Highly Birefringent and Dispersion Compensating Photonic Crystal Fiber Based on Double Line Defect Core

Yong Soo Lee¹, Chung Ghieu Lee², Yongmin Jung³, Myoung-kyu Oh¹, and Soeun Kim¹*

¹Integrated Optics Laboratory, Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 61005, Korea
²Department of Electronic Engineering, Chosun University, Gwangju 61452, Korea
³Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK

(Received May 10, 2016 : revised August 29, 2016 : accepted September 19, 2016)

We propose a highly birefringent and dispersion compensating photonic crystal fiber based on a double line defect core. Using a finite element method (FEM) with a perfectly matched layer (PML), it is demonstrated that it is possible to obtain broadband large negative dispersion of about -400 to -427 ps/(nm.km) covering all optical communication bands (from O to U band) and to achieve the dispersion coefficient of -425 ps/(nm.km) at 1.55µm. In addition, the highest birefringence of the proposed PCF at 1.55 µm is 1.92 × 10⁻² and the value of birefringence from the wavelength of 1.26 to 1.8 µm (covering O to U bands) is about 1.8 × 10⁻² to 1.92 × 10⁻². It is confirmed that from the simulation results, the confinement loss of the proposed PCF is always less than 10⁻³ dB/km at 1.55 µm with seven fiber rings of air holes in the cladding.

Keywords: Photonic crystal fibers, Dispersion compensating fiber, Polarization maintaining fiber
OCIS codes: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication; (060.5295) Photonic crystal fibers

I. INTRODUCTION

Investigations of optical fiber with high birefringence and broadband negative dispersion simultaneously would provide a new platform for optical fiber communication networks and optical fiber sensing systems, which can further improve the signal. A high level of birefringence in optical fiber is often required to preserve two orthogonal linear polarization states over long lengths of fiber in recent coherent optical communications, fiber optic gyroscopes and optical sensing applications [1, 2]. In addition, the dispersion must be compensated in the long-distance optical data transmission system to suppress the broadening of the pulse. One way to realize this is to use the dispersion compensating fibers (DCFs) having large negative dispersion, which can improve the transmitting quality by reducing attenuation and broadening signal [3]. So it is the best way to improve the quality of the system by designing PCF with high birefringence and negative dispersion simultaneously. Besides this, there is one more advantage of having both high birefringence and broadband negative dispersion, particularly in optical amplifications. Long conventional optical fiber links can not maintain linear polarization. Therefore, if linear polarization is maintained, gain efficiency may be improved by approximately a factor of 2 [4]. The optical fiber with high birefringence and large negative dispersion simultaneously can maintain linear polarization and show double Raman gains with relatively small fiber length.

It is well known that when using a conventional step index optical fiber, it is difficult to achieve high birefringence and negative dispersion simultaneously. Over the last two decades, photonic crystal fibers (PCFs) have been intensively studied to overcome the limitation of conventional step index optical fibers due to the design flexibility for the fiber cross section [5-8]. Various PCF designs have been explored to achieve an ultra-broadband single mode operation [9,
10], unique dispersion properties [11-13], high nonlinearity [14] and high birefringence [15-17]. Since the refractive index contrast between the core and the cladding in PCF is higher than that of conventional optical fiber, high birefringence can be easily realized in PCFs. So far, various highly birefringent PCFs (HB-PCFs) have been reported by breaking the symmetry of the fiber core or cladding [12, 15, 18-25]. The birefringence of these HB-PCFs ranges from 10\(^{-3}\) to 10\(^{-2}\), which is one to two orders of magnitudes higher than that of conventional HB fibers. Since the refractive index contrast between the core and the cladding in PCF is higher than that of conventional optical fiber, high birefringence can be realized in PCFs. So far, various highly birefringent PCFs (HB-PCFs) have been reported by breaking the symmetry of the fiber core or cladding [12, 15, 18-25]. The birefringence of these HB-PCFs ranges from 10\(^{-3}\) to 10\(^{-2}\), which is one to two orders of magnitudes higher than that of conventional HB fibers. The large index contrast between core and cladding in PCF can be obtained by arranging large air holes in the cladding which helps to increase the modal birefringence and low confinement loss but results in excessively large chromatic dispersion. Large index contrast between core and cladding using large air holes in the cladding of the conventional PCF induce high birefringence but the influence of the waveguide dispersion in the fiber becomes stronger. On the other hand, as air hole diameter decreases, index contrast becomes small. In this case, high birefringence cannot be expected. Therefore, by using a conventional PCF design, it is difficult to achieve large negative dispersion and high birefringence at the same time. The accumulated chromatic dispersion should be compensated by a dispersion compensating device such as a dispersion compensator or dispersion compensating fiber (DCF), which makes the systems complicated. The future development of a compact and low cost optical communication system needs a single simple device to perform the multi-objective function.

