Single-mode all-silica photonic bandgap fiber with 20-μm mode-field diameter

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Abstract: An all-silica photonic bandgap fiber with a cladding index difference of approximately 2 % and diameter-to-pitch ratio (d/Λ) of 0.12 was fabricated and studied. To our knowledge, this is the first report on the properties of photonic bandgap fiber with such a small d/Λ. The fiber is single-mode in the fundamental bandgap. The mode field diameter in the 1000-1200 nm wavelength range is 19-20 μm. The minimum loss in the same range is 20 dB/km for a 30-cm bending diameter. In our opinion, all-silica photonic bandgap fiber can serve as a potential candidate for achieving single-mode propagation with a large mode area.

OCIS codes: (060.2280) Fiber Design and Fabrication, (060.4005) Microstructured Fibers.

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1. Introduction

All-solid photonic bandgap fibers are a new and extraordinary object, different both from conventional index guiding and hollow-core bandgap fibers [1]. The fiber is made of silica glass and has a pure silica core. The cladding is a two-dimensional photonic crystal and consists of cylindrical high-index inclusions of germanium oxide doped silica glass embedded in a pure silica background in a hexagonal array with the axis parallel to the fiber axis. Light is confined in the fiber core due to the formation of a photonic bandgap by periodic elements in the fiber cladding. Spectral and dispersion properties of all-solid photonic bandgap fibers are similar to properties of air-core photonic bandgap fibers, but solid core fibers are easier to fabricate and splice. Also, active doping of the core region and photo inscription of Bragg gratings are easily implemented in this type of fibers.

Unusual spectral and dispersion properties of solid-core photonic bandgap fibers have already enabled some interesting applications. The sharp edge of the transmission window was used to suppress four-level amplified spontaneous emission in neodymium doped fibers [2]. The possibility of achieving anomalous dispersion at wavelengths around 1000 nm with mode field diameters larger than in fibers with holey cladding and solid core [3] was used for dispersion compensation in pulsed fiber lasers [4].

In this work, we consider another important laser systems application: single-mode large mode area propagation in a wide spectral range. This can be achieved through the fabrication of a cladding with a small rod-diameter-to-pitch ratio (d/Λ), where d is the rod diameter and Λ is the center-to-center distance between neighboring rods. When d/Λ decreases, the effective refractive index at the bottom of the bandgap increases and the bandgap becomes shallow [5]. This means that decreasing d/Λ, decreases the core numerical aperture. If a value of d/Λ is sufficiently reduced, a single-mode regime can be produced. In this case, all high-order modes are strongly coupled with cladding states and become evanescent. In this work we demonstrate that at $d/\Lambda=0.12$ robust single-mode propagation is achieved over a wide spectral range from 900 to 1500 nm with tolerable optical loss -20 dB/km.

A small diameter–to-pitch ratio in these fibers is also very important from the point of view of using such fibers in cladding pumped lasers. When cladding pumping this type of fiber through the fiber end, a part of the pump radiation will be captured by high index rods. The captured part is proportional to the ratio of rods area to total fiber cross sectional area. In contrast to the case of large diameter–to-pitch ratio, in which a small diameter–to-pitch ratio permits cladding pumping through the fiber end without capturing a large part of pump radiation by high-index rods. In the fiber design with diameter–to-pitch ratio equal to 0.12 only approximately 1-2 % of pump radiation will be captured.

In this work, an all-silica photonic bandgap fiber with a small ratio of rod diameter to pitch d/Λ was studied theoretically and experimentally. We demonstrate that small d/Λ results in robust single-mode operation over a wide spectral range from 900 to 1500 nm with mode field diameter of ~20 micron and confirm that it permits cladding pumping from the fiber end. We believe that this type of fiber compares favorably to "conventional" photonic crystal fiber [6] for large mode area single-mode propagation and is easer to fabricate.

2. Fiber fabrication

The fiber was made by the stack–and-draw technique widely used for fabrication of micro-structured fibers. The rods were drawn from a conventional MCVD perform in a fiber drawing tower. The preform core was doped by germanium dioxide during a modified chemical vapor deposition (MCVD) process and exhibits a gradient index profile with a maximum index difference of about 0.032. The rods were assembled into a micro-structured preform and then drawn into fiber.

A photograph of the Fiber end-face is shown in Figure 1. The distance between centers of neighboring rods is Λ = 11.4 microns. The fiber core was formed by omitting one doped rod.

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The core diameter is approximately 22.8 microns. The fiber cladding has seven layers; the outermost row is slightly distorted. The outer fiber diameter is 182 microns.

