Gain characteristics of two-pump fiber optical parametric amplifier based on a photonic crystal fiber with pump depletion

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The gain properties of two-pump fiber optical parametric amplifier (FOPA) based on photonic crystal fiber (PCF) are investigated numerically. The pump depletion is considered in. The influences of fiber length, nonlinear coefficient and fourth-order-dispersion of PCF on the gain bandwidth and peak gain are discussed. Furthermore, the effect of pump power is also taken into account. It is shown that, by properly selecting the PCF and setting the pump parameters, a broad gain of 63dB can be obtained in range of 420 nm, which is extremely useful for the optical communication system.

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1. Introduction

Recently the rapid development of optical fiber communications has led to increasing requirement of super-broadband and higher-gain optical amplifiers. Fiber optical parametric amplifiers (FOPAs), which utilize the principle of four-wave mixing (FWM) to amplify the signals, can amplify optical signals in a much wider wavelength range, and have been used in many applications [1-4]. In order to be practically applied in the dense wavelength division multiplexing (DWDM) system, the FOPAs with higher gain and wider bandwidth are extraordinarily required.

Photonic crystal fiber (PCF) presents higher nonlinearity, and lower dispersion than other kinds of fibers. Due to the excellent dispersion profile of PCF, different linear phase shift combinations of the second-order and fourth-order dispersion constants can lead to different gain spectra [5]. Moreover, a short PCF length helps not only to reduce the total fiber loss, but also to minimize the influence of stimulated Raman scattering (SRS) on the parametric effects [6,7]. Hence, PCFs have been proposed to constitute FOPAs [8, 9].

Usually, one-pump is adopted in the FOPA, and a gain bandwidth of more than 200 nm has been reported [10]. However, the gain spectrum is not uniform over the amplifier bandwidth for the one-pump case [11]. By cascading more fibers, broader and more flattened gain bandwidth can be obtained [1, 12], but the insertion loss is increased. Compared with the one-pump FOPA, much flatter and broader gain spectra can be achieved for two-pump FOPA [13]. The majority reports of the two-pump FOPAs based on PCF focus on the small signal gain, and under the assumption of neglecting fiber loss and pump depletion [14, 15].

In this communication, we theoretically analyze the parametric saturated gain and gain bandwidth of FOPAs based on PCF by considering the fiber loss and pump depletion [16]. The remainder of this paper is organized as follows. In Section 2, the theory and model of two-pump FOPA based on PCF with pump depletion is derived based on the FWM. In Section 3, the influences of fiber length, nonlinear coefficient and fourth-order-dispersion of PCF on the gain bandwidth and peak gain are discussed. And, the effect of pump power is also analyzed. Conclusions are given in Section 4.

2. Theory and model

Maxwell's equations in the fiber of the FWM take the form of the following coupled wave equations [8, 17], where the four waves are all continuous-waves (CW), and have the same linear polarization state:

$$\frac{dA_{p1}}{dz} = i\gamma\left[\left(|A_{p1}|^2 + 2\left(|A_{p2}|^2 + |A_s|^2 + |A_i|^2\right)\right)A_{p1} + 2A_{p2}^{*}A_sA_ie^{i\Delta\beta z}\right] - \frac{\alpha}{2}A_{p1} \quad (1)$$

$$\frac{dA_{p2}}{dz} = i\gamma\left[\left(|A_{p2}|^2 + 2\left(|A_{p1}|^2 + |A_s|^2 + |A_i|^2\right)\right)A_{p2} + 2A_{p1}^{*}A_sA_ie^{i\Delta\beta z}\right] - \frac{\alpha}{2}A_{p2} \quad (2)$$

$$\frac{dA_s}{dz} = i\gamma\left[\left(|A_s|^2 + 2\left(|A_{p1}|^2 + |A_{p2}|^2 + |A_i|^2\right)\right)A_s + 2A_i^{*}A_{p1}A_{p2}e^{-i\Delta\beta z}\right] - \frac{\alpha}{2}A_s \quad (3)$$

$$\frac{dA_i}{dz} = i\gamma\left[\left(|A_i|^2 + 2\left(|A_{p1}|^2 + |A_{p2}|^2 + |A_s|^2\right)\right)A_i + 2A_s^{*}A_{p1}A_{p2}e^{-i\Delta\beta z}\right] - \frac{\alpha}{2}A_i \quad (4)$$

where A_{p1}, A_{p2}, A_s and A_i are the slowly varying complex amplitudes of pump1, pump2, signal and idler waves, respectively; z is the distance along the fiber; γ is the nonlinearity coefficient of fiber, α denotes the transportation loss of PCF, and $\Delta\beta$ is the linear phase mismatch factor, where

$$\Delta\beta = \beta_s + \beta_i - \beta_{p1} - \beta_{p2} \tag{5}$$

where β_s, β_i, β_{p1}, and β_{p2} are the longitudinal propagation constants of the four waves, respectively.

