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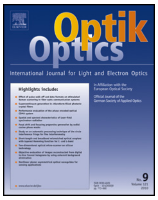

Original research article

Detail gain characteristics of dual-pump photonic crystal fiber optical parametrical amplifiers

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ABSTRACT

Dual-pump optical parametrical amplifiers based on photonic crystal fibers have been analytically and numerically investigated to describe gain distribution in this manuscript. Through controlling and optimizing multi-parameters, broadband and flat gain distribution can be obtained as the signal wavelength is nearby 1053 nm. The numerical results show that the regular and flat parametric gain zone just like "regular hexagon" can be formed when the pump-signal wavelength detuning is 2 nm and the pump power is 4.5 W. There are some ripples on the sideband of the central gain zone as the dispersion slope increases. And, the position of the ripples can shift and change under different dispersion slope and fourth order dispersion parameters. It is remarkable that the area of "regular hexagon" will extend to the largest corresponding to the third order dispersion coefficient $\beta_3 = 1 \times 10^{-41}$ s^3 m^{-1}.

1. Introduction

The fiber optical parametrical amplifiers (FOPAs) based on four-wave mixing (FWM) have been researched and applied in various fields due to the high gain, broad bandwidth and flexible design [1–3]. With the development of the fabrication technology of the photonic crystal fibers (PCFs), the optical parametrical amplifier based on PCF can endure high energy both for strong quasi-continuous waves (CW) and ultra-short pulses [4–6]. The dominated aim of the FOPA is to obtain high gain compared with traditional semiconductor optical amplifier (SOA), for which can be used in wavelength conversion (WC), wavelength division multiplex (WDM) for the next generation optical communications [7,8].

Research groups have obtained outstanding achievements in the field of FOPAs: In 2001, Jay. E Sharping et al. firstly realized the FWM phenomenon in small core area PCF in linear cavity experimentally [9]. It is observed the parametric gain is over 13 dB with the length of fiber 6.1 m and the pump peak power 6 W. In 2002, C. J. McKinstrie and S. Radic provided the earliest analytical and numerical study of the dual pump parametric process based on optical fiber, they designed an amplifier that produced the uniform gain over a wavelength range over 33 nm [10]. In 2006, Chen et al. investigated the dispersion fluctuation effect on optical parametric amplification in PCF [11]. The relative numerical and experimental results allowed the researchers to place limits on the required uniformity of a PCF for frequency conversion. In 2010, Tong et al. considered four different noise sources simultaneously in the single pumped FOPA model [12]. They also analyzed the influence of the different noises including the signal and idler on the gain spectra, for which can be formed symmetric gain spectra in the process of amplification. In 2016, Bigourd et al. have researched the broadband FOPA pumped by two chirped pulses [13], in which the opposite chirp value of the pumps can be used to obtain uniform spectro-temporal gain.

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Above research works focused on the influence of different parameters on the gain in the FOPA. In this manuscript, the detailed gain characteristics of the dual-pump OPAs based on PCFs have been described from the viewpoint of position of the signal wavelength, pump wavelength detuning, dispersion slope and pump power under the phase matching condition. Especially, relative simulation results show that through optimizing the parameters, regular and flat gain zone just like “regular hexagon” in spectral domain can be formed. While once the parameters such as dispersion slope of the PCF for the pump wavelength changes, the gain shape may be distorted and the gain contrast between the central and sideband will be enlarge, which caused the ripple in the gain zone.

2. Numerical modeling

The numerical modeling of the dual-pumps FOPA can be found in relative references [14,15], which can be described from the viewpoint of quantum mechanics as following: the pump photons with different frequencies of ω_1 and ω_2 ($\omega_1 \neq \omega_2$) are annihilated while the signal photon and idler photon are generated with frequencies of ω_3 and ω_4 at the same time respectively. In order to realize the basic phase matching condition for this process, the frequencies of the pumps can be tuned to load symmetrically near the zero-dispersion wavelength (ZDW) of the fibers. According to the four-wave mixing model for the linear parallel polarization pumps, the slow envelope of the light (including pump, signal and idler waves) propagation in the fibers can be written as the following coupled wave equations [15]:

$$\frac{dA_1}{dz} = i\gamma[|A_1|^2 + 2\left(|A_2|^2 + |A_3|^2 + |A_4|^2\right)]A_1 + 2i\gamma A_2^* A_3 A_4 e^{i\Delta\beta z} \tag{1}$$

