

Design and parametric amplification analysis of dispersion-flat photonic crystal fibers

Jingyuan Wang (汪井源)^{1,2}, Mingyi Gao (高明义)¹, Chun Jiang (姜 淳)¹, and Weisheng Hu (胡卫生)¹

¹State Key Laboratory of Advanced Optical Communication Systems and Networks,
Shanghai Jiao Tong University, Shanghai 200030

²Institute of Communications Engineering, PLA University of Science and Technology, Nanjing 210007

Received November 26, 2004

We present a modified method to design photonic crystal fibers (PCFs) with flattened dispersion characteristic. Using this modified PCF we design a broadband fiber optical parametric amplifier (FOPA), which provides a gain of 8 dB with 1.5-dB uniformity over a 260-nm bandwidth. Both the simulation results of total dispersion of PCF and the gain spectrum of FOPA are demonstrated.

OCIS codes: 260.2030, 060.2400.

In recent years, a new type of broadband amplifier, fiber optical parametric amplifier (FOPA) has been investigated, which utilizes four-wave mixing (FWM) to amplify the signals and offers a broadband amplification at arbitrary wavelengths^[1]. Though simple single-pump FOPA could offer a gain bandwidth of more than 200 nm, the gain spectrum is not flat over the amplifier bandwidth but has a difference as high as 15 dB between the lowest and the highest values, which brings to the difficulty to equalize the power of the various channels in wavelength division multiplexed (WDM) systems^[2]. For this reason, much research has been done recently to deal with the lack of flatness of the gain spectrum for single-pump FOPA^[3,4].

Photonic crystal fibers (PCFs) have opened up new chance of development to FOPA^[5,6]. PCFs are made from single material such as silica glass, with an array of microscopic air channels running along its length^[7-16]. A defect can be created by filling the central air-hole with glass to guide light by total internal reflection (TIR) between the solid core and the cladding region with multiple air-holes. These index-guiding PCFs also are called TIR-PCFs. Besides PCFs use a perfectly periodic structure exhibiting a photonic band-gap (PBG) effect at the operating wavelength to guide light in a low index core-region^[7,9]. PCF with relatively low dispersion slope is useful to flattening the gain spectrum of FOPA.

In this paper, modified index-guiding PCF is investigated, which can exhibit ultra-flattened dispersion and ultra-low dispersion slope over wide wavelength range. A broadband FOPA using this PCF can be obtained, which provides a gain of 8 dB with 1.5-dB uniformity over a 260-nm bandwidth.

For single-pump FOPA (similar to the condition of $\omega_1 = \omega_2$), the linear propagation-constant mismatch $\Delta\beta$ is given by^[17,18]

$$\Delta\beta = \beta^{(2)} \cdot \Omega^2 + \frac{1}{12} \beta^{(4)} \cdot \Omega^4, \quad (1)$$

where $\Omega = \omega_s - \omega_p$ is the frequency detuning between the signal frequency ω_s and the pump frequency ω_p . As $\beta^{(4)}$ is typically at the order of magnitude of 10^{-4} ps⁴/km, when the bandwidth $(\lambda_p - \lambda_s)$ operates within 100 nm,

its effects can be neglected. And then a convenient approximative transformation of Eq. (1) may be done from the frequency domain to the more generally used wavelength domain^[8]

$$\Delta\beta = -\frac{2\pi c}{\lambda_0^2} \frac{dD}{d\lambda} (\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2, \quad (2)$$

where $dD/d\lambda$ is the slope of the dispersion.

The total phase mismatch including the nonlinear phase shift is

$$k = \Delta\beta + \gamma(P_1 + P_2) = \Delta\beta + 2\gamma P_0. \quad (3)$$

The parametric gain coefficient is given by^[17]

$$g^2 = [(\gamma P_0)^2 - (\kappa/2)^2] = -\Delta\beta \left(\frac{1}{4} \Delta\beta + \gamma P_0 \right). \quad (4)$$

The small-signal power gain at the output can be expressed as^[17]

$$G_s = 1 + \left[\frac{\gamma P_0}{g} \sinh(gL) \right]^2. \quad (5)$$

From above theory, it is known that the shape of gain spectrum of FOPA mainly depends on the linear propagation-constant mismatch $\Delta\beta$, which is governed by the slope of the dispersion $dD/d\lambda$. The ultra-low slope of the dispersion can provide broad and flat gain spectrum of FOPA.

