Polarization-insensitive fiber optical parametric amplifier based on polarization diversity technique with dual parallel pumps*

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By analyzing the principle of dual-pump parametric amplification and the polarization dependent gain of fiber optical parametric amplifier (FOPA), a polarization-insensitive FOPA based on polarization-diversity technique with dual parallel pumps is presented. The performances of polarization-insensitivity, gain and BER are theoretically analyzed and numerically simulated by comparing the proposed scheme with parallel pump solution and orthogonal pump solution. The presented solution can reduce the complexity of state of polarization (SoP) of pumps.

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Compared with traditional optical amplifiers, any wavelength signal can be amplified by fiber optical parametric amplifier (FOPA) in theory, and FOPA can provide high and flat gain, wide bandwidth, and low noise[1-6]. In recent years, FOPA has made a great progress and has been proved with excellent performance[7-12]. However, it is demonstrated that the gain of signal is closely related to the state of polarization (SoP) of the signal and the pumps. In practice, SoPs of optical signals never stop changing, which affects the gain to a great extent. So it is necessary to further investigate the polarization-insensitive FOPA, and many relative studies are reported[13-20]. F. Yaman[13] and Colin J. McKinstrie[14] explained the theory on polarization-insensitive FOPA with birefringence fiber. Luo T.[15] obtained the polarization-insensitive gain by depolarizing the pump with a polarization controller. K. K. Y. Wong[16] demonstrated experimentally the single-pump FOPA using polarization diversity technique which can produce polarization-insensitive gain. In addition, the dual-pump schemes are also reported[17-19]. In 2006, G. Kalogerakis[20] reported a dual-pump FOPA by using the polarization diversity technique.

In this paper, the principle of parametric amplification with dual pumps based on vector equation is presented and the performances of the dual-parallel-pump FOPA with polarization diversity technique are demonstrated. Simulation results show that the polarization insensitive gain for any small optical signal with arbitrary SoP can be achieved.

If the strong pumps at the frequencies ω_1 and ω_2 are incident at the fiber, and the phase-matching condition is satisfied, the weak signal at ω_3 will be amplified while a new wave at ω_4 is generated simultaneously which is called the idler wave[6]. Averaging the vector coupled-mode equations over the fast SoP rotations, equations as follows can be obtained:

$$\frac{\mathrm{d}|A_1\rangle}{\mathrm{d}z}=\mathrm{i}\beta(\omega_1)|A_1\rangle+\mathrm{i}\gamma_\mathrm{e}(P_2+|A_1\rangle\langle A_1|+|A_2\rangle\langle A_2|)|A_1\rangle\ , \tag{1}$$

$$\begin{aligned}\frac{\mathrm{d}|A_2\rangle}{\mathrm{d}z}=&\mathrm{i}\beta(\omega_2)|A_2\rangle+\mathrm{i}\boldsymbol{b}_1(\omega_2-\omega_1)\cdot\boldsymbol{\sigma}|A_2\rangle+\\&\mathrm{i}\gamma_\mathrm{e}(P_1+|A_1\rangle\langle A_1|+|A_2\rangle\langle A_2|)|A_2\rangle\ ,\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\mathrm{d}|A_3\rangle}{\mathrm{d}z}=&\mathrm{i}\beta(\omega_3)|A_3\rangle+\mathrm{i}\boldsymbol{b}_1(\omega_3-\omega_1)\cdot\boldsymbol{\sigma}|A_3\rangle+\\&\mathrm{i}\gamma_\mathrm{e}(P_1+P_2+|A_1\rangle\langle A_1|+|A_2\rangle\langle A_2|)|A_3\rangle+\\&\mathrm{i}\gamma_\mathrm{e}(|A_1\rangle\langle A_2^*|+|A_2\rangle\langle A_1^*|)|A_4^*\rangle\ ,\end{aligned} \tag{3}$$

