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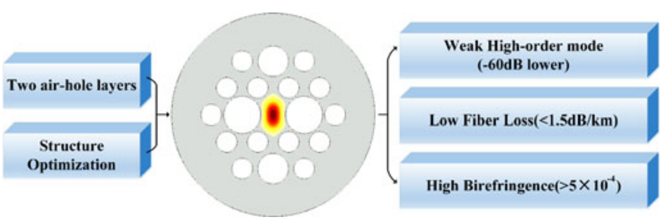

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Two-Layer Polarization-Maintaining Solid-Core Photonic Crystal Fiber

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Abstract: In this study, a two-layer polarization-maintaining solid-core photonic crystal fiber (SC-PCF) is proposed. The cladding has two large holes both in the first and second layers for high birefringence and confinement loss reduction, respectively. The structural parameters are determined from the confinement loss, birefringence, and mode fields, based on which the two-layer polarization-maintaining SC-PCF is fabricated. The experimental results indicate that the loss and birefringence are 1.25 dB/km and 5.2×10^{-4}, respectively.

Index Terms: Solid-core photonic crystal fiber, two-layer.

1. Introduction

The first photonic crystal fiber (PCF) was manufactured nearly two decades ago [1] and has been widely used in several areas such as fiber sensors [2], [3], fiber communication [4], and fiber lasers [5]. The solid-core photonic crystal fiber (SC-PCF) has various advantages, such as an endlessly single mode, low loss, and low radiation sensitivity, which makes it very suitable for application in fiber-optic gyroscopes (FOGs) [6]–[11]. High birefringence can be introduced into SC-PCF by adding different air holes along the two birefringent axes [12], or by replacing two neighboring air holes in the center by silica rods to obtain asymmetrical core [13], or by using elliptical air holes in the cladding [14]. Currently, the relatively mature highly birefringent SC-PCF has similar structure as conventional Panda fiber [15]. A four-layer SC-PCF with a diameter of only about 135 μm was designed and fabricated for application in FOGs in our previous study [16]. Although only 55 capillaries were stacked, it still caused issues during fiber fabrication, involving capillary cleaning and stacking. The PCF has a simpler fiber structure with fewer capillaries, which can simplify the fabrication process and improve productivity. The common method of fiber fabrication involves reducing the cladding layers. A single cladding layer was studied in [17], [18], but the fiber loss was too large (170 dB/km at 1064 nm). Double layers was investigated and the fiber loss was reduced to 2.3 dB/km at 1550 nm combined with a germanium-doped core [19]. However, all these single and double-layer fibers are not polarization-maintaining.

In this study, for the first time to the best of our knowledge, we investigated a two-layer low-loss polarization-maintaining SC-PCF. Only 18 capillaries were stacked and two large holes were used in the first (inner) layer to improve the birefringence [20]–[23]. More importantly, two additional large holes were used in the second (outer) layer to reduce light leakage and fiber loss. The two-layer

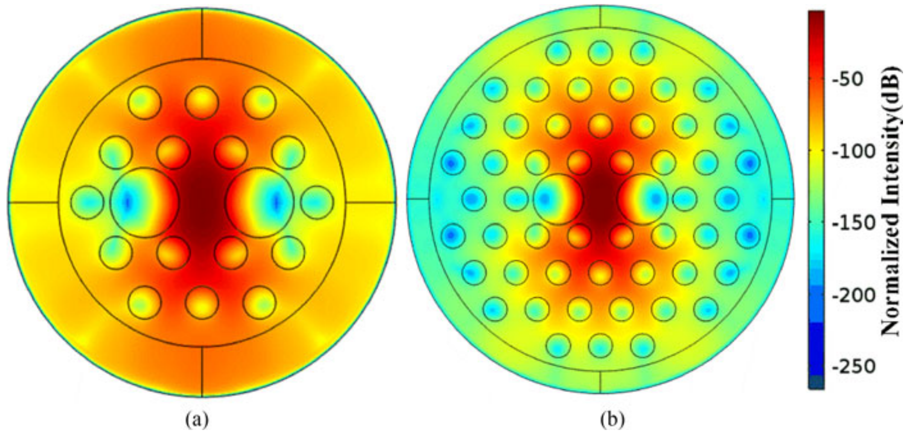


Fig. 1. Comparison of light leakage for (a) two-layer and (b) four-layer polarization-maintaining SC-PCF.