A desirable property of PCFs is that the additional design parameters of hole diameter d and holes pitch Λ offer much greater flexibility in the design of dispersion to get the required application, as shown in Fig. 1(a). By manipulating circular air-hole diameter d and pitch Λ , it is possible to control the PCF dispersion properties, for example, to change the zero-dispersion wavelength or to engineer the dispersion curve to be ultra-flattened^[10,19,20]. Furthermore, the diameters of different rings' air-holes around the core can be designed respectively in order to get more flattened dispersion curve^[19,21].

The effective refractive index of the fundamental mode is given as $n_{\text{eff}} = \beta/k_0$, where β is the propagation constant, $k_0 = 2\pi/\lambda$ is the free-space wave number. Once

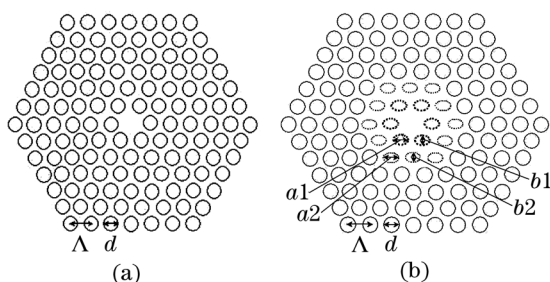


Fig. 1. Cross sections of the triangular (a) and the modified PCF (b) with hole diameter d and pitch Λ . a_1 , a_2 and b_1 , b_2 are the widths and heights of the ellipse of the two central rings, respectively.

the modal effective indexes n_{eff} are solved, the dispersion parameter D can be obtained by $D(\lambda) = -(\lambda/c)(d^2 n_{\text{eff}}/d\lambda^2)$, where c is the velocity of the light in vacuum and λ is the operating wavelength. Apparently the geometry parameters of PCFs affect the dispersion property significantly. Furthermore, most optical energy is confined in the core region and it is found that the air holes close to the core influence the dispersion curve more than those farther to the core. In our previous research, we replace the circular air-holes in the first central ring with elliptical air-holes^[22]. This method provides us more design freedom to tailor the PCFs' dispersion property, and the design parameters of width a and height b of the ellipse can be optimized to present more flattened and lower dispersion curve.

From the previous research, the dispersion curve can be flattened by decreasing the area or increasing the ellipticity of the ellipse air holes in the first central ring. Meanwhile, the zero-dispersion wavelength moves to shorter wavelength. To design PCF, which can be used in FOPA, in this paper we focus on the dispersion property by replacing both the circular air-holes of the first and second central rings with elliptic air-holes, as show in Fig. 1(b). The air-holes of the first ring around the core are elliptic, which are described with width a_1 and height b_1 . The air-holes of the second ring around the core are also elliptic, which are described with width a_2 and height b_2 . This new controlling technique is applied to design PCF with ultra-flattened dispersion and ultra-low dispersion slope over a wide wavelength range.

Full-vectorial plane-wave expansion (PWE) method that is highly suited for the analysis of periodic structures is applied to analyze the dispersion property of the triangular PCF and it has been one of the major tools for the analysis and understanding of PCFs^[7,9]. Numerical results have shown that dispersion curve changed with the value of a_1 , a_2 and b_1 , b_2 . With the parameters of $\Lambda = 2.3 \mu\text{m}$, $d = 0.6394 \mu\text{m}$, $a_1 = a_2 = 0.6394 \mu\text{m}$, $b_1 = 0.496 \mu\text{m}$, $b_2 = 0.625 \mu\text{m}$, high-index core triangular PCF with the zero-dispersion wavelength around 1490 nm, the total dispersion parameter value between $\pm 0.2 \text{ ps}/(\text{nm}\cdot\text{km})$ over a wavelength range of 250 nm from 1450 to 1700 nm has been thus designed, as shown in Fig. 2. Furthermore, we get the slope of dispersion between 0 and $0.004 \text{ ps}/(\text{nm}^2\cdot\text{km})$ from wavelength 1480 to 1730 nm. That means more uniform gain of FOPA over a relatively wide bandwidth can be attained. For comparison, the total dispersion and the dispersion slope of PCF with $\Lambda = 2.3 \mu\text{m}$, $d = 0.6394 \mu\text{m}$, $a_1 = b_1 = 0.5634$

