Silica-Based Nanostructure Core Fiber

X. Yu, P. Shum, *Senior Member, IEEE*, N. Q. Ngo, *Senior Member, IEEE*, W. J. Tong, J. Luo, G. B. Ren,
Y. D. Gong and J. Q. Zhou

***Abstract*— we report the fabrication and characterization of a new type of silica-based all-solid fiber with a two-dimensional (2D) nanostructure core. The nanostructure core fiber (NCF) was formed by a 2D array of high-index rods of sub-wavelength dimensions. The NCF's attenuation of as low as 3.5 dB/km at 1550 nm has been obtained experimentally. We also measured the chromatic dispersion, differential group delay (DGD) and polarization dependent loss (PDL) of the NCF. Higher macro- and micro-bending losses compared with that of the single-mode fiber (SMF) due to the reduced index difference has been observed experimentally, and this result suggests that NCF is potentially useful for curvature and strain sensing applications.**

***Index Terms*— Photonic crystal fiber, nanostructure, attenuation, dispersion, bending loss**

I. INTRODUCTION

It has been a new era for fiber optics ever since the first photonic crystal fiber (PCF) was fabricated by Knight *et al.* in 1996 [1]. These novel microstructure fibers are formed by an array of air holes running along the fiber length. They have attracted research attention worldwide and been extensively studied owing to their enormous potential applications in optical communication and sensing technologies [2]. Many properties of PCF such as the cutoff wavelength, dispersion, birefringence, nonlinearity, and bending loss can be tailored beyond the possibilities available in a conventional step-index single-mode fiber (SMF). Most previous studies have concentrated on PCFs with a photonic crystal (PC) cladding and a homogeneous core. In the preliminary stages [1], [2], the reason that PCF has attracted great research attention was that the fundamental space-filling mode index of the cladding lattice is a strong function of wavelength. In fact, a fiber is also able to guide light within a PC core as shown in our earlier work [3]. However, this heterostructured PCF guides light by the photonic bandgap mechanism. An index-guiding birefringent fiber with a finite one-dimensional (1D) array of PC core has been fabricated [4]. Only a few numerical modeling works for 1D PC core have been extended to two-dimensional (2D) PC core [5]. However, to our knowledge, there is no report on the fabrication and characterization of silica-based fibers with 2D PC core.

In this paper, we report, for the first time a silica-based all solid non-ringed nanostructure core fiber (NCF) formed by a 2D array of high-index rods. The proposed NCF has all-solid silica structure [4], [6], [7]. The fiber core rather than cladding is formed by a periodic structure with the core index that is a function of wavelength. If the composite core material is made homogenous, such a design will be very similar to that of a typical SMF.

II. FABRICATION

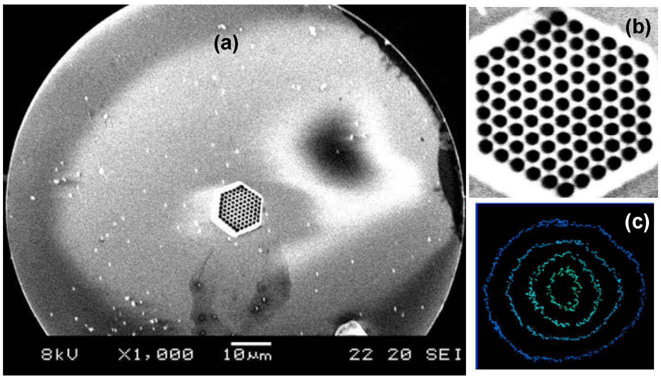

Fig. 1 (a) SEM picture of the fabricated NCF. (b) The nanostructure core region with periodic high-index rods. The black region is the germanium-doped parts. (c) Measured contour plot of the guided mode profile for the fiber shown in (a). Contours trace the 90%, 70%, 30% and 5% intensity levels and are all confined within the nanostructure regions that define the core.

