Defect and lattice structure for air–silica index-guiding holey fibers

Soan Kim, Y. Jung, and K. Oh
Department of Information and Communications, Gwangju Institute of Science and Technology (GIST), 1 Oryong-dong, Buk-gu, Gwangju 500-712, South Korea
J. Kobelke, K. Schuster, and J. Kirchhof
Institut für Physikalische Hochtechnologie, Jena e.V. Albert-Einstein-Strasse 9, 07745 Jena, Germany

Received July 1, 2005; revised September 23, 2005; accepted September 23, 2005

We propose new design parameters for index-guiding holey fiber that can provide flexibility in defect and lattice design and adiabatic mode transformation capability. The new defect consists of a central air hole and a germanosilicate ring surrounding it, which results in a large-area annulus mode profile, low splice losses to standard fiber, 0.7 dB at 1.55 μm, and chromatic dispersion with a low slope, 0.002 ps/km nm². © 2006 Optical Society of America.

Air–silica structured index-guiding holey fibers (IGHFs) have been intensively investigated in recent years due to their unique optical properties.1,2 Recently, Oh et al. introduced a new type of optical fiber, called a hollow optical fiber (HOF).3 Because of the high index contrast between the central air hole and the high index ring core of the HOF an annulus mode field was achieved, and various guiding properties have been reported along with versatile device applications.3,4

In this Letter we present a novel IGHF with an annulus mode profile by introducing a new ring defect design, as shown in Fig. 1. The outside rings are index matched to silica by codoping P2O5 and F. The germanosilicate ring plays two pivotal roles: (i) providing flexible defect design by varying dcore, Wring, and ΔGe and (ii) generating a sublattice structure that results from the difference in viscosity relative to P2O5 and F codoped rings in the cladding.5 The cross-sectional lattice profile proposed in Fig. 1(a) clearly shows two sets of lattice parameters, dcore, Δcore versus dclad, Δclad, which can provide new degrees of freedom to the flexible design of guiding structures. In this Letter we theoretically analyzed and experimentally demonstrated the potential of germanosilicate ring defects in IGHF, for the first time to the best of our knowledge.

Scanning electron microscope (SEM) images of the fabricated fibers and the calculated mode field of the proposed fibers are shown in Figs. 2(a)–2(d), respectively. As shown in Figs. 2(a) and 2(b), germanosilicate ring defect layers resulted in a smaller hole size and pitch than with P2O5–F codoped ring layers in the cladding. Especially in the case of the double-defect layered structure, shown in Fig. 2(b), the hole diameter of the germanosilicate rings was 17.2 μm, and the seven air holes were spaced by Δcore =5.5 μm to make dcore/Δcore =0.26. The dimensional parameters of the cladding were Δcladding=7.7 μm and dclad/Δclad =0.64. Applying the plane-wave expansion method,5 the modal shape and mode field diameter are numerically analyzed in Figs. 2(c) and 2(d).

In comparison with prior IGHFs, the proposed defect structures resulted in a unique annulus modal shape with a large modal area, which makes the proposed IGHFs most suitable for clad-pumped fiber laser applications. Another notable feature of the proposed IGHF is the unique capability of adiabatic mode transformation, which is inherited from the HOF.5 When the proposed fiber is collapsed by electrical arc discharge in a fusion splicer, the germanosilicate ring defects are transformed into solid high index cores, which will provide a solid core–cladding structure similar to single-mode fibers (SMF). Figure 3 shows a comparison between a fiber with open germanosilicate ring defects and that with fully collapsed defects. The near-field pattern in Fig. 3(a)(ii) is annulus mode shaped, and it is almost similar to the calculated fundamental mode in Fig. 3(a)(i). The effective mode area of the annulus mode in Fig. 3(a) was measured to be as large as 240.5 μm² at λ=1.55 μm by averaging the values of x and y directions, which are significantly larger than the values of recently reported large mode area (LMA) IGHFs.2

Meanwhile, when the fiber was drawn in a higher temperature or lower internal pressure, the ring defects collapsed to result in solid multiple high index cores. In this case, the modal shape is no longer annular but becomes highly compatible with that of the...
LP_{01} mode of conventional SMF as shown in Fig. 3(b), which was experimentally confirmed by the near-field measurements presented in the inset of Fig. 3(b)(ii). Therefore the proposed fibers can provide a unique adiabatic modal transformation by tapering the fibers. In this case, the average modal area was measured to be 58.1 \mu m^2, and the corresponding mode field diameter (MFD) was 8.6 \mu m at \lambda = 1.55 \mu m, which is comparable with 11.4 \mu m, the MFD of conventional SMF.