Recently, several PCF designs for high birefringent and broadband dispersion compensating have been reported [26-29], but it requires a very sophisticated manufacturing process to realize the reported PCFs because their cross sections are not based on the conventional lattice structure and all air holes are not circular.

In this study, we propose a highly birefringent and dispersion compensating photonic crystal fiber based on a double line defect core. The proposed PCF is based on the square lattice cladding structure due to the superiority of square lattice PCF compared to triangular lattice PCF from the previous report [30, 31]. It is reported that the PCF based on the square lattice cladding shows a wider range of single mode operation compared to the triangular lattice PCF with the same structure parameters [30] and the effective area of the square lattice PCF is larger than that of the triangular lattice PCF, which leads to low coupling loss between the PCF with square lattice and the conventional single mode fiber in optical communication systems [31]. The notable point of the proposed PCF is that broadband high birefringence and negative dispersion can be obtained at the same time along with design of the double line defect core.

Using a finite element method (FEM) with a perfectly matched layer (PML), it is demonstrated that it is possible to obtain broadband large negative dispersion of about -400 to -427 ps/(nm.km) covering all optical communication bands (from O to U band) and to achieve the dispersion coefficient of -425 ps/(nm.km) at 1.55 \(\mu\)m. In addition, the highest birefringence of the proposed PCF at 1.55 \(\mu\)m is 1.92\(\times 10^2\) and the value of birefringence from the wavelength of 1.26 to 1.8 \(\mu\)m (covering O to U bands) is about 1.8\(\times 10^2\) to 1.92\(\times 10^2\). According to the simulation work, the confinement loss of the proposed PCF is always less than 10\(^{-3}\) dB/km at 1.55 \(\mu\)m with seven fiber rings of air holes in the cladding.

**II. DESIGN ALGORITHM AND OPTICAL PROPERTIES**

Figure 1 shows the way to form a double line defect...
core PCF from the conventional square lattice PCF. The proposed PCF design in this study is started from a square lattice cladding and a rectangular core by removing six air holes from the center (type I). The lattice, lattice cladding and a rectangular core by removing six air holes from the conventional square lattice PCF. The proposed PCF design in this study is started from a square core PCF from the conventional square lattice PCF. The lattice, lattice cladding and a rectangular core by removing six air holes from the center (type I). The lattice, lattice cladding and a rectangular core by removing six air holes from the center (type I). The lattice, lattice cladding and a rectangular core by removing six air holes from the center (type I). The lattice, lattice cladding and a rectangular core by removing six air holes from the center (type I). The lattice, lattice cladding and a rectangular core by removing six air holes from the center (type I).

Next, in Fig. 1(b), a straight single line defect of small air holes is added both up and down in the core region symmetrically (type II). Finally, in order to further enhance the asymmetry of the core and reduce the dispersion value and slope, an additional line is added into the core as shown in Fig. 1(c). This is the proposed PCF design in this paper which has a double line defect core (type III). In order to reduce the confinement loss of the guided mode, we set the size of air holes in the square lattice cladding large enough (about \(d/c = 0.33\)). Double line defect in the core introduces a high asymmetry in the core and its small sized air holes with small pitch provide much greater impact on dispersion compensation of the PCF. In the consideration of guiding condition in the core, the number of defect lines is optimized to 2. If one more line defect is added to the core, the guiding mode does not satisfy the guiding condition in the core and it decays.