The four waves propagate simultaneously with the angular frequencies ω_{p1}, ω_{p2}, ω_s and ω_i, respectively, which satisfy $\omega_{p1} + \omega_{p2} = \omega_s + \omega_i$. Here, we define two parameters, the central frequency of the two pumps $\omega_c = (\omega_{p_1} + \omega_{p_2})/2$, and the average difference of the pumps frequency $\omega_p = (\omega_{p_1} - \omega_{p_2})/2$. We expand the *n*th derivative of β around the central frequency of the two pumps ω_c. From Ref. [17], $\Delta\beta$ can be expressed as:

$$\Delta\beta = \beta_2((\omega_s - \omega_c)^2 - \omega_p{}^2) + \frac{1}{12}\beta_4((\omega_s - \omega_c)^4 - \omega_p{}^4) \tag{6}$$

Considering of the pump depletion, the phase mismatch parameter κ can be expressed as:

$$\kappa = \Delta\beta + \gamma\left(P_{p1} + P_{p2} - P_s - P_i\right) \tag{7}$$

where P_{p1}, P_{p2}, P_s and P_i denote the power of pumps, signal and idler, respectively.

The Cross section of the triangular PCF is shown in Fig. 1. By manipulating the circular air-hole diameter, *d*, and the hole pitch, Λ, it is possible to control the dispersion properties of the PCF, where $\gamma = n_2\omega/cA_{eff}$ and affective cross-sectional area $A_{eff} \propto \Lambda/d \times \Lambda^2$, such as changing the zero dispersion wavelength(ZDW) or engineering the dispersion curve to be ultra-flattened [18,19].

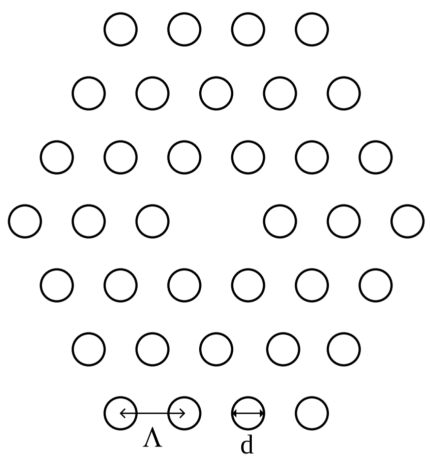

Fig. 1. Cross section of the triangular PCF with hole diameter d, pitch Λ..

3. Results and discussions

Based on the analysis mentioned above, it is known that the gain spectrum of two-pump FOPA with pump depletion mainly depends on the pump powers and wavelengths, the dispersion coefficient, the nonlinear coefficient and the length of PCFs. In this work, the ZWD of the PCF is 1550 nm.

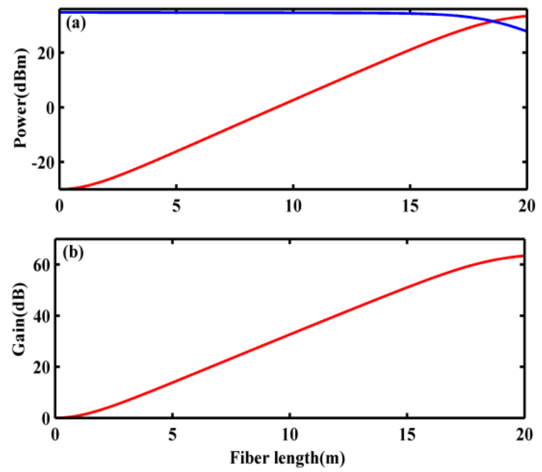

Fig. 2. (a) Power, (b) gain as a function of fiber length for two-pump FOPA with pump depletion.

To begin with, we present a first sight of the evolution of power of pumps and signal with the fiber length in Fig.2 (a). Here, the nonlinear coefficient of the PCF is γ=80W^{-1}km^{-1}, the transportation loss is α=15dB/km, which usually can not be neglected for PCF, and the fiber length is 20 m. The wavelengths for the two pumps are 1545 nm and 1555 nm, respectively, and the two input pump powers are both 34.77 dBm. The signal wavelength is 1430 nm, and the input signal power is set to be -30 dBm. As shown in Fig. 2(a), with the increase of the fiber length, both pumps power reduce to 27.8dBm, and the signal power increases to 33.6 dBm at the output of the PCF with pump depletion. The signal gain as a function of fiber length is also shown in Fig. 2(b). It can be seen that, the signal gain achieves to 63.6 dB. That is to say, the signal is significantly amplified.

Next, we focus on the gain characteristics of the FOPA based on PCF, the roles of PCF and pump power are considered. The gain as a function of signal wavelength for different nonlinear coefficients of PCF is shown in Fig. 3. It can be seen that, when γ=80W^{-1}km^{-1}, gain with a value higher than 63 dB is presented in the wavelength range from 1370 nm to 1790 nm, moreover, the gain spectrum is quite flat over the range. For the cases of the other two nonlinear coefficients, it can be seen that, with the decrease of nonlinear coefficients, the peak gain and the gain bandwidth are both decreased. We also check even larger nonlinear coefficients, and higher peak gain and wider gain bandwidth can be further obtained.