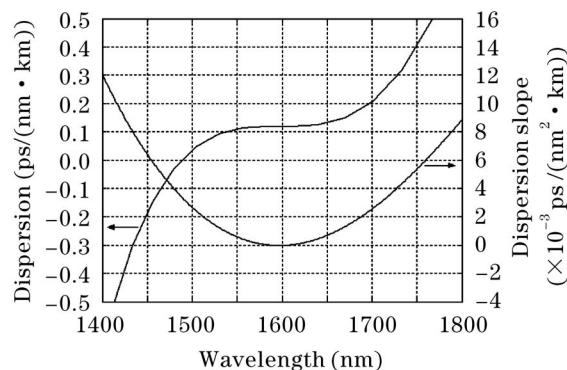


Fig. 2. Total dispersion and dispersion slope of modified PCF with $a_1 = a_2 = 0.6394 \mu\text{m}$, $b_1 = 0.496 \mu\text{m}$, $b_2 = 0.625 \mu\text{m}$.

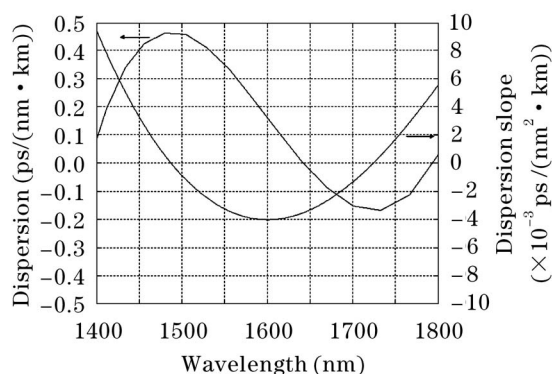


Fig. 3. Total dispersion and dispersion slope of modified PCF with $a_1 = b_1 = 0.5634 \mu\text{m}$, $a_2 = b_2 = 0.6322 \mu\text{m}$.

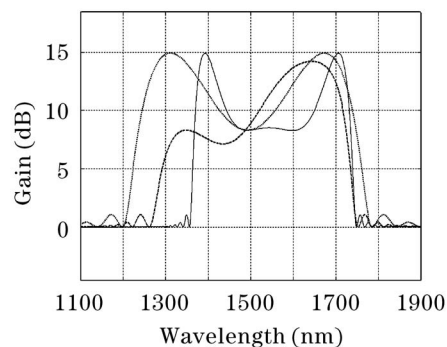


Fig. 4. Gain spectra of FOPA when considering the relation of the dispersion slope and wavelength shown in Fig. 2 (solid curve) and Fig. 3 (dashed curve), also the dispersion slope as constant of $0.004 \text{ ps}/(\text{nm}^2\cdot\text{km})$ (dotted curve) is presented.

μm , $a_2 = b_2 = 0.6322 \mu\text{m}$ are demonstrated in Fig. 3, while keeping the same area of each ring as the modified PCF of Fig. 2.

The simulation results are demonstrated in Fig. 4. Using the modified PCF with $\Lambda = 2.3 \mu\text{m}$, $d = 0.6394 \mu\text{m}$, $a_1 = a_2 = 0.6394 \mu\text{m}$, $b_1 = 0.496 \mu\text{m}$, $b_2 = 0.625 \mu\text{m}$ in FOPA, the effective mode area of the field A_{eff} is about $12 \mu\text{m}^2$ and the fiber nonlinear coefficient γ is about $12 \text{ W}^{-1}\text{km}^{-1}$. From Fig. 2, the zero-dispersion wavelength is around 1490 nm and the slope of dispersion is between 0 and $0.004 \text{ ps}/(\text{nm}^2\cdot\text{km})$ from wavelength 1480 to 1730 nm. We select the pump wavelength $\lambda_p = 1492 \text{ nm}$, the pump power $P = 12.7 \text{ W}$, length $L = 12.5 \text{ m}$ ^[5]. Considering the relation between the slope of dispersion and wave-

length, which is considered to be constant in previous research, we present the gain of FOPA, as the solid curve shown in Fig. 4. As the figure shows, FOPA using the modified PCF has more flattened gain with 1.5-dB uniformity over a wavelength range from 1420 to 1680 nm. Furthermore, the gain ripple is very small close to 0.2 dB from the wavelength 1470 to 1620 nm. Considering the slope of dispersion as constant of $0.004 \text{ ps}/(\text{nm}^2 \cdot \text{km})$, while other parameters are same as discussed above, the gain spectrum is also shown, which is the dotted curve in Fig. 4. Obviously, the flatness of gain spectrum is very poor. Also, the gain of FOPA using PCF of Fig. 3 is also shown in Fig. 4 and the flatness of gain spectrum is unacceptable.