Figure 2 shows how to change the transverse field distributions for y- and x-polarized fundamental modes from type I to type III PCFs at 1.55 \(\mu\)m, where \(\Lambda = 1.2\) \(\mu\)m, \(D/\Lambda = 0.83\), \(\Lambda_x = \Lambda/2\), \(\Lambda_y = \Lambda/3\) and \(d_x/\Lambda = 0.33\). By adding line defects one by one, the core shape becomes more and more rectangular and the mode profile becomes more squeezed. From these results, we can expect that higher birefringence can be achieved in type III PCF and x-polarized fundamental mode can have lower confinement loss.

To illustrate the impact of the double line defect on optical properties we compared optical properties of three different types of PCF using Finite Element Method (FEM) and eigen-mode solver with circular perfectly matched layer (PML) boundary condition. The modal birefringence of the fiber is defined as [32]

\[
B = \Delta n = \left| n_{eff}^x - n_{eff}^y \right|
\]

where \(n_{eff}^x\) and \(n_{eff}^y\) are effective refractive indices of the y- and x-polarized fundamental modes, respectively. The proposed solid-core PCF are made of pure fused silica and the material dispersion is given by the Sellmeier equation [33]. Therefore, the total dispersion of the PCF can be calculated by the following formula [16]:

\[
D = -\frac{\lambda}{c} \cdot \frac{d^2 \text{Re}[n_{eff}]}{d\lambda^2}
\]

where \(c\) is the speed of light in free space. The confinement loss of PCF is calculated from the imaginary part of effective refractive index and it is given by the following formula [16].

\[
L = \frac{40\pi}{\ln(10)} \cdot \lambda \cdot \left| n_{eff} \right| = 8.686 \cdot \lambda \cdot \left| n_{eff} \right|
\]

where \(k_0 = 2\pi/\lambda\) and \(\lambda\) is the wavelength of the light.

Figure 3 shows the difference of optical properties for three types of PCFs in Fig. 1. Figure 3(a) shows the modal birefringence of the three types of PCF, where \(\Lambda = 1.2\) \(\mu\)m, \(D = 1\) \(\mu\)m, \(\Lambda_x = 0.6\) \(\mu\)m, \(\Lambda_y = 0.4\) \(\mu\)m, \(d_x = 0.4\) \(\mu\)m. The modal birefringence is gradually increased by adding line defect from type I to type III and the corresponding maximum achievable birefringence of the double line defect core PCF reaches up to 1.42×10\(^{-2}\) at 1.55 \(\mu\)m. The modal birefringence of the proposed double line defect core PCF was 10 times larger than that of the PCF for type I due to the enhanced core asymmetry by double line defect. It is worthy to note that high birefringence above the order of 10\(^{-7}\) can be achieved from the proposed double line defect core PCF (type III) in a broad range of wavelengths from 1 \(\mu\)m to 2 \(\mu\)m. Figure 3(b) shows the dispersion properties for three types of PCF as a function of wavelength. We found that the dispersion value was steadily decreased and the dispersion slope sign was changed as adding one more line defect. For type III, the dispersion...
value of x- and y-polarized modes can reach to -130 ps/(nm.km) and -250 ps/(nm.km) at 1.55 µm, respectively. From these results in Fig. 3(a) and (b), the modal birefringence and chromatic dispersion are remarkably enhanced by adding one more defect line from type II to type III. However, the confinement loss becomes larger from adding these defect lines in the core region as shown in Fig. 3(c). At a glance, the fundamental mode of type III looks like it is more tightly confined to the core but the result is the opposite. The confinement loss can be deduced from the imaginary part of the complex effective mode index defined by eq. (3). Therefore, the increased confinement loss of type III is due to the increased decay rate at the interface between core and small sized air holes. However, note that the value of confinement of type III is still small enough (less than 10^{-4}dB/km at 1.55 µm) and thus we can neglect these.

III. OPTIMIZATION OF STRUCTURE
PARAMETERS FOR THE DOUBLE LINE DEFECT CORE PCF

In this section, we investigate the impacts of the structure parameters (Λ and d_{c}) on the birefringence, dispersion and confinement loss in order to achieve the optimum structural parameters for simultaneous high birefringence and high negative dispersion at 1.55 µm. First, the impact of the structure parameter of Λ on fiber birefringence, and dispersion was analyzed in detail.