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$$\frac{\mathrm{d}|A_4\rangle}{\mathrm{d}z}=\mathrm{i}\beta(\omega_4)|A_4\rangle+\mathrm{i}\boldsymbol{b}_1(\omega_4-\omega_1)\cdot\boldsymbol{\sigma}|A_4\rangle+$$
$$\mathrm{i}\gamma_{\mathrm{e}}(P_1+P_2+|A_1\rangle\langle A_1|+|A_2\rangle\langle A_2|)|A_4\rangle+$$
$$\mathrm{i}\gamma_{\mathrm{e}}(|A_1\rangle\langle A_2^*|+|A_2\rangle\langle A_1^*|)|A_3^*\rangle\ , \tag{4}$$

where $\gamma_{\mathrm{e}}=8\gamma/9$, which stands for the decrease of γ due to the fast SoP rotations.

The evolution of pump SoPs can be described in the Stokes space as:

$$\frac{\mathrm{d}\boldsymbol{P}_1}{\mathrm{d}z}=\gamma_{\mathrm{e}}\boldsymbol{P}_2\times\boldsymbol{P}_1\ , \tag{5}$$

$$\frac{\mathrm{d}\boldsymbol{P}_2}{\mathrm{d}z}=\gamma_{\mathrm{e}}\boldsymbol{P}_1\times\boldsymbol{P}_2\ . \tag{6}$$

Even though the pump SoP rotates along the fiber, the two pumps conserve their power. Another concealed condition is that the sum of the Stokes vectors of the two pumps remains constant: $\boldsymbol{P}_0=\boldsymbol{P}_1+\boldsymbol{P}_2$. Since the pump SoPs rotate around the axis along $\boldsymbol{P}_0$, with the Pauli matrices considered, the equation as below can be noted:

$$|A_1\rangle\langle A_1|+|A_2\rangle\langle A_2|=\frac{1}{2}[(P_1+P_2)\boldsymbol{\sigma}_0+(\boldsymbol{P}_1+\boldsymbol{P}_2)\cdot\boldsymbol{\sigma}]\ , \tag{7}$$

which shows an important fact that the right side of the pump field in Eqs.(1) and (2) remains constant along the fiber.

By introducing the unit vectors: $\boldsymbol{p}_1=\boldsymbol{P}_1/P_1$, $\boldsymbol{p}_2=\boldsymbol{P}_2/P_2$ and $\boldsymbol{p}_0=(\boldsymbol{p}_1+\boldsymbol{p}_2)/\sqrt{2}$, Eqs.(1)-(4) can be solved for the signal field and the gains of the two polarization components G_x and G_y of it can be obtained:

$$|B_3(z)\rangle=G_x|B_{3\mathrm{P}}\rangle+G_y|B_{3\perp}\rangle\ , \tag{8}$$

$$G_{x/y}=\cosh(g_{x/y}z)+\frac{\mathrm{i}\kappa}{g_{x/y}}\sinh(g_{x/y}z)\ , \tag{9}$$

where $g_{x/y}=\sqrt{M_{x/y}^2-\kappa^2}$, $M_{x/y}=M_0[1\pm\cos(\theta_{\mathrm{s}}/2)]$, $M_0=\gamma_{\mathrm{e}}\sqrt{P_1P_2}$, the phase-mismatch parameter is $\kappa=\Delta\beta+\gamma_{\mathrm{e}}(P_1+P_2)$ and θ_{s} is the angle between the Stokes vectors of the two pumps, which is defined as $\theta_{\mathrm{s}}=\cos^{-1}(\boldsymbol{p}_1\bullet\boldsymbol{p}_2)$. Combining Eqs.(8) and (9), the relationship between the signal gain and the relative angle between the SoPs of the fields can be obtained:

$$G_3(L)=P_3(L)/P_3(0)=\frac{|G_x|^2+|G_y|^2}{2}+\frac{|G_x|^2-|G_y|^2}{2}\boldsymbol{p}_0\cdot\boldsymbol{p}_3, \tag{10}$$

$$|G_{x/y}|^2=1+\left[\frac{M_{x/y}}{g_{x/y}}\sinh\left(g_{x/y}L\right)\right]^2\ . \tag{11}$$

As shown above, when the input pumps have orthogonal polarization states in the Jones space, in other words, the Stokes vectors corresponding to the two pumps make an angle of π , the signal gain is independent of the signal SoP. If the two pumps are not orthogonally polarized, when the unit Stokes vector of signal $\boldsymbol{p}_3$ is in the same direction as $\boldsymbol{p}_0$, the largest gain $|G_x|^2$ can be obtained, and when it is orthogonal to $\boldsymbol{p}_0$, it experiences the minimum gain $|G_y|^2$. However, if the SoP of signal is orthogonal to that of parallel pumps, there is no signal gain at all.