With the same value of d/Λ , we can get greater nonlinear coefficient γ by decreasing the pitch Λ . And the gain of FOPA can be adjusted to the fiber length, nonlinear coefficient, and the pump power.

In conclusion, we get ultra-low and ultra-flattened dispersion curves by replacing both the circular air-holes of the first and second central rings with elliptic air-holes. Based on the theory model of FOPA, a fiber optical parametric amplifier using modified PCF is put forward, which provides a gain of 8 dB with 1.5-dB uniformity over a wide wavelength range from 1420 to 1680 nm. And the gain flatness has been improved at a large extent. Notably, because of the deformity of the air holes, the degenerate fundamental mode is split into linear x - and y -polarized bound modes. In fact, the fundamental mode of the PCF we study here is one of these two polarized modes, which has higher effective index than the other one. The influence of the birefringence to the FOPA is still under research.

This work was supported by the National Natural Science Foundation of China under Grant No. 60377023. J. Wang's e-mail address is wellok@sjtu.edu.cn.

References

1. R. H. Stolen and J. E. Bjorkholm, *IEEE J. Quantum Electron.* **18**, 1062 (1982).
2. M.-C. Ho, K. Uesaka, M. Marhic, Y. Akasaka, and L. G. Kazovsky, *J. Lightwave Technol.* **19**, 977 (2001).
3. W. Zhang, C. Wang, J. Su, C. Jiang, and W. Hu, *IEEE Photon. Technol. Lett.* **16**, 1652 (2004).
4. C. J. McKinstrie, S. Radic, and A. R. Chraplyvy, *IEEE J. Sel. Top. Quantum Electron.* **8**, 538 (2002).
5. R. Tang, J. Lasri, P. Davgan, J. E. Sharping, and P. Kumar, *Electron. Lett.* **39**, 195 (2003).
6. J. E. Sharping, M. Fiorentino, A. Coker, and P. Kumar, *Opt. Lett.* **26**, 1048 (2001).
7. A. Bjarklev, J. Broeng, and A. S. Bjarklev, *Photonic Crystal Fibers* (Kluwer Academic Publishers, Boston, 2003).
8. J. C. Knight, T. A. Birks, P. S. J. Russell, and D. M. Atkin, *Opt. Lett.* **21**, 1547 (1996).
9. J. Broeng, D. Mogilevstev, S. E. Barkou, and A. Bjarklev, *Optical Fiber Technology* **5**, 305 (1999).
10. W. H. Reeves, J. C. Knight, and P. S. J. Russell, *Opt. Express* **10**, 609 (2002).
11. T. A. Birks, J. C. Knight, and P. S. J. Russell, *Opt. Lett.* **22**, 961 (1997).
12. P. Russell, *Science* **299**, 358 (2003).
13. Y. Ni, L. Zhang, and J. Peng, *Chin. Opt. Lett.* **1**, 385 (2003).
14. G. Zhou, Z. Hou, L. Hou, and J. Liu, *Chin. Opt. Lett.* **1**, 15 (2003).
15. Y. F. Li, Q. Y. Wang, and M. L. Hu, *Chin. J. Lasers* (in Chinese) **31**, 1332 (2004).
16. S. Q. Lou, Z. Wang, G. B. Ren, and S. S. Jian, *Acta Opt. Sin.* (in Chinese) **24**, 1310 (2004).
17. M. E. Marhic, N. Kagi, T.-K. Chiang, and L. G. Kazovsky, *Opt. Lett.* **21**, 573 (1996).
18. J. Hansryd, P. A. Andrekson, M. Westlund, J. Li, and P.-O. Hedekvist, *IEEE J. Sel. Top. Quantum Electron.* **8**, 506 (2002).
19. K. Saitoh, M. Koshiba, T. Hasegawa, and E. Sasaoka, *Opt. Express* **11**, 843 (2003).
20. F. Poli, A. Cucinotta, S. Selleri, and A. H. Bouk, *IEEE Photon. Technol. Lett.* **16**, 1065 (2004).
21. A. Ferrando, E. Silvestre, P. Andrés, J. J. Miret, and M. V. Andrés, *Opt. Express* **9**, 687 (2001).
22. J. Y. Wang, C. Jiang, W. S. Hu, and M. Y. Gao, *Optics & Laser Technol.* (to be published).