The scanning electron micrograph (SEM) of the fabricated cross section of the NCF is shown in Fig. 1(a). The background material is pure silica. The maximum refractive index difference between the germanium-doped region and the pure silica is ~3%. In the fabrication process, a doped silica preform was used to build the high-index periodic structure of the core. The doped rods were etched to obtain the appropriate core/cladding diameter ratio. The preform was drawn to cane and stacked in a hexagonal pattern. This stacked core was overclad with a pure-silica thick jacket. Finally the whole structure was drawn to realize the fiber with a nanostructure core. Fig. 1 (b) shows the NCF's cross section close to the core. To clearly view the structure details, the fiber was etched in 50% hydrofluoric acid for two minutes until outer diameter reduces to 114 μm from 125 μm. The lattice spacing in the core is 1 μm. The diameters of high-index rods are 800 nm. The un-doped silica region in Fig. 1 (b) is brighter than the cladding silica due to strong discharging effects. High-index rods with 7 concentric rings were included in the fabrication so that the core size matches

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X. Yu, P. Shum, N. Q. Ngo, G. B. Ren and J. Q. Zhou are with Network Technology Research Centre, Nanyang Technological University, 50 Nanyang Drive, Research TechnoPlaza, 4th Storey, Singapore 637553
(phone: 65 67904682; fax: 65 67926894; e-mail: xyu@ntu.edu.sg).
W. J. Tong and J. Luo are with Yangtze Optical Fiber and Cable Company Ltd., Guanshan 2 Road, Wuhan, China 430073.
Y. D. Gong is with Lightwave Department, Institute for InfoComm Research, 21 Heng Mui Keng Terrace, Singapore 119613

well with that of the Corning SMF-28 [8]. The fiber was coated with polymer during the drawing. The modal profile of the fiber was measured by injecting 1550 nm light from a tunable laser into the NCF. The near-field output was imaged onto an infrared camera. The intensity profile observed is shown in Fig. 1(c). The mode is mainly confined in the core region. No higher-order core modes were observed when we varied the input power or bending/pressing the fiber.

III. CHARACTERIZATION

The attenuation for 500-m long NCF was measured using the cut-back method, as shown in Fig. 2. A highly-nonlinear PCF-based broadband supercontinuum light source was coupled into SMF which was spliced with the 500-m NCF. The output transmission spectrum was observed with an optical spectrum analyzer (ANDO AQ6317B with a resolution of 0.01 nm). The minimum attenuation of ~2.6 dB/km occurs at a wavelength of 1590 nm. The attenuation is 3.5 dB/km at 1550 nm. The large attenuation variation near 1060 nm is the residual pump signal. The highest attenuation peak at around 1385 nm (~100 dB/km) and the peaks at 944 nm and 1247 nm are due to OH^- absorption. It is believed these water peaks were mainly caused by water contamination accumulated in the stacking process. This can be further improved by adequate cleaning.

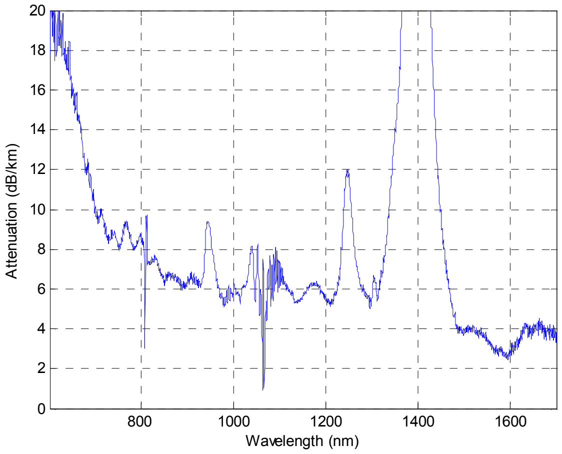


Fig. 2 Measured attenuation spectrum of the fabricated NCF using the cutback method.

