

# Air-silica microstructure fiber based variable optical attenuator device

C. Kerbage<sup>1</sup>, J. Ging, P. Steinvurzel, A. Hale, A. Yablon, R. S. Windeler, and B. J. Eggleton<sup>2</sup>

*Bell Labs, Optical Fiber Solutions, Lucent Technologies  
700 Mountain Avenue, Murray Hill, NJ 07974*

<sup>1</sup>*Phone(908) 582 6138, fax(908) 582 6055, email:kerbage@lucent.com*

<sup>2</sup>*Also with Specialty Fiber Devices, Optical Fiber Solutions, Lucent Technologies  
Somerset, NJ 08873*

**Abstract:** We present a design for modulating light in an optical fiber, which achieves efficient modal field interaction between the fundamental mode of an air-silica microstructure optical fiber and tunable materials incorporated in the air-holes of the fiber.

**OCIS codes:** (230.3930) Microstructure devices; (250.5460) Polymer waveguides-fibers.

## 1. Introduction

As the data throughput and lengths of transmission spans of lightwave communications systems increase, dynamic control becomes a necessary feature for many standard optical components. Numerous types of tunable optical devices have been proposed for these systems, including tunable filters, variable attenuators, and switches. This tunability must be achieved with the highest possible dynamic range while still maintaining certain characteristics such as low insertion loss, large operating bandwidth, and low polarization dependent loss (PDL). These characteristics can be most easily attained in all-fiber devices, which are typically less polarization-sensitive and have lower insertion loss than devices based on bulk optics or planar waveguides

In this paper we present a tunable all-fiber optical device based on an air-silica microstructure fiber (ASMF). ASMF is all-silica fiber with airholes incorporated in the cladding region that run along the length of the fiber [1]. The size, number, and position of the airholes can be chosen to achieve specific optical properties and guidance mechanisms for the propagating modes in these fibers [2]. One may also fill the airholes with materials having, for example, certain refractive index or polarization properties, in order to further tailor the propagating modes. The device that we introduce here consists of a tapered ASMF in which the airholes are filled with a polymer with a highly temperature-dependent refractive index to provide tunability. The geometry of the fiber allows for low loss and robust splices with conventional fibers and the taper design enables efficient interaction between the tunable material and the propagating mode field. We demonstrate a fully integrated, spliced and packaged electrically tunable variable optical attenuator device (VOA) with about 30 dB dynamic range, insertion loss of less than 0.8 dB, and minimal polarization dependence.

## 2. Device physics

Fig. 1(a) shows a cross section of the ASMF used in the VOA. The fiber consists of a solid germanium doped core of 8  $\mu\text{m}$  in diameter and  $\Delta = ((n_1 - n_2)/n_1) \sim 0.35\%$ , where  $n_1$  and  $n_2$  are the refractive indices of the germanium core and silica cladding, respectively. Six large airholes in the cladding, each  $\sim 40 \mu\text{m}$  in diameter, symmetrically surround the core [3]. These airholes form an inner cladding region of diameter  $\sim 32 \mu\text{m}$ . The lowest order mode of the fiber is guided in the germanium doped core by total internal reflection at the core-cladding interface and is unaffected by the presence of the airholes in the cladding [4,5].

In order to achieve an efficient field interaction between the core mode and the airholes, the fiber is adiabatically tapered by heating and stretching the fiber such that the diameter decreases while the cross-sectional profile remains approximately the same. As shown in Fig. 1(b), by tapering the fiber down to small diameter sizes, the core diameter decreases and becomes extremely small. As light propagates through the taper, the core mode spreads into the cladding region where it is confined by the airholes-cladding interface [6]. In the waist of the tapered fiber, the waveguide resembles a very high-delta fiber ( $\Delta \sim 35\%$ ) similar to a glass rod surrounded by air. The large modal field interaction with the surrounding airholes in the waist of the taper makes the core mode very sensitive to any index change at the interface. Tunable refractive index materials, such as polymers, with a thermal coefficient that is an order of magnitude larger than that of silica may be introduced into the holes, as shown in Fig. 1(c), and will affect the guiding mechanisms of light in the optical fiber.

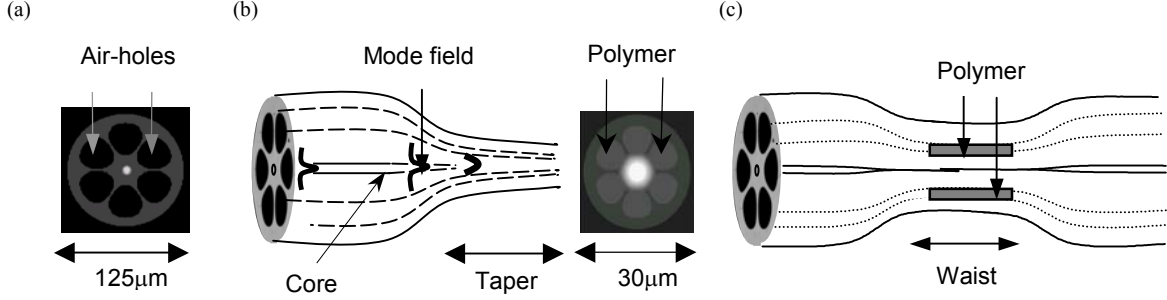


Fig. 1. (a) Cross section of the ASMF. (b) Mode profile evolution along the tapered fiber. (c) Schematic diagram of the all-fiber variable attenuator device based on tapered microstructured fiber.