Figure 4(a) shows the birefringence as a function of wavelength for different lattice constant, Λ = 1.2 µm, 0.96 µm and 0.72 µm when D/Λ = 0.83, Λ_{c} = Λ/2, Λ_{y} = Λ/3, d_{c}/Λ = 0.33. Other parameters are reduced in the same ratio. It can be clearly seen in Fig. 4(a), the birefringence peak was shifted to shorter wavelengths as the lattice constant of cladding was reduced maintaining the value of birefringence, which means the change of Λ does not affect the asymmetry of the core. When the lattice constant, Λ is 0.96 µm, the proposed PCF can reach to high birefringence of 1.547×10^{3} at 1.55 µm.

In Fig. 4(b), we plot the calculated dispersion for three different lattice constants, Λ = 1.2 µm, 0.96 µm and 0.72 µm. These results show that as lattice constant decreases, the negative dispersion becomes higher. From the results of Fig. 4, it is confirmed that the change of Λ has a small impact on the extent of asymmetry for the core and mainly affects the peak wavelength of birefringence and the value of dispersion. When Λ is 0.96 µm, which is the value of Λ for highest birefringence at 1.55 µm in Fig. 4(a), the fiber dispersion value of the y-polarized fundamental mode is -325 ps/km/µm at 1.55 µm. For Λ=0.96 µm, the proposed double line defect core PCF satisfies highest birefringence and high negative dispersion at 1.55 µm at the same time. Confinement loss becomes larger as Λ decreases as shown in Fig. 4 (c). However the value is 2.10 × 10^{-4} dB/km at 1.55 µm when Λ = 0.96 µm, which is small enough to neglect. Therefore, we set the optimized parameter of Λ to be 0.96 µm from the simulation results of Fig. 4.

Secondly, we investigate the impact of the micro-variation

FIG. 3. (a) Modal birefringence, (b) chromatic dispersion and (c) confinement loss according to the wavelengths for three types of PCFs (type I: black line, type II: red line, type III: blue line), when Λ = 1.2 µm, D/Λ = 0.83, Λ_{c} = Λ/2, Λ_{y} = Λ/3 and d_{c}/Λ = 0.33.
Highly Birefringent and Dispersion Compensating Photonic Crystal Fiber

Yong Soo Lee et al.

FIG. 4. Impact of lattice constant (Λ) on (a) modal birefringence (b) dispersion properties for the proposed PCF (Λ = 0.96 μm: red line, Λ = 0.72 μm: black line, Λ = 1.20 μm: blue line).

FIG. 5. Impact of \(d_c\) on the modal birefringence (a) and dispersion properties (b) and confinement loss (c) according to the wavelength for the proposed PCF (\(d_c = 0.28\) : black line, \(d_c = 0.32\) : blue line, \(d_c = 0.34\) : red line).

of small sized air holes (\(d_c\)) in the core on the birefringence, the dispersion and the confinement loss of the proposed PCF. As shown in Fig. 5(a), the birefringence was almost uniform in the wavelength range from 1.4 μm to 1.7 μm and it monotonically increased with the increase of \(d_c\) because the larger \(d_c\) enhances the asymmetry of the core. And the change of \(d_c\) does not affect the excited wavelength of 1.55 μm. The value of birefringence maintains in the order of 10^{-2} for small variation of \(d_c\) such as B = 1.92×10^{-2} for \(d_c = 0.34\) μm, B = 1.547×10^{-2} for \(d_c = 0.32\) μm and B = 1.073×10^{-2} for \(d_c = 0.28\) μm at \(λ = 1.55\) μm. When \(d_c\) is 0.34 μm, the value of birefringence from the
wavelength of 1.26 to 1.8 µm (covering O to U bands) is about 1.8×10⁻² to 1.92×10⁻².

In Fig. 5(b), the fiber shows higher negative dispersion for larger \(d_c\). This is because larger air holes raise the air filling fraction, which can reduce the effective refractive index of the fundamental mode. This has previously been observed in Ref [34] and is further evidenced by the fact that dispersion compensation PCF requires a large air fill fraction especially for the first ring of holes [11]. When \(d_c = 0.34\) µm, the proposed PCF has broadband large negative dispersion of about -400 to -427 ps/(nm.km) covering all optical communication bands (from O to U band) and to achieve the dispersion coefficient of -425 ps/(nm.km) at 1.55 µm. Finally, the impact of \(d_c\) on confinement loss of the proposed PCF is shown in Fig. 5 (c). As \(d_c\) increases, the confinement loss increases a little, however the value is small enough to neglect (about 10⁻² dB/km at 1.55 µm).