Higher resolution of loss and chromatic dispersion of our NCF were measured using an optical dispersion analyzer (ODA, Agilent 86038A). The measured loss spectrum in C and L bands is shown in Fig. 3 (a). The measured loss of the 500-m NCF at 1550 nm is 5.5~6 dB, which is larger than that obtained from Fig. 2 due to two splicing points. In fact, from the optical time domain reflectometry measurement, we observed that the total loss of the two splicing points is ~4 dB. Therefore, the actual attenuation is 3~4 dB/km. This agrees well with the loss obtained from the cut-back method (Fig. 2). Note that the loss spectrum in Fig. 3 (a) has a small resonance beating. This might be due to the Fabry-Perot fringes between the Fresnel-reflecting surfaces (between the connector at the measurement port of ODA), which is usually about a few hundred microns apart.

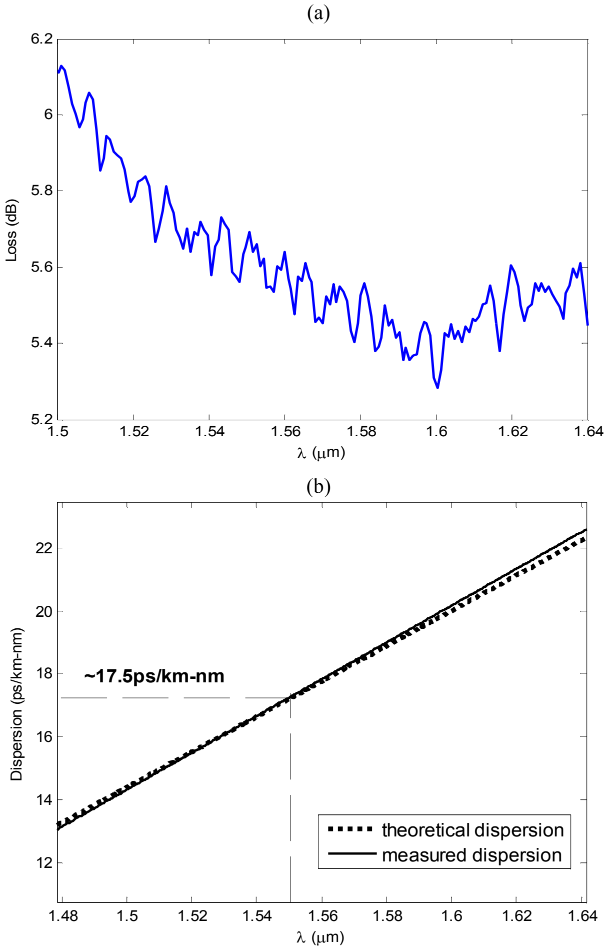
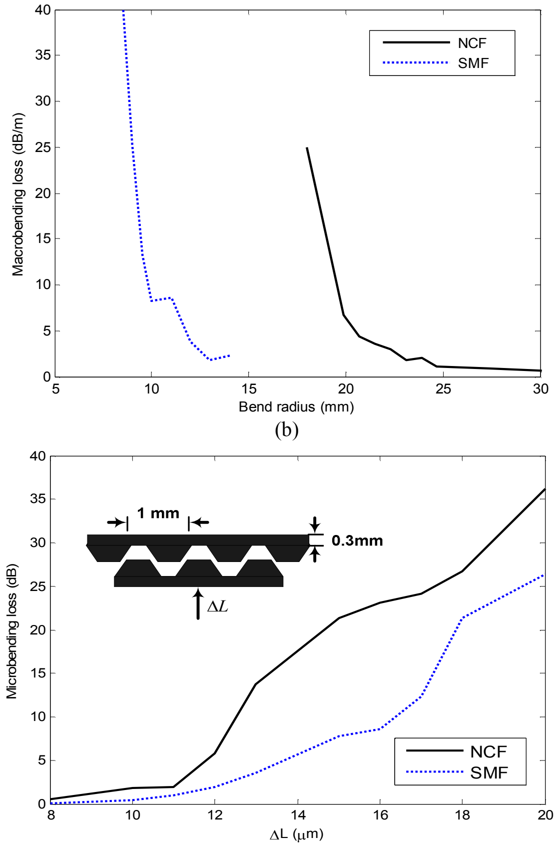


Fig. 3 (a) Measured loss spectrum of the 500-m NCF using an ODA. (b) Theoretical and measured chromatic dispersions in C and L bands using an ODA.