SC-PCF has a similar performance to conventional multi-layer polarization-maintaining SC-PCFs [23], but with a simple structure, simple fabrication process, and small diameter potential.

2. Two-Layer SC-PCF Design

The typical full vector finite element method and the software COMSOL Multiphysics 5.0 were used to design and optimize PCF structures. The dependence of confinement loss on the number of cladding layers and the air filling ratio has been investigated in previous studies [21], and they demonstrate that the confinement loss decreases with the cladding layer number and air filling ratio, e.g., the confinement loss of the two-layer polarization-maintaining SC-PCF is several times higher than that of the four-layer case when the air filling ratio is 0.5, as illustrated in Fig. 1. It is clear that there is a significant amount of light leakage in the y-direction where no large holes can confine the light, and the leakage is stronger for the two-layer SC-PCF. As a rule, two methods can reduce the confinement loss of the two-layer polarization-maintaining SC-PCF. The air filling ratio could be increased, and two large holes could be added in the y-direction. Increasing the air filling ratio of the holes in the cladding could induce more air regions and a lower equivalent refractive index in the cladding, which could make the light more strongly confined within the core, but also cause more high-order modes if the air filling ratio is too large. Adding two large air holes in the y-direction would suppress light leakage in the y-direction, similar to that in the x-direction, but for other directions, this method could have a limited effect. Therefore, we promote the use of these two methods to reduce the confinement loss for the two-layer polarization-maintaining SC-PCF, and the designed structure is illustrated in Fig. 2.

As illustrated in Fig. 2, 18 air holes are triangularly arrayed in the two-layer cladding, including two large holes in the first layer and two in the second layer. The two large holes in the first layer are used to produce geometry birefringence and reduce the loss in the x-direction, and those in the second layer are used to reduce the loss in the y-direction. All the holes in the cladding are absolutely necessary. The distance between two neighboring air hole centers is $\wedge$, d is the diameter of the small holes, D_c and D_s are the diameters of the large holes in the first and second layer, respectively, and $D = D_c = D_s$ when they are equal.

2.1 Confinement Loss

Confinement loss is determined by $d/\wedge$, $D/\wedge$, and $\wedge$. The dependence of the confinement loss on $\wedge$ under different values of $d/\wedge$ is shown in Fig. 3(a) for the promoted two-layer polarization-maintaining SC-PCF. Larger $d/\wedge$ and $\wedge$ values result in a smaller confinement loss, and $d/\wedge$ is one of the primary factors determining the confinement loss because of the fact that a larger $d/\wedge$ induces

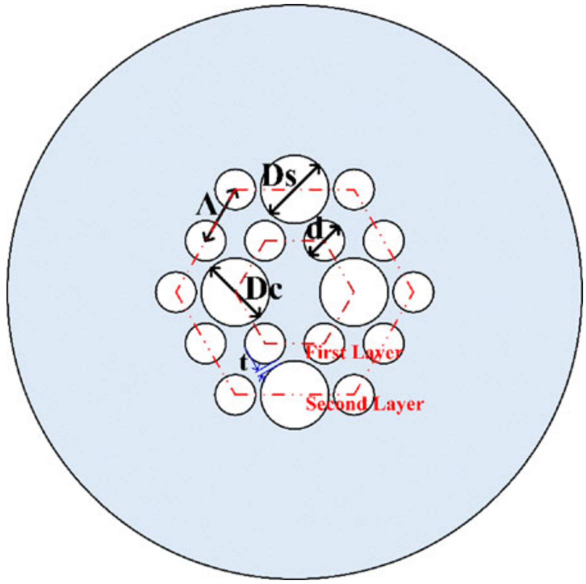


Fig. 2. Promoted structure of two-layer polarization-maintaining SC-PCF.

