Wavelength-tunable Dual-concentric-core Photonic Crystal Fibers

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Abstract— A wavelength-tunable and strongly dispersion-compensating photonic crystal fiber based on a hybrid structure of dual-concentric-core photonic crystal fiber (DCC-PCF) structure and depressed-clad photonic crystal fiber (DeC-PCF) is proposed. To enhance the dispersion compensation effect, we used a hybrid structure of DCC-PCF and DeC-PCF as a basic structure. In the central core of the hybrid fiber, different kinds of liquid with various refractive indices are filled into the air hole with appropriate diameter. The numeric results show that the operation wavelength is determined by the refractive index of the liquid.

1. INTRODUCTION

Chromatic dispersion in transmission fibers induces temporal optical pulse broadening, resulting in serious restrictions in transmission data rates in optical fiber communication systems. Currently, dispersion-compensating fibers (DCFs) are extensively used to minimize the negative effects of chromatic dispersion. The absolute dispersion value of conventional MCVD DCFs was approximately −250 ps/km-nm [1]. J. L. Auguste et al. reported another design of DCF based on a dual-concentric core fiber (DCCF) structure with a high dispersion coefficient of −1800 ps/km-nm [2]. Additional dispersion-compensation research involved altering the air hole size of a specific layer of photonic crystal fiber (PCF) to design dual-concentric core PCFs (DCC-PCFs) [3–7]. We had proposed a liquid-filled hybrid structure of DCC-PCF and depressed clad photonic crystal fiber (DeC-PCF) with an ultra-large dispersion coefficient of −40400 ps/km-nm at a wavelength of around 1.55 µm [7]. The design of this hybrid structure can avoid the restriction of "mutual involvement" between two supermodes, significantly increasing the index slope difference between two supermodes and thereby enlarging the dispersion coefficient.

In this study, we present a wavelength-tunable dispersion-compensating photonic crystal fiber (WT-DCPCF) with large dispersion coefficient based on a hybrid structure of DCC-PCF and DeC-PCF due to an ultra-large dispersion coefficient of this structure as mentioned above. Furthermore, to achieve a wavelength-tunable capability, different kinds of liquid with various refractive indices were selected to fill into the air hole with appropriate diameter in the central core of the hybrid fiber. Ultimately, the numeric results indicated that the proposed WT-DCPCF with chromatic dispersion coefficients of −32352 ps/km-nm to −41575 ps/km-nm at a wavelength range between 1472 nm to 1617 nm.

In general, a single-wavelength dispersion compensation photonic crystal fiber (DC-PCF) has a value of dispersion coefficient considerably larger than that of a broadband DC-PCF [8–11]; however it is just suitable for using at a fixed wavelength. In addition to with a high dispersion coefficient close to a single-wavelength DCC-PCF, the proposed WT-DCPCF is even more having an advantage of flexible wavelength-variation fabrication.

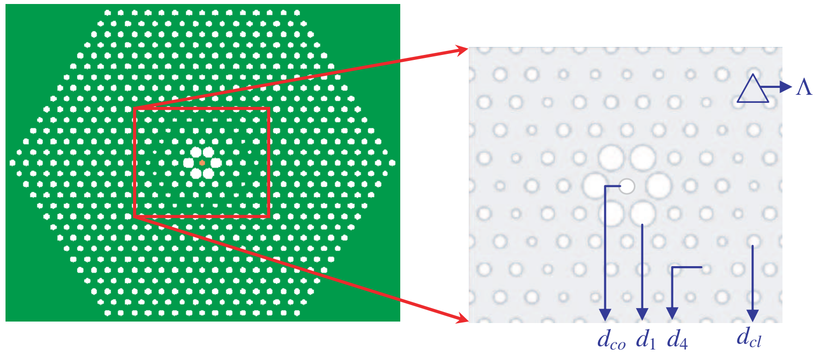

Figure 1: Cross-sectional view of the proposed WT-DCPCF.

2. SIMULATION MODEL AND PRINCIPLES

The Cross-sectional view of the proposed WT-DCPCF structure is shown in Figure 1. The cladding of the proposed WT-DCPCF consists of a triangular lattice of air holes with a diameter of $d_{cl} = 1.40\,\mu\text{m}$ and a pitch (center-to-center distance between the holes) of $\Lambda = 2.50\,\mu\text{m}$ in a background of undoped silica, whose refractive index can be estimated using the Sellmeier equation [12]:

$$n(\lambda) = \left[1 + \frac{0.6961663\lambda^2}{\lambda^2 - (0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.896161)^2}\right]^{1/2}. \quad (1)$$

where λ represents the operating wavelength.