The measured chromatic dispersion is fitted with a linear curve as shown in Fig. 3(b). The theoretical result ~17.5 ps/km·nm at 1550 nm is calculated using a beam propagation method [9]. Polarization dependent loss (PDL) and differential group delay (DGD) were measured at 1550 nm using the Muller matrix method [10] to be 0.080 dB and 0.040 ps for 14-m NCF, respectively. The polarization effects are negligibly small due to the fiber core symmetry [11]. The small PDL value may be due to the connectors used and system measurement errors rather than the fiber itself.

We investigate the effect of bend radius on macrobending loss by measuring the transmission loss at 1550 nm of a 14-m NCF with different bend radii. The attenuation of the NCF with different bend radii for ten turns is shown in Fig. 4(a). The critical bend radius is ~20 mm, below which the bending loss exceeds 10 dB/km. By applying a periodic grooved fixture with a tooth pitch of 1 mm on the NCF, as shown in the inset of Fig. 4(b), the bending loss increases with an increase in the applied stress.

(a)



(b)

Fig. 4 (a) Measured macro-bending losses for NCF and step-index SMF. (b) Measured micro-bending losses for NCF and step-index SMF. The inset is the side view of a periodic grooved fixture used to induce micro-bending effect.

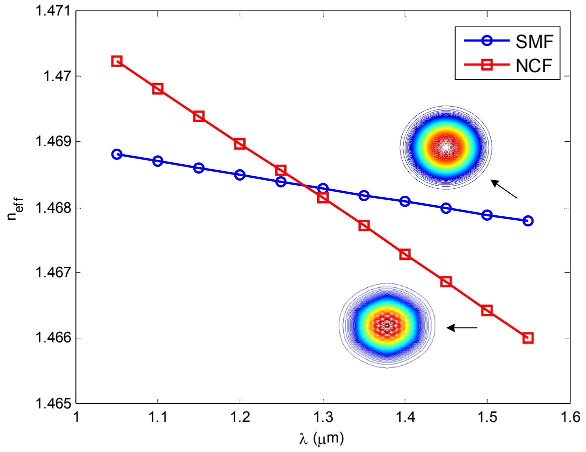


Fig. 5 Numerical results for the effective indices of the fundamental modes of SMF and NCF. The contour plots are the mode profiles for the two fibers.

Bending loss is an important phenomenon that can be used in curvature and stress sensing. The loss is caused by coupling the core mode to radiation modes. The same measurements on macro- and microbending losses were performed on the step-index Corning SMF28 and the results are also plotted in Fig. 4 for comparison. Note that the critical bending radius is twice of that of SMF. The index difference between the guided fundamental core mode and leaky cladding modes of the NCF is numerically found to be smaller than that of SMF (see Fig. 5). Therefore, mode coupling occurs with a larger macrobending radius and a smaller microbending curvature, which corresponds to a larger bending sensitivity. As the bending was applied to a coated fiber, the bending displacement of the coated fiber is larger than that of the bare glass fiber by a factor that depends on the thickness and the elastic properties of the coating material.

IV. CONCLUSION

We have fabricated and characterized, to our knowledge, for the first time a silica-based all-solid NCF. The nanostructure core was formed with a lattice of high-index rods doped with germanium. The NCF has a measured minimum attenuation of 2.6 dB/km at 1590 nm. The index difference between the core mode and leaky modes in our NCF is much smaller compared with that of SMF. This results in an improved bending sensitivity which will have potential applications for curvature and stress sensing. In addition, NCF with elliptical lattices is promising for achieving high birefringence and novel functionalities.

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