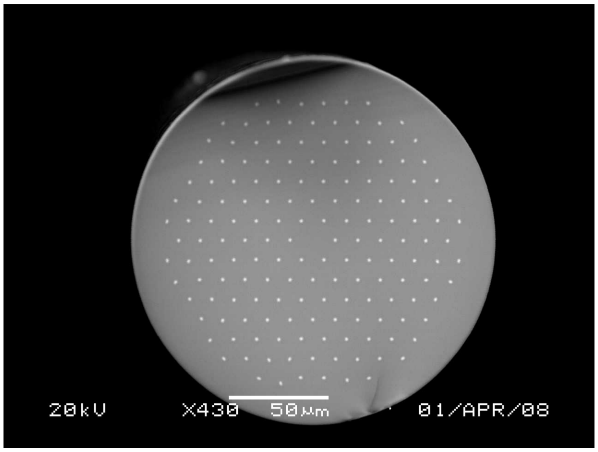

Fig. 1. SEM image of fiber end face.

3.Theoretical modeling

To ensure that the fiber is single-mode, theoretical modeling (to compare the optical loss of the fundamental and second order core modes) was done, using the measured parameters of the manufactured fiber. We perform our calculations using the CUDOS MOF software package [7, 8], based on the multipole method, with the fiber design as presented in Figure 1. For the calculation, the graded refractive index profile of the rods was represented by an equivalent step index profile [9]. The resulting parameters are: $d/\Lambda=0.12$, rod spacing (pitch) $\Lambda=11.4$ μm, refractive index difference between the rods and the pure silica matrix – 0.028. The calculation was performed for four layers of rods in the cladding.

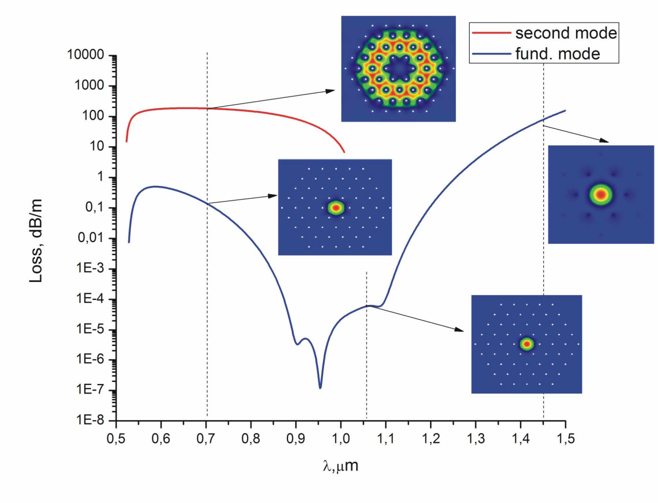

Fig. 2. The calculated loss of the fundamental and second order modes in the fundamental bandgap of a SC PBG fiber with parameters $d/\Lambda=0.12$, rod spacing $\Lambda=11.4$ μm, refractive index difference between the rods and the pure silica matrix – 0.028. In insets – the longitudinal Poynting vector distribution for different modes.

Calculation results for optical loss of the fundamental and second core modes in the fundamental or long-wavelength bandgap are shown in Figure 2. The short wavelength edge of the fundamental bandgap is at 500 nm. The second mode localizes only from the short wavelength edge to the center of the bandgap. Optical loss of the second core mode is approximately 100 dB/m and more then 100 times larger than the loss of the fundamental mode. This difference changes greatly with wavelength. The longitudinal Poynting vector calculation is presented in the insets of Fig. 2. The longitudinal Poynting vector of the second mode extends into the cladding, indicating that the second mode is leaky. At the same time, the fundamental mode is guided, as can be seen from the localization of the Poynting vector distribution.

In our opinion, one possible way to explain single-mode behavior is that at small diameter to pitch ratio the band gaps become shallow, decreasing the core numerical aperture [5]. When d/Λ is small enough, all high-order modes are coupled with cladding states and become leaky. Only the fundamental mode propagates because it has the lowest numerical aperture (NA).

4. Experimental results

We measured the loss spectra of an 80-m segment of fiber by the cut-back technique. To make sure that the light propagates in the core, an additional index guiding fiber with a mode field diameter of 6 μm was spliced to the input and output ends of the tested fiber. The light propagation in the core was controlled with a CCD-camera after the measurements. The optical loss was measured from 900 nm to 1500 nm. The minimum loss of 20 dB/km was found in the 1000-1200 nm range. Loss spectra were measured with the fiber in a free coil having a 30-cm bend diameter. Compared with the calculation results, the minimum optical loss is red-shifted by 100 nm. This shift is due to index profile changes during fiber drawing process [10].

To investigate the limits of single-mode propagation in the bandgap fiber, we butt coupled a conventional step index fiber with a mode-field diameter (MFD) of 6 µm in an offset-launch from a supercontinuum source. When the cores of both fibers are strictly coaxial, mainly the fundamental, lowest order mode is excited. For the case when the fiber supports only that mode, introducing offset results in reduced light intensity at the output of a fiber under test, but the near field pattern remains unchanged and nearly Gaussian. For the case when higher order modes are supported, they are clearly observed and eventually dominate the output for increasing offset of the launch.