In the proposed double line defect core PCF, the parameter of \(d_c\) is the main parameter to control the level of high birefringence and negative dispersion. As expected, both the birefringence and the negative dispersion increase with increase of \(d_c\). In order to achieve both high birefringence and large dispersion compensation, \(d_c\) should be set to be as large as possible due to the significant increase of negative dispersion and the birefringence as the size of \(d_c\) increases. However, the maximum possible value of \(d_c\) is set to be 0.34 µm from the geometrical feasibility, which value is the limitation of \(d_c\) not to overlap air holes of the double line. Through the optimization technique of structure parameters, we chose the optimum parameters of \(\Lambda = 0.96\) µm, \(D/\Lambda = 0.83\), \(d_c = 0.34\) µm for the proposed PCF with high birefringence and high negative dispersion at the same time.

In a standard fiber draw, ±1% variations in fiber occur during the fabrication process [35]. Therefore, it should be confirmed that there is roughly an accuracy of ±2% of tolerance for birefringence, dispersion and confinement loss. To investigate for this structural variation, lattice constant, \(\Lambda\) and diameter of small air hole, \(d_c\) is varied up to ±2% from the optimum values while keeping other structure parameters fixed. Figure 6 shows the effect of variation of \(\Lambda\) and \(d_c\) on birefringence, dispersion and confinement loss within the variation of ±2% from the optimum values. Here, solid lines indicate increments in parameters and dashed lines indicate decrements in parameters. From Fig. 6 (a), the birefringence increases/decreases within ±0.0015 with increase/decrease in \(d_c\) as much as ±2%. Whereas, ±2% change of \(\Lambda\) does not affect the value of birefringence in Fig. 6(a). Next, to analyze the impact of the fiber tolerance on the dispersion, we have also checked the impact of \(\Lambda\) and \(d_c\) on the dispersion. From the results of Fig. 6(b), the dispersion shifts to the down/up direction as much as 34 ps/ (nm.km) with increase/decrease in ±2% change of \(d_c\). In contrast, the dispersion shifts to up/down direction as much as 10 ps/ (nm.km) with increase/decrease in ±2% change of \(d_c\). Finally, we have checked the influence of ±2% change of \(d_c\) and \(\Lambda\) on the confinement loss. The value of confinement loss is changed a little by the ±2% change of \(d_c\) and \(\Lambda\) however the value is still small enough to neglect. From the above results, it is clear for the change
Highly Birefringent and Dispersion Compensating Photonic Crystal Fiber … - Yong Soo Lee et al.

IV. CONCLUSIONS

To summarize this paper, we have demonstrated a new fiber design for controlling the chromatic dispersion and achieving high birefringence at the same time by introducing a double line defect core in a conventional square lattice. The double line defect core enhances high birefringence of the fiber and its smaller air holes around the core effectively control the waveguide dispersion to achieve broadband negative dispersion. For the optimized double line defect core PCF, the fiber can achieve broadband high birefringence of about 1.8×10^{-2} to 1.92×10^{-2} and large negative dispersion of of about -400 to -427 ps/(nm.km) over the wavelength from 1.26 to 1.8 μm (covering O to U bands). According to the simulations, the highest birefringence of the optimized proposed PCF at 1.55 μm is 1.92×10^{-2} and the largest negative dispersion at 1.55 μm is -425 ps/(nm.km). In addition, it is confirmed that from the simulation results, the confinement loss of the proposed PCF is always less than 10^{-4} dB/km at 1.55 μm with seven fiber rings of air holes in the cladding. So, it can be concluded that the proposed PCF is a good example of a combined integrated waveguide with multiple functions of polarization maintenance, broadband dispersion compensation and low confinement loss for the optical communication and smart sensing applications over all optical communication bands.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2015058057)