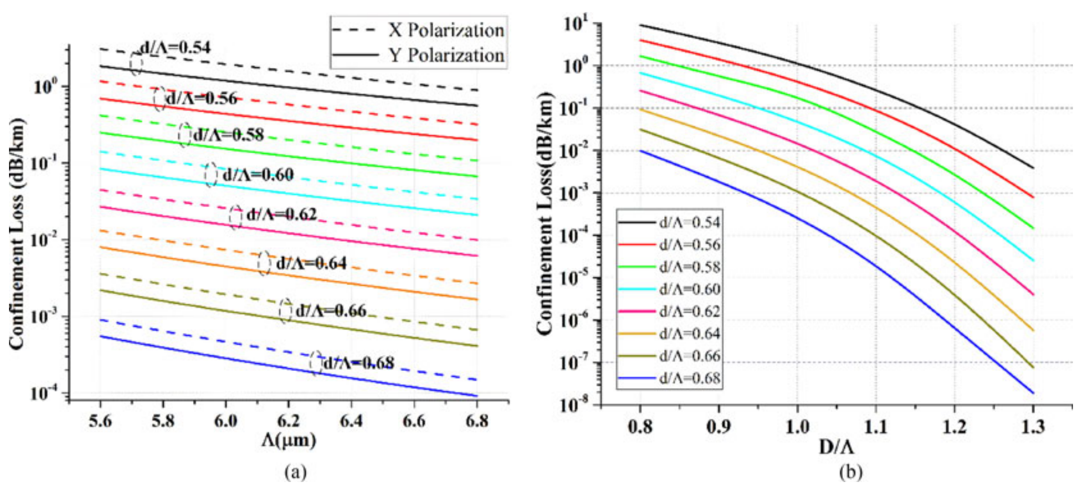


Fig. 3. (a) Relation between confinement loss, d/∧, and ∧ for two-layer polarization-maintaining SC-PCF under the condition of D = ∧. (b) The dependence of confinement loss on d/∧, and D/∧ f under the condition of ∧ = 6 μm.

more air regions and a lower equivalent refractive index in the cladding. Generally, the confinement loss should be smaller than 1×10^{-3} dB/km and the mode field should be approximately 6 μm, which are the values for our four-layer polarization-maintaining SC-PCF [16], so ∧ and d/∧ are determined here to be larger than 6 μm and 0.62, respectively, according to Fig. 3. Although the confinement loss is still large, other methods will be used to reduce the loss.

The dependence of the confinement loss on D/∧ under different values of d/∧ is shown in Fig. 3(b). The confinement loss sharply decreases as D/∧ increases, and its effect is much more significant than that induced by the increase in d/∧ and ∧. D/∧ and d/∧ should be larger than 1 and 0.6, respectively, for a confinement loss smaller than 1×10^{-4} dB/km.

Therefore, from the perspective of the confinement loss, d/∧, D/∧, and ∧ are determined to be 0.64, more than 1.05, and 6 μm, respectively. The combination of these parameters should guarantee a confinement loss of about 1×10^{-3} dB/km.