To enhance the dispersion compensation effect, a hybrid structure of DCC-PCF and DeC-PCF was used [7], that is to say, we enlarged the size of holes at first layer ($d_1 = 2.00\,\mu\text{m}$). The outer ring core with smaller-diameter air holes ($d_4 = 0.68\,\mu\text{m}$), which is designed to locate at fourth layer of the WT-DCPCF, separates the cladding region into inner and outer cladding. The mode-couple between inner and outer modes then results in a negative dispersion of the fiber at the phase-matching wavelength. In the inner core, different kinds of the Cargille® optical liquid with various refractive indices (n_{co}), which is colored in orange in the figure, are filled into the central air hole with appropriate diameter of $d_{co} = 1.00\,\mu\text{m}$. The refractive index of $n_{co}(\lambda)$ is defined by the Cauchy equation as

$$n_{co}(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}. \quad (2)$$

Here, the Cauchy coefficients A, B and C, which are provided by Cargille Laboratories, are different for various liquids. The numeric results show that the operation wavelength is determined by the refractive index of the liquid.

The chromatic dispersion coefficient D is used to quantify the amount of chromatic dispersion. $D(\lambda)$ is defined as

$$D(\lambda) = \frac{-\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}, \quad (3)$$

where c is the speed of light in a vacuum, and n_{eff} is the effective indices of the fundamental guided modes on a fiber at various wavelengths.

In this work, the effective refractive index (n_{eff}) of the fundamental mode is first estimated using the plane-wave expansion (PWE) method. The dispersion coefficient $D(\lambda)$ is then evaluated by substituting n_{eff} into Equation (3).

3. NUMERICAL RESULTS AND DISCUSSIONS

Figure 2 indicates the dependence of the chromatic dispersion coefficients on wavelength for various indices of the liquids filled in the central hole. Here the denoted refractive index n_D values of the

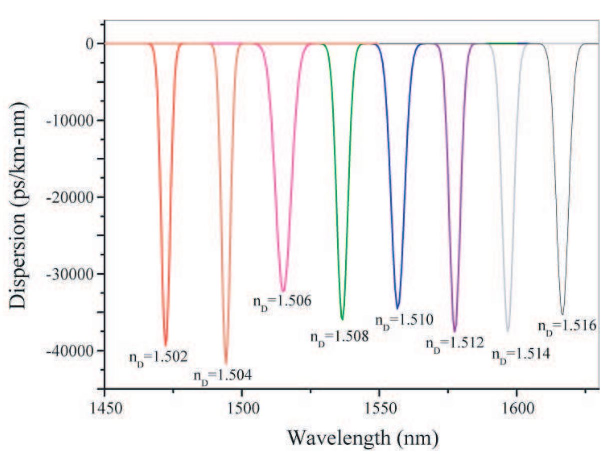

Figure 2: Dependence of the chromatic dispersion on wavelength for various indices of the liquids.

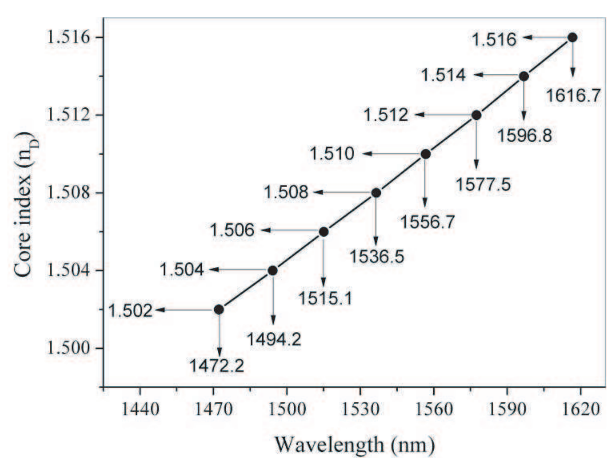

Figure 3: Relationship between the n_D of the filled liquid and the minimum-dispersion wavelength for the proposed WT-DCPCF.

used Cargille optical liquid are measured at 25°C, Sodium D Line ($\lambda = 589.3$ nm). As shown in the figure, the refractive index of the liquid determines the operation wavelength. The numeric results indicate that the proposed WT-DCPCF with chromatic dispersion coefficients of −32352 ps/km-nm to −41575 ps/km-nm at a wavelength range between 1472 nm to 1617 nm.