REFERENCES

1. F. Orlando, M. T. Baptista, and L. Santos, “Recent Advances in High-Birefringence Fiber Loop Mirror Sensors,” Sensors 7, 2970-2983 (2007).
2. M. Karimi, T. Sun, and K. T. V. Grattan, “Design evaluation of a high birefringence single mode optical fiber-based sensor for lateral pressure monitoring applications,” IEEE Sensors J. 13, 4459-4464 (2013).
3. A. M. Vengsarkar and W. A. Reed, “Dispersion-compensating single-mode fibers: efficient designs for first- and second-order compensation,” Opt. Lett. 18, 924-926 (1993).
4. R. H. Stolen, “Polarization effects in fiber Raman and Brillouin lasers,” IEEE J. Quantum Electron. 15, 1157-1160 (1979).
5. J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, “All-silica single-mode optical fiber with photonic crystal cladding,” Opt. Lett. 21, 1547-1549 (1996).
6. J. C. Knight, J. Broeng, T. A. Birks, and P. St. J. Russell, “Photonic band gap guidance in optical fibers,” Science 282, 1476-1478 (1998).
7. J. C. Knight and P. St. J. Russell, “Photonic crystal fibers:

---

TABLE 1. Comparison between properties of the proposed PCF and other HB and ND PCFs

| PCFs          | Birefringence | Dispersion   |
|---------------|---------------|--------------|
| Ref. [26]     | 1.81×10^{-2}  | -588 ps/(nm.km) |
| Ref. [27]     | 0.65×10^{-2}  | -393 ps/(nm.km)   |
| Ref. [28]     | 1.67×10^{-2}  | -611.9 ps/(nm.km)  |
| Ref. [29]     | 1.025×10^{-2} | -601.67 ps/(nm.km) |
| Proposed PCF  | 1.92×10^{-2}  | -425 ps/(nm.km)    |

λ = 1.55 μm

of Λ and d, within ±2% that high birefringence with the notable optical properties of the proposed double line defect core PCF such as the order of 10^{-2}, large negative dispersion about -400 ps/(nm.km), and low confinement loss with the order of 10^{-4} dB/km are obtained.

In order to understand the proposed PCF in detail, a comparison is made between properties of birefringence and dispersion of the proposed PCF and some other fibers designed for high birefringence and negative dispersion simultaneously. Table 1 compares those fibers taking into the value of negative dispersion and birefringence. From this comparative work, it is confirmed that it is not easy to obtain high birefringence and negative dispersion at the same time with fixed design parameters. Otherwise the previously reported PCF, the proposed PCF with high birefringence and negative dispersion simultaneously is based on the conventional lattice cladding, which is the strong point of the proposed PCF on the fabrication.

Finally, we consider the possibility of fabrication for the proposed PCF. The proposed PCF cladding structure is conventional square lattice and the core is porous rectangular structure with a double line defect. There are two possible methods for close realization of the proposed PCF. For the first fabrication method, the proposed PCF can be fabricated by two step procedures. For a start, the double line defect core cane can be obtained by an extrusion method [36] and a mechanical drilling method [37]. Next, our proposed fiber design can be reliably fabricated by two-step stack-and-draw procedure due to all circular air holes and conventional lattice structure with core cane [38-41]. For the other method, Bisen et al. reported a sol-gel method [42, 43] for micro- and nano-structure fabrication in 2005. It can also be used to fabricate almost any PCF structure. The air-hole size, shape and spacing can be adjusted independently in this method.

With the advance of a complex photonics system, the functions of various optical components should be combined in a single optical device to reduce the system complexity. The proposed PCF is a good example of a combined integrated waveguide with multiple functions of polarization maintenance, broadband dispersion compensation, low loss, and true single-mode operation for the optical communication and smart sensing applications.