Based on this novel adiabatic modal transformation, we studied the splicing between the proposed IGHF and SMF. Direct fusion splicing of the SMF to prior IGHFs has provoked a critical problem of high loss due to collapsing air holes in IGHF by the arc. In prior IGHFs, the fully collapsed region turned into a blank silica segment that does not have a core guiding structure, which results in high splicing losses over 2 dB at \lambda = 1.55 \mu m. \(6\) Recently the optimization conditions using a short arc duration and weak power were reported\(^6\) with an improved loss of 0.6–0.7 dB but significantly degraded tensile strength.\(^7\) A mechanism of splicing between the proposed fibers and the SMF based on adiabatic mode transformation is presented schematically in Fig. 4. In contrast to prior IGHFs, the proposed fibers are fully collapsed and slightly tapered to turn the germanosilicate ring defect into multiple solid cores. Note that the fundamental mode along the longitudinal position of the proposed fiber taper at z=A corresponds to Fig. 3(a), while that of z=B corresponds to Fig. 3(b). Even in the fully collapsed region, the proposed IGHF can provide a unique core guiding structure that is highly compatible with conventional SMF. The splicing loss between the collapsed IGHF segment and the SMF calculated utilizing MFD was predicted to be 0.4 dB at \lambda = 1.55 \mu m. \(^8\) In experiments, the splicing loss was measured to be less than 0.7 dB for 20 trials using conventional SMF splicing conditions. Note that this loss is equivalent to that of optimized values in prior IGHFs with sophisticated arc conditions.\(^6\) In addition, the splice showed a highly improved tensile strength of 3 Gpa, which is almost equivalent to that of SMF to SMF splicing. The error between the calculated and the experimental results
in the splice, 0.3 dB, can be attributed to loss induced in imperfect adiabatic mode conversion and background loss of the proposed fiber. The attenuation of the fabricated fiber was 10 dB/km at 1.55 μm with three-layered air holes as a cladding.

Finally, we studied the effect of the defect parameters on the chromatic dispersion of the fundamental mode in the proposed structure. For the smaller value of $d_{\text{core}}/\Lambda_{\text{core}}$, the chromatic dispersion decreases and the zero dispersion wavelength shifts to longer wavelengths. For the fiber with a larger $W_{\text{ring}}$ and higher $\Delta_{\text{Ge}}$, the dispersion changes in a similar manner with decreasing dispersion and a redshift of zero dispersion wavelength. The calculated dispersion slope for the fundamental mode is $\sim 0.002$ ps/km nm$^2$, which is significantly lower than that of the standard nonlinear step index fibers, $\sim 0.02$ ps/km nm$^2$. We measured the chromatic dispersion over the range from $\lambda = 1510$ nm to $\lambda = 1590$ nm for the sample length of 50 m. The experimental and calculated values at $\lambda = 1550$ nm were 33.09 and 35.58 ps/(km nm), respectively, showing good agreement in Fig. 5(b). As shown in Fig. 5, we could confirm that our proposed structure can also provide high versatility and controllability in chromatic dispersion and its slope in wide ranges of optical communication windows.

In conclusion, adiabatic mode conversion contributing to low splice loss and high tensile strength was achieved in the proposed structure from the annulus mode to a mode generated from the solid multicore fiber, which was compatible with the LP01 mode in the conventional single mode. The new hollow germanosilicate ring defect parameters, $W_{\text{ring}}$ and $\Delta_{\text{Ge}}$, were also found to flexibly control the chromatic dispersion and dispersion slope over the optical communication windows.

This work was partially supported by KOSEF through UFON, an ERC program, by MOE-BK21 and the Deutsche Forschungsgemeinschaft in the priority program “Photonic Crystals” (SPP113). S. Kim’s e-mail address is sekim@kjist.ac.kr.

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