To realize what the filled liquid is needed for a specific operating wavelength in an optical communication system, Figure 3 indicates the relationship between the wavelengths of the minimum dispersions shown in Figure 2 and the n_D of the filled Cargille optical liquid. The precise values of the minimum-dispersion wavelengths and the n_D's are denoted in the figure. As shown in the figure, the relation curve of these two parameters is quite linear. Therefore, by using interpolation or extrapolation in Figure 3, it is helpful for designing a WT-DCPCF with an operating wavelength excluded from the numerical results of this work.

4. CONCLUSIONS

This study proposes a wavelength-tunable dispersion compensating photonic crystal fiber (WT-DCPCF) with an ultra-large negative dispersion coefficient. The operating wavelength is determined by the refractive index of the Cargille optical liquid filled in the central hole of the core. The numeric results show that the proposed WT-DCPCF with chromatic dispersion coefficients of −32352 ps/km-nm to −41575 ps/km-nm at a wavelength range between 1472 nm to 1617 nm while filled liquids with n_D's of 1.502 to 1.516. The wavelength range covers the whole C band and great parts of L and S bands. Furthermore, the relationship between the n_D of the filled liquid and the operating wavelength is quite linear. Therefore, it can be predicted that the tunable range of wavelengths can be more widely extended by filling liquid with an n_D beyond the investigated range of 1.502 to 1.516.

REFERENCES

1. Vengsarkar, A. M. and W. A. Reed, "Dispersion-compensating single-mode fibers: Efficient designs for first- and second-order compensation," *Opt. Lett.*, Vol. 18, 924–926, 1993.
2. Auguste, J. L., J.-M. Blondy, J. Maury, B. Dussardier, G. Monnom, R. Jindal, K. Thyagarajan, and B. P. Pal, "Conception, realization, and characterization of a very high negative chromatic dispersion fiber," *Opt. Fiber Technol.*, Vol. 8, 89–105, 2002.
3. Gerome, F., J.-L. Auguste, and J.-M. Blondy, "Design of dispersion compensating fibers based on a dual-concentric-core photonic crystal fiber," *Opt. Lett.*, Vol. 29, 2725–2727, 2004.
4. Zhao, X., G. Zhou, S. Li, Z. Liu, D. Wei, Z. Hou, and L. Hou, "Photonic crystal fiber for dispersion compensation," *Appl. Opt.*, Vol. 47, 5190–5196, 2008.
5. Yang, S., Y. Zhang, X. Peng, Y. Lu, S. Xie, J. Li, W. Chen, Z. Jiang, J. Peng, and H. Li, "Theoretical study and experimental fabrication of high negative dispersion photonic crystal fiber with large area mode field," *Opt. Express*, Vol. 14, 3015–3023, 2006.
6. Yu, C. P., J. H. Liou, S. S. Huang, and H. C. Chang, "Tunable dual-core liquid-filled photonic crystal fibers for dispersion compensation," *Opt. Express*, Vol. 16, 4443–4451, 2008.
7. Hsu, J. M. and G. S. Ye, "Dispersion ultra-strong compensating fiber based on a liquid-filled hybrid structure of dual-concentric core and depressed clad photonic crystal fiber," *J. Opt. Soc. Am. B*, Vol. 29, 2021–2028, 2012.
8. Fujisawa, T., K. Saitoh, K. Wada, and M. Koshiba, "Chromatic dispersion profile optimization of dual-concentric-core photonic crystal fibers for broadband dispersion compensation," *Opt. Express*, Vol. 14, 893–900, 2006.
9. Varshney, S. K., T, Fujisawa, K, Saitoh, and M, Koshiba, "Design and analysis of a broadband dispersion compensating photonic crystal fiber Raman amplifier operating in S-band," *Opt. Express*, Vol. 14, 3528–3540, 2006.
10. Begum, F., Y. Namihira, S. M. A. Razzak, S. Kaijage, N. H. Hai, T. Kinjo, K. Miyagi, and N. Zou, "Novel broadband dispersion compensating photonic crystal fibers: Applications in high-speed transmission systems," *Opt. Laser Technol.*, Vol. 41, 679–686, 2009.
11. Beltrán-Mejía, F., C. M. B. Cordeiro, P. Andrés, and E. Silvestre, "Broadband dispersion compensation using inner cladding modes in photonic crystal fibers," *Opt. Express*, Vol. 20, 3467–3472, 2012.
12. Malitson, I. H., "Interspecimen comparison of the refractive index of fused silica," *J. Opt. Soc. Am.*, Vol. 55, 1205–1209, 1965.