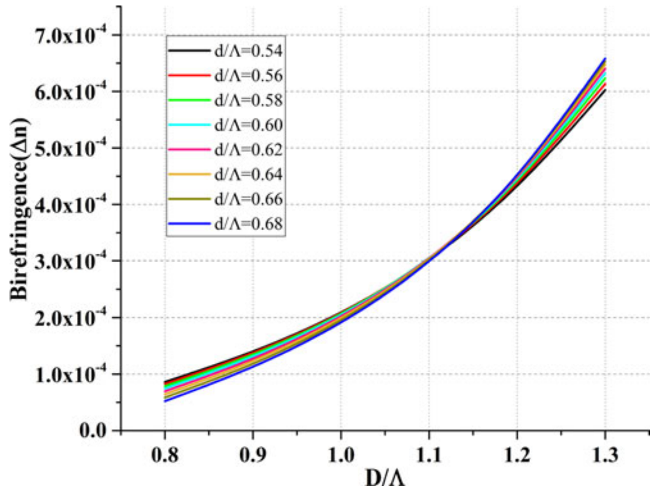


Fig. 4. Dependence of birefringence ($\triangle$n) on D/$\wedge$ under different d/$\wedge$ values.

2.2 Birefringence

Birefringence in the two-layer polarization-maintaining SC-PCF is a kind of geometry birefringence and is primarily determined by the size (D) of the two large holes in the first layer because these holes directly affect the core shape. Birefringence can be expressed by the refractive difference ($\triangle$n) between the x and y-polarization modes. As illustrated in Fig. 4, $\triangle$n significantly increases with D/$\wedge$, but barely changes with d/$\wedge$ as it does not contribute much to the shape of the fiber core. Generally, birefringence should be larger than 5×10^{-4}, the value for our four-layer polarization-maintaining SC-PCF [13]. Therefore, D/$\wedge$, in this case, should not be smaller than 1.2 based on Fig. 4. A larger D/$\wedge$ is beneficial for high birefringence, but the thickness (t) of the strut between the large and small holes (see Fig. 2) becomes too small, which can cause the air holes to deform during the fiber drawing process; thus, D/$\wedge$; = 1.2 is ultimately chosen.

2.3 Modes

The mode is another point that must be considered in the design of the PCF structure. d/$\wedge$ is so large (0.64) that high-order modes must exist in the designed two-layer polarization-maintaining SC-PCF. In order to reduce the intensity of the high-order modes and maintain as much as possible the properties of the fundamental mode, we further optimize the diameter (D_s) of the two large holes in the second layer. Ds is chosen as a tool to change the high-order modes because these two large holes are far away from the core and do not affect the birefringence designed in the previous section.

As shown in Fig. 5, the confinement loss of both the fundamental and high-order modes increases as $D_s/\wedge$ decreases, and the fundamental mode loss is as small as 1×10^{-4} dB/km for the designed value of $D_s/\wedge = 1.2$, but the loss is also a little small (smaller than 10^{-2} dB/km) for the high-order mode, so $D_s/\wedge$ could be reduced to increase the loss of the high-order mode and, at the same time, ensure the loss of the fundamental mode is not higher than 1×10^{-3} dB/km.

According to the simulation and analysis results from the confinement loss, birefringence, and mode fields, the ultimate structural parameters of the two-layer polarization-maintaining SC-PCF are summarized in Table 1. With these structural parameters, the confinement loss, birefringence, and high-order mode loss are 1×10^{-3} dB/km, 4.5×10^{-4}, and 0.1 dB/km, respectively.