---

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2015058057)

REFERENCES

1. F. Orlando, M. T. Baptista, and L. Santos, “Recent Advances in High-Birefringence Fiber Loop Mirror Sensors,” Sensors 7, 2970-2983 (2007).
2. M. Karimi, T. Sun, and K. T. V. Grattan, “Design evaluation of a high birefringence single mode optical fiber-based sensor for lateral pressure monitoring applications,” IEEE Sensors J. 13, 4459-4464 (2013).
3. A. M. Vengsarkar and W. A. Reed, “Dispersion-compensating single-mode fibers: efficient designs for first- and second-order compensation,” Opt. Lett. 18, 924-926 (1993).
4. R. H. Stolen, “Polarization effects in fiber Raman and Brillouin lasers,” IEEE J. Quantum Electron. 15, 1157-1160 (1979).
5. J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, “All-silica single-mode optical fiber with photonic crystal cladding,” Opt. Lett. 21, 1547-1549 (1996).
6. J. C. Knight, J. Broeng, T. A. Birks, and P. St. J. Russell, “Photonic band gap guidance in optical fibers,” Science 282, 1476-1478 (1998).
7. J. C. Knight and P. St. J. Russell, “Photonic crystal fibers:
New way to guide light,” Science 296, 276-277 (2002).
8. J. C. Knight, “Photonic crystal fibres,” Nature 424, 847-851 (2003).
9. K. Saitoh and K. Masanori, “Single-polarization single-mode photonic crystal fibers,” IEEE Photonics Technol. Lett. 15, 1384-1386 (2003).
10. T. A. Birks, J. C. Knight, and P. St. J. Russell, “Endlessly single-mode photonic crystal fiber,” Opt. Lett. 22, 961-963 (1997).
11. F. Poletti, V. Finazzi, T. M. Monro, N. G. Broderick, V. Tse, and D. J. Richardson, “Inverse design and fabrication tolerances of ultra-flattened dispersion holey fibers,” Opt. Express 13, 3728-3736 (2005).
12. A. Ferrando, E. Silvestre, J. J. Miret, and Andries, “Nearly zero ultraflattened dispersion in photonic crystal fibers,” Opt. Lett. 25, 790-792 (2000).
13. K. Saitoh, M. Kodama, T. Hasegawa, and E. Sasaoka, “Chromatic dispersion control in photonic crystal fibers: application to ultra-flattened dispersion,” Opt. Express 11, 843-852 (2003).
14. J. C. Knight and D. V. Skryabin, “Nonlinear waveguide optics and photonic crystal fibers,” Opt. Express 15, 15365-15376 (2007).
15. A. Ortigosa-Blanch, J. C. Knight, W. J. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, and P. S. J. Russell, “Highly birefringent photonic crystal fibers,” Opt. Lett. 25, 1325-1327 (2000).
16. H. Ademgil and S. Haxha, “Highly birefringent photonic crystal fibers with ultralow chromatic dispersion and low confinement losses,” J. Lightwave Technol. 26, 441-448 (2008).
17. D. Chen and S. Linfang, “Ultrahigh birefringent photonic crystal fiber with ultralow confinement loss,” IEEE Photon. Technol. Lett. 19, 185-187 (2007).
18. T. Matsui, K. Nakajima, and I. Sankawa, “Dispersion compensation over all the telecommunication bands with double-cladding photonic crystal fiber,” J. Lightwave Technol. 25, 757-762 (2007).
19. J. Ju, W. Jin, and M. S. Demokan, “Properties of a highly birefringent photonic crystal fiber,” IEEE Photon. Technol. Lett. 15, 1375-1377 (2003).
20. T. Hansen, J. Broeng, S. E. B. Libori, E. Knuders, A. Bjarklev, J. R. Jensen, and H. Simonsen, “Highly birefringent index-guiding photonic crystal fibers,” IEEE Photon. Technol. Lett. 13, 588-590 (2001).
21. Soan Kim, Chul-Sik Kee, Jongmin Lee, Yongmin Jung, Hyoung-Gyu Choi, Kyungwhwan Oh, “Ultrahigh birefringence of elliptic core fiber with irregular air holes,” J. Appl. Phys. 101, 016101 (2007).
22. M. J. Steel and R. M. Osgood, “Elliptical-hole photonic crystal fibers,” Opt. Lett. 26, 229-231 (2001).
