V are a modified Bessel function of the second kind of the first order, the free-space wave number, propagation constant of the fiber before polishing, normalized transverse propagation constant in the core and cladding of the single mode fiber, and fiber V number, respectively. Plus, V_p is the V number in the dielectric plate, expressed as $V_p = k_0 a \sqrt{n_p^2 - n_{cl}^2}$. In our calculation, the n_{cl} , n_{co} , a and d_0 are assumed to be 1.444, 1.448, $4.0 \mu\text{m}$, and $0.0 \mu\text{m}$, respectively.

III. EXPERIMENTS AND ANALYSIS

We have manufactured two kinds of side-polished fiber blocks with large curvatures, 50 cm, and 100 cm curvature using the fused silica block (width, height, length : 10 mm, 5 mm, 35 mm). The fiber cladding was polished on the pitch plate with CeO_2 powder. To avoid too much polishing, the remaining cladding thickness was carefully monitored during the polishing based on liquid drop method [9]. The prepared side-polished fibers exhibited a minimal excess loss about 0.1 ~ 0.2 dB. But they showed 38 dB for $R=50$ cm, 63 dB for $R=100$ cm when the liquid index approaches to that of fiber core at 1550 nm wavelength. The experimental and theoretical results on the transmission losses of the side-polished fibers covered with high index liquids are shown in Fig. 3.

In order to prepare the upper block, some part of a fused silica block was removed and then a Pyrex plate with 1.1 mm thickness was bound at the removed part. The refractive indices of Pyrex measured using by the prism coupler were 1.4698, 1.4655, 1.4591 and 1.4561 at the 630, 830, 1310, and 1550 nm of wavelength under

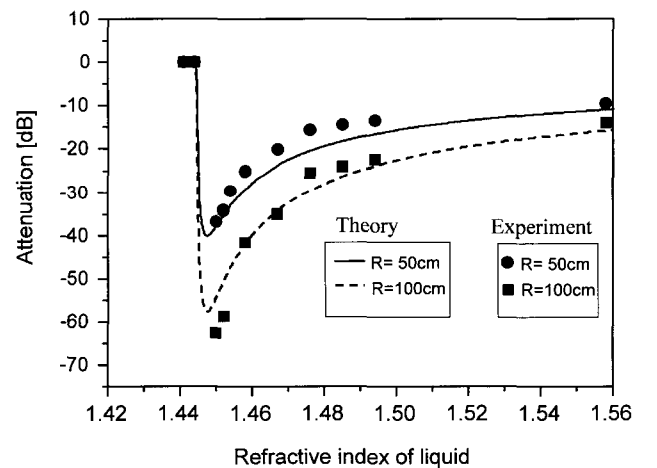


FIG. 3. Measured and calculated losses of the side-polished single mode fibers covered with the high index liquid. The refractive indices of liquids were measured at 1550 nm.

22°C, respectively. The refractive index of Pyrex satisfied the condition for the high radiation coupling loss. The Pyrex plate was tilted by 30° with respect to the fiber axis. It was also polished in a same manner. The side-polished block (lower block) and the moving block were physically contacted by a prepared holder which was equipped with a micrometric screw. The interference pattern produced within the thin layer of air between lower and upper blocks provides important information about the quality of the polished surface. At most one interference fringe (Newton ring) confirms the high quality polished surface. An oil whose refractive index was close to the fiber cladding index was filled in 0.1~0.2 μm of the air gap between two blocks by capillary action.

After assembling, the upper block could be moved to vertical direction with respect to the fiber direction (z direction) using the micrometric screw. Fig. 4 shows the measured and calculated optical loss in accordance with z_p . The center point (i. e. $z_p=0$) is defined as the position where the attenuation is half the maximum value. The center point has been determined by measuring the attenuation as a function of upper block position. The patterns of attenuation of the devices were in good agreement with the theoretical predictions. Achieved variable range of the device were 27 dB and 49 dB for $R=50$ cm and $R=100$ cm, respectively. The measured excess losses were 0.1~0.2 dB.

The polarization dependent losses (PDL) of the variable attenuator with 100 cm curvature were 0.1 dB, 0.2 dB and 0.4 dB at attenuation of 10 dB, 20 dB, and 30 dB, respectively. The origin of the measured PDL is likely to come from the anisotropic structure of the side-polished fiber covered with a high index dielectric. It is expected that the device performance in an aspect of the PDL and the dynamic range will be improved if a dielectric whose refractive index is

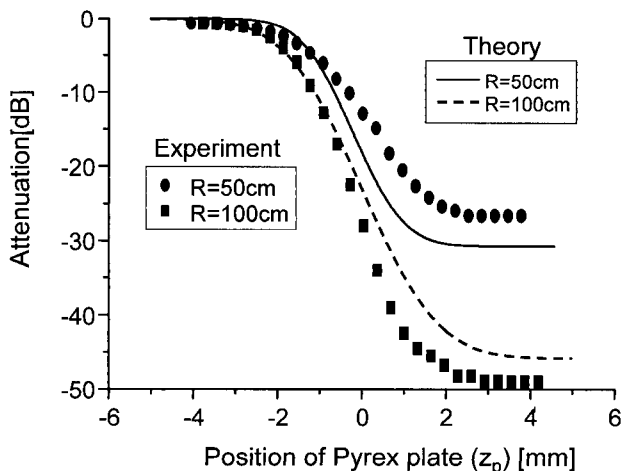


FIG. 4. Measured and calculated optical attenuation of the device in accordance with z_p .