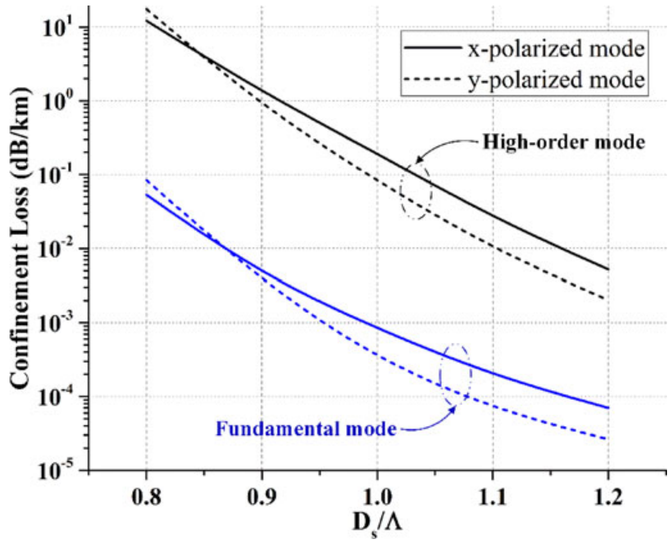
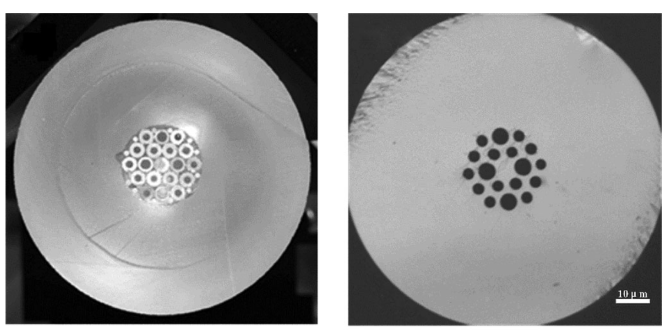


Fig. 5. Dependence of confinement loss of fundamental mode and high-order mode on $D_s/\wedge$.

TABLE 1
Ultimate Structural Parameters for Two-Layer Polarization-Maintaining SC-PCF

Parameter	$\wedge$	$d/\wedge$	$D_c/\wedge$	$D_s/\wedge$
Value	6 μm	0.64	1.2	1



(a) (b)

Fig. 6. (a) Preform and (b) final prototype of the designed two-layer polarization-maintaining SC-PCF.

3. Experimental Tests and Results

According to the designed structural parameters in Table 1, the two-layer polarization-maintaining SC-PCF is fabricated using the popular "stack-draw" method [22], [24]. As illustrated in Fig. 6(a), the capillaries with a diameter of about 2.4 mm are arrayed within a tube based on the designed structure in Fig. 2. For the big holes within the first and second layer, the four capillary tubes have the same air filling ratio of $\sim$0.67, which leads to $D_c = D_s = D$. It is a little different from the designed values in Table 1, but significantly simplifies the fabrication process. There are fewer capillaries

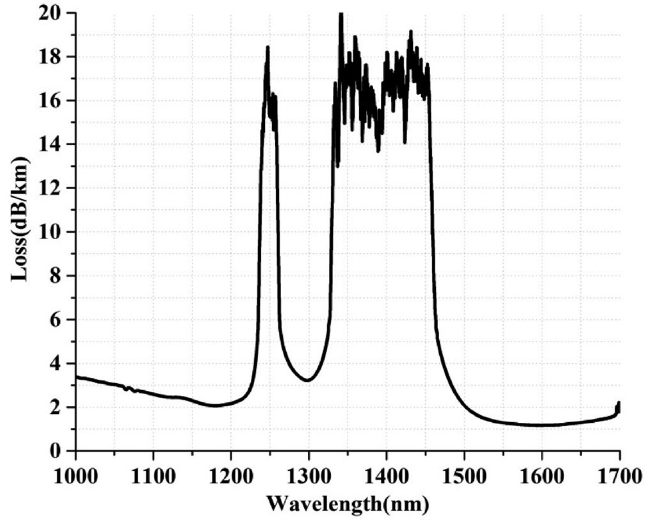


Fig. 7. Loss spectrum of two-layer polarization-maintaining SC-PCF.