23. L. Zhang and C. Yang, “Photonic crystal fibers with squeezed hexagonal lattice,” Opt. Express 12, 2371-2376 (2004).
24. P. Song, L. Zhang, Z. Wang, Q. Hu, S. Zhao, S. Jiang, and S. Liu, “Birefringence characteristics of squeezed lattice photonic crystal fiber,” J. Lightwave Technol. 25, 1771-1776 (2007).
25. J. Noda, K. Okamoto, and Y. Sasaki, “Polarization maintaining fibers and their applications,” J. Lightwave Technol. 4, 1071-1089 (1986).
26. Md. S. Habib, Md. S. Habib, S.M. A. Razzak, Md. A. Hussain, “Proposal for highly birefringent broadband dispersion compensating octagonal photonic crystal fiber,” Opt. Fiber Technol. 19, 461-467 (2013).
27. M. A. Islam and M. S. Alam, “Design optimization of equiangular spiral photonic crystal fiber for large negative flat dispersion and high birefringence,” J. Lightwave Technol. 30, 3545-3551 (2012).
28. W. Wang, B. Yang, H. Song, and Y. Fan, “Investigation of high birefringence and negative dispersion photonic crystal fiber with hybrid crystal lattice,” Optik 124, 2901-2903 (2013).
29. S. Kim, Y. S. Lee, C. G. Lee, Y. Jung, and K. Oh, “Hybrid Square-Lattice Photonic Crystal Fiber with Broadband Single-Mode Operation, High Birefringence, and Normal Dispersion,” J. Opt. Soc. Korea 19, 449-455 (2015).
30. F. Poli, M. Foroni, M. Bottacini, M. Fuochi, N. Burani, L. Rosa, A. Cucinotta, and S. Selleri, “Single-mode regime of square-lattice photonic crystal fibers,” J. Opt. Soc. Am. A 22, 1655-1661 (2005).
31. A. H. Bouk, A. Cucinotta, F. Poli, and S. Selleri, “Dispersion properties of square-lattice photonic crystal fibers,” Opt. Express 12, 941-946 (2004).
32. Kubota, S. Kawanishi, S. Koyanagi, M. Tanaka, and S. Yamaguchi, “Absolutely single polarization photonic crystal fiber,” IEEE Photon. Technol. Lett. 16, 182-184 (2004).
33. P. Klocek, Handbook of infrared Optical Materials (Marcel Dekker, New York, NY, 1991).
34. F. Poli, A. Cucinotta, S. Selleri, and A. H. Bouk, “Tailoring of flattened dispersion in highly nonlinear photonic crystal fibers,” IEEE Photon. Technol. Lett. 16, 1065-1067 (2004).
35. W. H. Reeves, J. C. Knight, and P. S. J. Russell, “Demonstration of ultra-flattened dispersion in photonic crystal fibers,” Opt. Express 10, 609-613 (2002).
36. K. M. Kiang, K. Frampton, T. M. Monro, R. Moore, J. Tucknott, D. W. Hewak, D. J. Richardson, and H. N. Rutt, “Extruded single mode non-silica glass holey optical fibres,” Electron. Lett. 38, 546-547 (2002).
37. J. Canning, E. Buckley, K. Lyttkaien, and T. Ryan, “Wavelength dependent leakage in a Fresnel-based air silica structured optical fibre,” Opt. Commun. 205, 95-99 (2002).
38. R. Buczynski, “Photonic crystal fibers,” Acta physica Polonica: A 106, 141-167 (2004).
39. R. Buczynski, P. Szamiak, D. Pysz, I. Kujawa, R. Stepień, and T. Szoplík, “Double-core photonic crystal fiber with square lattice,” Proc. SPIE 5450, 223-230 (2004).
40. F. Couny, P. J. Roberts, T. A. Birks, and F. Benabid, “Square-lattice photonic crystal fibers,” J. Opt. Soc. Am. A 20, 205-216 (2003).
41. P. Falkenstein, C. D. Merritt, and B. L. Justus, “Fused preforms for high birefringence and large negative dispersion,” Opt. Lett. 22, 2371-2376 (2004).
42. Y. D. Hazan, J. B. MacChesney, T. E. Stockert, D. J. Trevor, and R. S. Windeler, “Sol-gel method of making an optical fiber with multiple apertures,” US Patent 6467312 B1 (2000).
43. R. T. Bise and D. J. Trever, “Sol-gel derived microstructured fiber: fabrication and characterization,” in Proc. Optical Fiber Communication Conf. 2005 (Anaheim, California United States, March 2005), CD, paper OWL6.