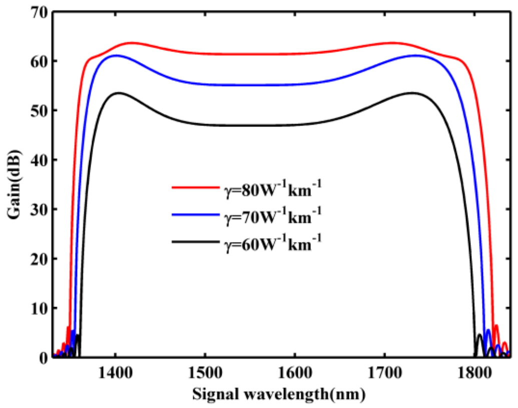

Fig. 3. Signal gain of two-pump FOPA of pump depletion at the output of the PCF with different nonlinear coefficients.

Correspondingly, the effects of fiber length on the gain are shown in Fig. 4. It can be observed that the longer the fiber length, the higher gain can be obtained. However, the gain bandwidth is hardly affected by the fiber length.

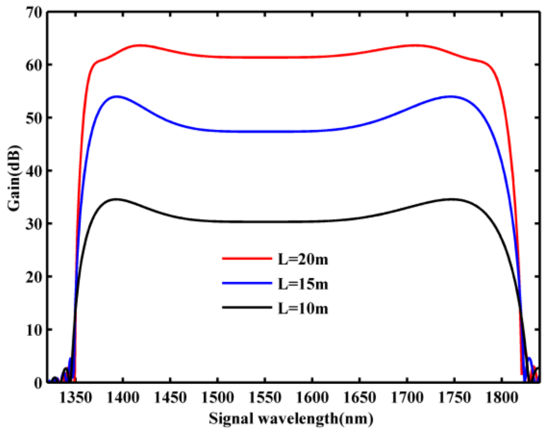

Fig. 4. Signal gain of two-pump FOPA of pump depletion at the output of the PCF with different fiber lengths.

In most researches, the fourth-order dispersion is considered as a constant because its little variation is ignored, however, the impact of its fluctuation on gain performance of FOPA is also very important. Here, we consider three cases of -1.605×10^{-5}, 1.605×10^{-5}, and -2×10^{-4} ps^{4}km^{-1}[20], and present the gain spectra in Fig. 5. Obviously, small absolute value of β_4 can lead to larger gain bandwidth, but the peak gain is slightly modified by the value of β_4.

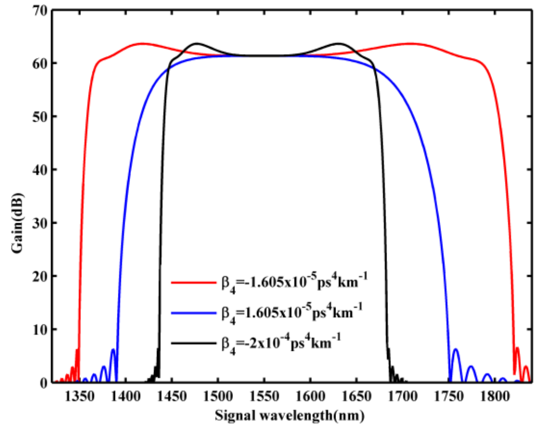

Fig. 5. Signal gain of two-pump FOPA of pump depletion at the output of the PCF with different β_4.

At last, the roles of pump power on the gain properties are discussed. The signal gain as a function of signal wavelength for different pumps power is shown in Fig. 6. It can be seen that, when $P_{p1} = P_{p2} = 34.77$dBm, higher and broader gain can be obtained than lower pump powers. While for the rest pump powers, it can be seen that, with the decrease of pump power, the peak gain and the gain bandwidth are both decreased.

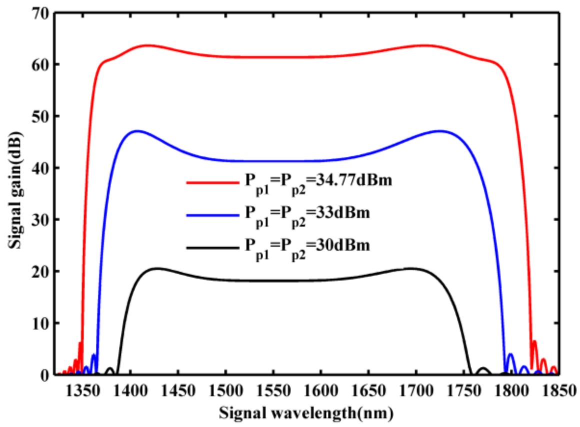

Fig. 6. Signal gain of two-pump FOPA of pump depletion at the output of the PCF with different pump powers.

4. Conclusion

In summary, the gain properties of two-pump FOPA based on PCF with pump depletion is investigated. It is shown that, the nonlinear coefficient of PCF and the pump power can modify the peak gain as well as the gain bandwidth. Larger nonlinear coefficients or pump powers would lead to higher peak gain and wider gain bandwidth. The fiber length mainly changes the peak gain, while the fourth-order dispersion mainly affects the gain bandwidth.

By properly setting the pump parameters and selecting the PCF, a broad gain of 63 dB is obtained in the wavelength range of 420 nm, which is extremely useful for the optical communication system.

Acknowledgements

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