Set the parameters as follows: $\gamma=17\ \mathrm{W^{-1}/km}$, the zero-dispersion wavelength $\lambda_0=1550$ nm , $\beta_3=0.1\ \mathrm{ps^3/km}$, $\beta_4=10^{-4}\ \mathrm{ps^4/km}$, $\lambda_1=1502.66$ nm , $\lambda_2=1600.6$ nm , $P_1=P_2=300$ mW, and fiber length is 500 m. The relative angle between the two pumps is set as 0, $\pi/16$, $\pi/8$, $\pi/4$ and $\pi/2$ respectively (0 stands for the case of parallel pumps and $\pi/2$ stands for the case of orthogonal pumps). The results are shown in Fig.1.

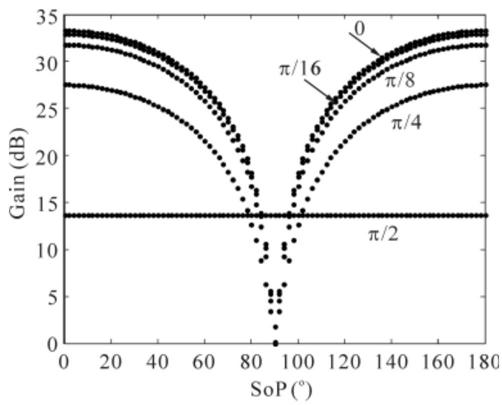

Fig.1 Signal gain for dual-pump FOPA with different signal SoPs (relative to $\boldsymbol{p}_0$)

The theory of polarization dependency of dual-pump FOPA represented in this section is demonstrated in Fig.1. Furthermore, when the pumps are not orthogonally polarized, the signal gain attenuates as the signal SoP increases from 0° to 90° relative to $\boldsymbol{p}_0$ (in the case of 90°-180°, it experiences the opposite tendency); the maximum gain decreases as the relative angle between pumps increases, and when the pumps are orthogonal to each other, the signal gain is independent of the SoP. But the gain is smaller than the maximum which can be obtained by the parallel-pump FOPA with the same parameters, and the SoP is hard to control or adjust in practice. So it is necessary to develop a scheme with polarization-insensitive gain which can be obtained more easily, but the gain can also be kept at a higher level.

For conveniently discussing, fields are decomposed into two directions x and y. It is demonstrated that the two polarization components evolve independently[9]. The principle of the parallel-pump FOPA based on polarization diversity technique is shown in Fig.2.

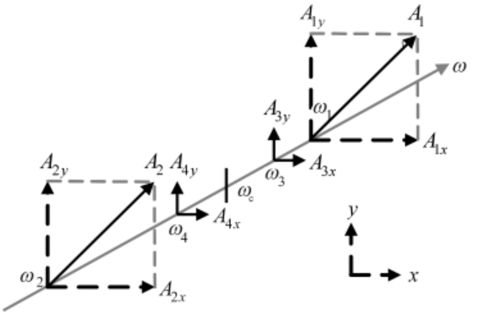

Fig.2 Theory of parallel-pump FOPA based on polarization diversity technique

In Fig.2, A_1 and A_2 stand for the pumps which are copolarized, two components of which are indicated by the subscripts x and y. $A_{k,m}$ (k=3 or 4, m stands for x or y) stands for the component of signal and idler wave in x or y direction. When the SoP of signal is copolarized with axis x /y it experiences the maximum gain in x /y direction, while it has no gain in y/x direction at all. In the parametric amplification process, the power is mainly transferred from the components of the pumps which have the smaller relative angles with the SoP of signal to the signal, while the other components of the pumps act as the compensation, and the total gain keeps constant, regardless of the input SoP. In other words, the polarization-insensitive gain is obtained.