$$\frac{dA_2}{dz} = i\gamma[|A_2|^2 + 2\left(|A_1|^2 + |A_3|^2 + |A_4|^2\right)]A_2 + 2i\gamma A_1^* A_3 A_4 e^{i\Delta\beta z} \tag{2}$$

$$\frac{dA_3}{dz} = i\gamma[|A_3|^2 + 2\left(|A_1|^2 + |A_2|^2 + |A_4|^2\right)]A_3 + 2i\gamma A_1 A_2 A_4^* e^{-i\Delta\beta z} \tag{3}$$

$$\frac{dA_4}{dz} = i\gamma[|A_4|^2 + 2\left(|A_1|^2 + |A_2|^2 + |A_3|^2\right)]A_4 + 2i\gamma A_1 A_2 A_3^* e^{-i\Delta\beta z} \tag{4}$$

where A_1, A_2, A_3, A_4 represent the amplitudes of the two pumps, signal and idler waves respectively; γ is the nonlinear coefficient of the PCFs; $\Delta\beta$ in the equation is the linear propagation constant mismatch; z is the propagation distance along the PCF.

The central frequency ω_c can be defined from the ω_1 and ω_2, it is written as $\omega_c = (\omega_1 + \omega_2)/2 = (\omega_3 + \omega_4)/2$. In the parametric process, the pumps power are much more intense than that of signal and idler, which means the pumps are not depleted. The parametric gain coefficient of the OPA based PCF can be given by [16]:

$$g = \sqrt{\left(2\gamma\sqrt{P_1 P_2}\right)^2 - \left(\frac{\kappa}{2}\right)^2} \tag{5}$$

where P_1 and P_2 is the pumps power, κ is the phase mismatch constant, as is shown below [17]

$$\kappa = \beta_2\left[(\omega_3 - \omega_c)^2 - (\omega_1 - \omega_c)^2\right] + \frac{1}{12}\beta_4\left[(\omega_3 - \omega_c)^4 - (\omega_1 - \omega_c)^4\right] + \gamma(P_1 + P_2) \tag{6}$$

here β_2 and β_4 are the second order dispersion and fourth order dispersion at the frequency of ω_c. Under this condition, the small signal gain in this parametric process can be written as [15]:

$$G = 1 + \left[2\gamma\sqrt{P_1 P_2}\sinh(gL)/g\right]^2 \tag{7}$$

here L is the fiber length. Under phase matching condition, the parametric gain can be obtained from Eq. (7).

3. Numerical results and discussion

The PCF used in the numerical simulation is LMA5-PM produced by NKT, the relative parameters of which are as following: nonlinear coefficient $\gamma = 0.01\ \mathrm{w}^{-1}\ \mathrm{m}^{-1}$, the third order dispersion coefficient $\beta_3 = 6.75 \times 10^{-41}\ \mathrm{s}^3\ \mathrm{m}^{-1}$, the fourth order dispersion coefficient $\beta_4 = -1 \times 10^{-55}\ \mathrm{s}^4\ \mathrm{m}^{-1}$. The zero dispersion wavelength $\lambda_0 = 1053$ nm, which loads in the infrared wavelength range. We can calculate the phase matching curve of this kind PCF given the pump power P_1 and P_2, which can be seen as Figs. 1 and 2. Fig. 1 shows the phase matching curves when the pumps power are $P = P_1 = P_2$, which changes from $P = 5$ W to $P = 15$ W. The corresponding parametric sideband can be tuned from −50 nm to 50 nm near the central wavelength of the dual-pump. There is existed the steeping phase matching curve near the ZDW (1053 nm) of the PCF.

It can be observed from Fig. 2 that the parametric sidebands will increase with the fixed pump power $P_1 = P_2 = 5$ W. And, it is evident that the fluctuation of the ZDW changes 10 nm (from 1045 nm to 1055 nm), the total sideband can enlarge to 60 nm on the sideband of the pump wavelength. Furthermore, the typical gain spectra can be obtained based on the equations from Eq. (1) to Eq. (7), which is shown in Fig. 3 under the condition of pump power $P_1 = P_2 = 4.5$ W, one pump wavelength $\lambda_1 = 1051$ nm and fiber length $L = 18$ m. In Fig. 3, the parametric gain is most flat when the pump wavelength detuning