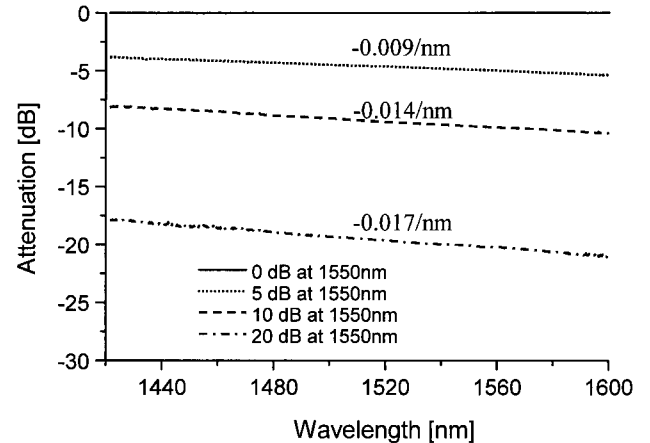


FIG. 5. Measured attenuation versus wavelength of the variable attenuator with $R=100$ cm.

very close to that of the fiber core is employed, instead of the Pyrex.

The wavelength sensitivity of the fabricated variable attenuator with 100 cm of curvature has been measured and the results were presented in Fig. 5. It was found that the attenuation was linearly increased with the wavelength. We found experimentally that the difference between the refractive indices of the Pyrex and fiber cladding (fused silica) was almost constant at several wavelengths. Therefore, as the wavelength became longer the modal field at coupling region spread into Pyrex more deeply and attenuation increased.

IV. CONCLUSION

In conclusion, we have proposed and demonstrated an in-line optical attenuator with simple structure, low insertion loss and wide variable range based on the evanescent wave coupling between a side-polished single mode fiber and an index matched dielectric plate. The influence of structure parameters on the performance of the device has been investigated. The device structure to achieve the precise control of attenuation and wide dynamic range has been presented. It was shown that the patterns of attenuation of the devices were in good agreement with the theoretical predictions. As predicted, the fabricated variable attenuator exhibited 0.1~0.2 dB of small insertion loss and 49 dB of wide dynamic range. The wavelength sensitivity was measured to be -0.017 dB at 20 dB attenuation. 0.4 dB of PDL was observed at 30 dB attenuation.

ACKNOWLEDDEMENTS

This work was supported by Regional Research Center for Photonic Materials and Devices at Chonnam

National University under grant R12-2002-002 of Korea Science and Engineering Foundation (KOSEF)

*Corresponding author : ktkim@honam.ac.kr

REFERENCES

- [1] S. S. Lee, Y. S. Jin, and T. K. Yoo, "Polymeric tunable optical attenuator with an optical monitoring tap for WDM transmission network," *IEEE Photon. Technol. Lett.*, vol. 11, no. 5, pp. 590-592, 1999.
- [2] T. Kawai, M. Koga, M. Okuno, and T. Kitoh, "PLC type compact variable optical attenuator for photonic transport network," *Electron. Lett.* vol. 34. no. 24, pp. 264-265, 1998.
- [3] C. Marxer, P. Ggriss, and N. F. de Rooij, "A variable optical attenuator based on silicon micromechanics," *IEEE Photon. Technol. Lett.*, vol. 11, no. 2, pp.233-235, 1999.
- [4] N. A. Riza and S. Sumriddetechkajorn, "Digitally controlled fault-tolerant muliwavelength programmable fiber optic attenuator using a two dimensional digital micro-mirror devices," *Opt. Lett.*, vol. 24, no. 5, pp. 83-84, 1999.
- [5] V. Morozove, H. Fan, L. Eldada, L. Yang and Y. Shi, "Fused optic variable attenuator," *Proc. of the 2000 Optical Fiber Communication Conference*, vol. 4, pp. 22-24, 2000
- [6] Q. Li, A. A. Au, C. H. Lin, E.R. Lyons, and H. P. Lee, "An efficient all-fiber variable optical attenuators via acoustooptic mode coupling," *IEEE Photon. Technol. Lett.* vol. 14, no. 11, pp. 1563-1565, 2002.
- [7] K. T. Kim and J. W. Song, "Investigation of thermo-optically tunable fiber-to-planar waveguide coupler," *Opt. Comm.* vol. 205, pp.113-121, 2002.
- [8] A. K. Das and A. Hussain, "Single-mode fiber-linearly tapered planar waveguide tunable coupler," *App. Opt.* vol. 36, no. 27, pp. 6822-6826, 1997.
- [9] S. P. Ma and S. M. Tseng, "High-performance side-polished fiber and application as liquid crystal clad fiber polarizers," *IEEE J. of Lightwave Tech.* vol. 15, no. 8, pp. 864-867, 1997.