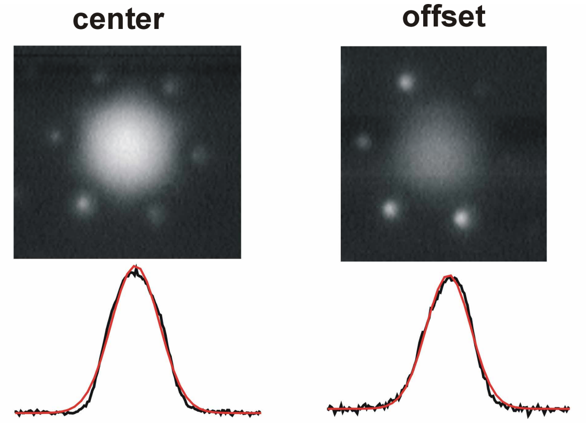

Fig. 3. Near field patterns for different launching conditions at the wavelength 1.1 μm. Fiber length is 10 cm.

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We examined the near field pattern for different launch conditions (Figure 3). A straight 10-cm long fiber was used. At both centered and offset positions the intensity distribution in the near field remains unchanged and nearly Gaussian. In the investigated range 700-1300 nm the fiber is single mode. In the range of minimum loss, 1000-1200 microns, the mode field diameter at $1/e^2$ is 19-20 μm.

At small diameter–to-pitch ratio, band gaps of all-solid photonic bandgap fiber become shallow [5]. This results in high bend loss [11]. To investigate how transmission changes at different bend diameters we measure the loss by the cut-back technique in 3 meters of fiber coiled with different diameters (Figure 5). To avoid microbending, the fiber is wound in a free coil without a spool. At bend diameters smaller than 17 cm, several strong loss peaks are observed. Our hypothesis is that they appear due to the core mode coupling to different cladding modes in the bent fiber. The change of cladding states at different bend diameters results in the blue shift of the peaks position. No significant loss increase is observed in the fiber coiled with the diameter larger than 17 cm.

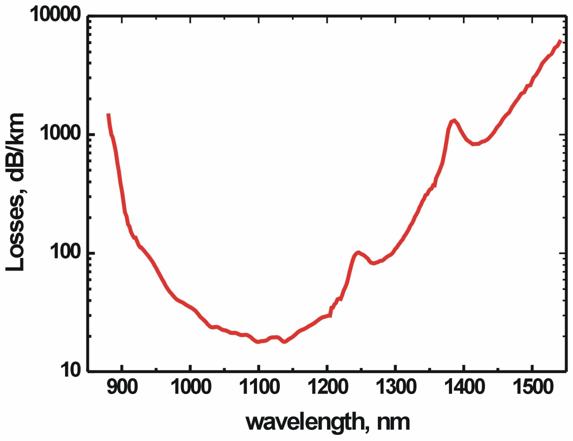

Fig. 4. Fiber loss measured by thecut back method in the fundamental bandgap.

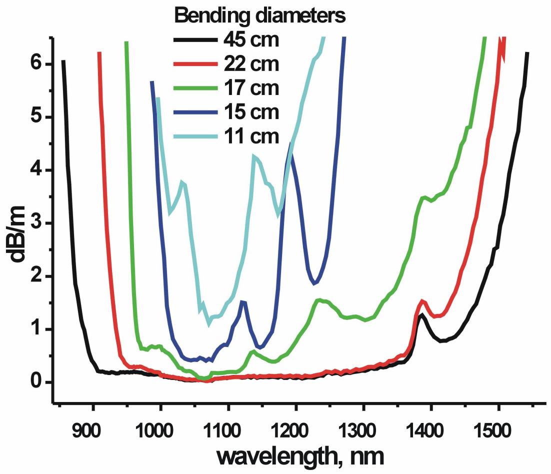

Fig. 5. Bend loss at different bending diameters.

5. Conclusion

All-silica photonic bandgap fiber with cladding index difference of 2 % and diameter-to-pitch ratio of 0.12 was fabricated and studied. To our knowledge, this is the first report on properties of fiber with such small d/Λ. At small d/Λ the core-mode numerical aperture decreases and robust single mode propagation can be obtained with a large mode field diameter in the fundamental bandgap. In contrast to large diameter–to-pitch ratio, small diameter–to-pitch ratio permits end pumping of this type of fiber without capturing a large part of pump radiation in the high index rods. For fiber designs with a diameter–to-pitch ratio equal to 0.12, approximately 1-2 percent of pump radiation is captured by the high-index rods. The existence of a single-mode propagation region was proven theoretically, by optical loss and longitudinal Poynting vector calculations, and experimentally, by mode structure analysis. Mode The mode field diameter at wavelengths from 1-1.2 μm is 19-20 μm. The fundamental bandgap extends from 900 to 1500 nm. The minimum optical loss in the region 1.0-1.2 microns is 20 dB/km at a 30-cm bend diameter. For bend diameters smaller than 17 cm several strong loss peaks, caused by core-cladding mode coupling, were observed. No significant loss increase was observed for bend diameters larger than 17 cm.

In our opinion, all-silica photonic bandgap fiber can serve as a potential candidate for achieving large mode area single-mode propagation. Simplicity of fabrication makes it attractive compared with holey fiber designs [12].

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