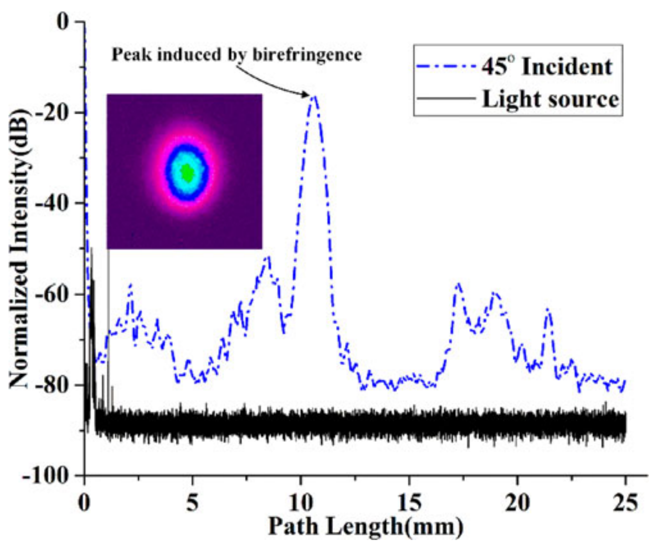


Fig. 8. Birefringence, mode field, and near-field test results for the two-layer polarization-maintaining SC-PCF.

compared to the four-layer SC-PCF, so stacking, cleaning, and drawing becomes much simpler; moreover, less pollution is generated during the fabrication of the preform. During the drawing process, gas pressure and temperature should be precisely controlled to reduce expansion of big air holes in order to avoid distortion to the fiber core and other small air holes. Fig. 6(b) shows the final two-layer polarization-maintaining SC-PCF, indicating that $\wedge = 5.7\,\mu$m, $D/\wedge = 1.1$, and $d/\wedge = 0.63$. $\sim$6-km two-layer polarization-maintaining SC-PCF prototype has been fabricated, and it is wound on a barrel having a diameter of $\sim$16 cm. The loss spectrum of this prototype is measured with cutting-back method and presented in Fig. 7. The cutting length is $\sim$10 m that is sufficient to eliminate other stray modes. The water peak is broad because the capillaries have been deposited for a long time after they are produced, but it rapidly falls off at about 1450 nm. The fiber loss is about 1.25 dB/km at 1.55 μm, the value of which is even better than that of commercial five-layer polarization-maintaining SC-PCFs.

To determine the birefringence of the fiber prototype, linearly polarized light is launched into the 20-m fiber with a 45° alignment angle to the birefringent axes, and the output light travels into an optical coherence domain polarimetry instrument that is used to determine the phase delay and intensity of the secondary waves [25]. The results are presented in Fig. 8, which indicates that the fiber birefringence is approximately 5.3×10^{-4}. It also indicates that other secondary waves exist because of the high-order and bulk modes, which is reasonable and agrees well with the theoretical expectation in the previous section owing to the large $d/\wedge$. However, the intensity of the high-order and bulk modes is only about –60 dB of the fundamental mode, so they do not affect the domination of the fundamental mode, as illustrated in the inset of Fig. 8, which shows the near-field image of the fiber. Therefore, this two-layer polarization-maintaining SC-PCF is suitable for long-distance, single-mode, and polarization-maintaining applications, such as FOGs. Moreover, it provides the potential for smaller-diameter fibers because of the smaller inner-cladding diameter.

4. Conclusions

A two-layer polarization-maintaining SC-PCF is promoted, designed, and fabricated in this study. It has a two-layer cladding, confinement loss is reduced through a high air filling ratio and two large holes in the y-direction, and the structural parameters are optimized from the perspectives of the birefringence and mode fields. Based on these parameters, a two-layer polarization-maintaining SC-PCF prototype is fabricated, and the test results indicate that the loss and birefringence are 1.25 dB/km and 5.3×10^{-4}, respectively. The two-layer polarization-maintaining SC-PCF prototype has similar optical properties to four- or five-layer polarization-maintaining SC-PCFs, but with a much simpler fabrication process. It is suitable for long-distance, single-mode, and polarization-maintaining applications, such as FOGs. Furthermore, extremely small diameter SC-PCFs might be fabricated by this two-layer structure for FOG application in the future.

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