The principle of the device is summarized in Fig. 2, which shows the cross sectional index profile for different values of polymer refractive index, and the corresponding calculated mode field cross sectional intensities, calculated using beam propagation method [4]. The simulation includes absorption losses in the polymer of 0.2 dB/mm [4]. The outer diameter of the waist of the taper is 30  $\mu\text{m}$  with a corresponding inner diameter of  $\sim 8 \mu\text{m}$ . Fig. 2(a) shows the taper when no polymer is infused in the air-holes and the mode field propagates without any change. If the index of the infused polymer is lower than that of silica ( $n_p=1.42$ ) as shown in Fig. 2(b), the mode is confined in the cladding by total internal reflection, and only a small percentage of the optical field will be in the material. In this case the mode propagates through the taper with minimal loss. On the other hand, if the index of the material is close to that of silica, as shown in Fig. 2(c) ( $n_p=1.44$ ) or higher than that of silica ( $n_p=1.5$ ), as in Fig. 2(d), the mode field will refract into the high index medium, resulting in dramatic loss for the propagating mode. This is exacerbated by the material losses of the polymer and interstitial region between airholes, which results in the leakage of modes out of the inner cladding region. Light is therefore attenuated by the spread of the evanescent mode field, which depends on the refractive index of the material infused in the air-holes.

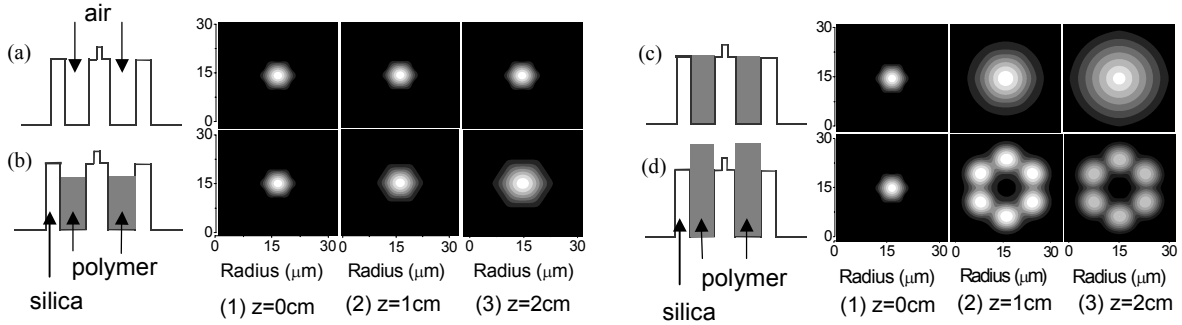


Fig. 2. Index cross-sectional profile in the waist of the fiber (a) with no polymer and with polymer of index (b) lower ( $n_p=1.42$ ), (c) same as ( $n_p=1.44$ ) and (d) higher ( $n_p=1.5$ ) than that of silica. The corresponding calculated intensity cross sectional mode profile are shown at (1)  $z=0$  cm, (2)  $z=1$  cm and (3)  $z=2$  cm along the length of the waist.

### 3. Experiment and results

The fiber was tapered from 125  $\mu\text{m}$  to 30  $\mu\text{m}$  in outer diameter over a length of 1 cm with the waist of the fiber 2 cm in length. An acrylate monomer mixture (viscosity  $\sim 30$  centipoise) was infused into the air-holes in the waist of the taper at a rate of 0.03 cm/sec by applying vacuum to one end while inserting the other end of the fiber into a reservoir of liquid monomers. Then the monomer mixture was UV-cured for about 15 minutes to form a polymer with a refractive index of 1.424 at room temperature at 1550 nm.

Fig. 3 shows both the experimental (dots) and simulated (circles) plot of the transmission through the fiber as a function of temperature (bottom axis) and corresponding polymer index (top axis) at 1550 nm. The attenuation of the device varies from  $-30$  dB to  $-0.8$  dB with the highest insertion loss occurring at the lowest temperature. At room temperature, even though the index of the polymer is lower than that of silica, it is high enough to allow significant penetration of the field into the polymer and leakage through the webbings between the air-holes, which results in high insertion loss, as shown in Fig. 2(b). When the fiber is heated, the index of the polymer decreases by  $dn/dT \sim -4 \times 10^{-4}/^\circ\text{C}$  (inset of Fig. 3), thus reducing the penetration of the field into the polymer and causing guidance of light in the fiber (Fig. 2). We note that microstructured fiber exhibits 6-fold rotational symmetry and is expected to exhibit very low birefringence [7] and thus minimal PDL.

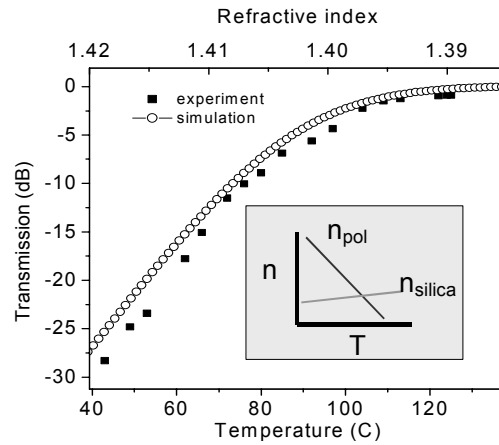


Fig. 3. Transmission (output) of the tapered microstructure fiber plotted in dB scale as a function of temperature and refractive index at 1550 nm.

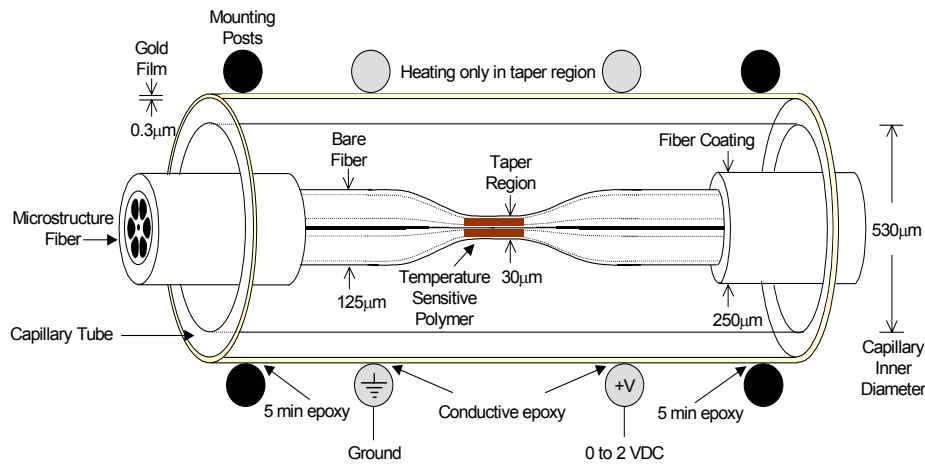


Fig. 4. Schematic diagram showing the tapered microstructure fiber with capillary heater.

To create a compact device the taper can be packaged in a fused silica micro-capillary tube as shown in Fig.4. The tube is coated with a thin film of gold, which acts as an efficient resistive heater when voltage is applied. The maximum power consumption is 375mW, corresponding to about 2 V of applied voltage. The measured PDL was less than 0.5 dB, which may be attributed to the material absorption and irregular boundaries between the cladding and airholes that vary along the tapered fiber. The wavelength dependence of the device is about 0.3 dB over a range of 30nm (1530-1560nm). Even though the fiber is tapered to a small diameter, the device is robust and easily packaged with very low loss splice (<0.1 dB)[6]. The response time of such a device can be of the order of one second using integrated capillary heaters [8].

#### 4. Conclusion

We demonstrated an all-fiber variable attenuator using a tapered ASMF. Efficient modal field interaction between the propagating mode and tunable materials infused into the air-holes of the fiber results in a dynamic range of 30 dB, insertion loss 0.8 dB, and PDL of 0.5 dB. Further analysis of the device design, including optimization of polymer index, device length and taper diameter should result in reduced insertion loss and increased dynamic range.

#### 5. References

1. P.V. Kaiser, and H.W. Astle, *The Bell System Technical Journal* **53**, 1021-1039 (1974).
2. R.F. Cregan, B.J. Mangan, J.C. Knight, T.A. Birks, P. S. J. Russell, P. J. Roberts, and D. C. Allan, *Science* **285**, 1537-1539 (1999).
3. C. Kerbage, B.J. Eggleton, P.S. Westbrook, and R. S. Windeler, *Optics Express* **7**, 113-123,(2000).
4. B.J. Eggleton, P.S. Westbrook, C.A. White, C. Kerbage, R.S. Windeler, and G. L. Burdge, *J. Lightwave Tech.* **18**, 1084-1100 (2000).
5. P.S. Westbrook, B.J. Eggleton, R.S. Windeler, A. Hale, T.A. Strasser, and G. L. Burdge, *IEEE Phot. Tech. Lett.* **12**, 495-497 (2000).
6. J. K. Chandalia, B.J. Eggleton, R.S. Windeler, S.G. Kosinski, X. Liu, and C. Xu, *IEEE Phot. Tech. Lett.* **13**, 52-54 (2001).
7. M.J. Steel, T.P. White, C. Martijn de Sterke, R.C. McPhedran, and L.C. Botten, *Optics Letters* **26**, 488-490 (2001).
8. B.J. Eggleton, A. Ahuja, P.S. Westbrook, J.A. Rogers, P. Kuo, T.N. Nielsen, and B. Mikkelsen, *J. Lightwave Tech.* **18**, 1418-1432 (2000).