Set the simulation system as Fig.3.

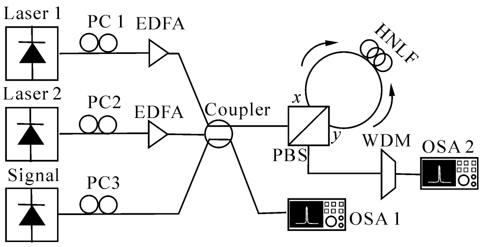

Fig.3 System of polarization-insensitive FOPA with parallel pumps

Take tunable laser sources Laser1/2 as strong pumps, and the signal is a weak one, which are aligned with polarization controllers PC1/2/3 respectively. The pumps and signal are coupled into a polarizing beam splitter (PBS), which decomposes the input into x and y polarized directions. With no signal launched, the power of the pumps in two orthogonal directions is monitored with OSA and the power of the two components of each pump is the same by adjusting PC1 and PC2. It is obvious that the pumps are parallel at this time, and it is much easier to realize by monitoring the power than adjusting the PC. The suitable highly nonlinear fiber (HNLF) and parameters are chosen to satisfy the phase-matching condition so that efficient FWM takes place in x and y polarized directions and the signal is amplified at a high level. A ring configuration is used here. Optical waves in x direction propagate in the fiber clockwise while those in y direction propagate counterclockwise. Since outputs of the PBS are orthogonal to each other, they experience independent parametric processes and the interactions of them can be neglected. The output waves are launched into a wavelength division multiplexing (WDM) and monitored by OSA2.

Parameters are set as below: frequencies of Laser1 and Laser2 are 193.74 THz and 190.38 THz respectively, powers of them are 20.46 dBm and 20.32 dBm respectively, frequency of signal is 192.41 THz, and power of it is −27.85 dBm. Zero-dispersion wavelength of HNLF is 1562.49 nm, the slope of dispersion is 0.01 ps/nm^2•km, length of fiber is 1 km, and γ = 17 W^{-1}/ km.

The relationships of gain and SoP in three schemes are compared in Fig.4.

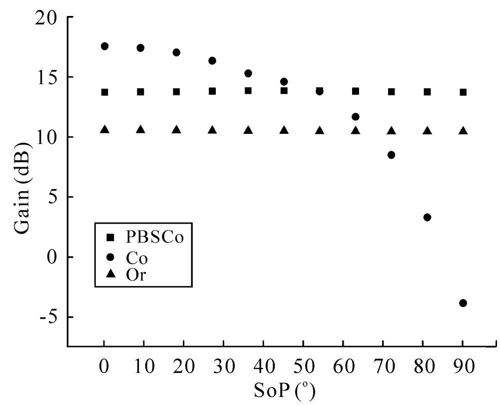

Fig.4 Signal gains of different SoPs in three schemes for dual-pump FOPA (PBSCo, Co and Or stand for the parallel-pump FOPA based on polarization diversity technique, the parallel-pump FOPA and the orthogonal-pump FOPA respectively.)

Fig.4 shows obviously that in the same conditions, gain of parallel-pump FOPA attenuates as the relative angle between signal SoP and the pumps increases; gains of orthogonal-pump FOPA and parallel-pump FOPA based on polarization diversity technique are polarization-insensitive; the maximum gain of parallel-pump FOPA (G_{Co}) can be obtained when the signal is copolarized with the pumps, which is higher than that of the orthogonal-pump FOPA (G_{Or}); gain of parallel-pump FOPA based on polarization diversity technique (G_{PBSCo}) is smaller that G_{Co} but higher than G_{Or}. It shows in Fig.4 that the differences between G_{Co} and G_{PBSCo}, G_{PBSCo} and G_{Or} are about 3 dB. Calculated from the data, the polarization sensitivity of orthogonal-pump FOPA is about 0.38 dB, while that of the parallel-pump FOPA based on polarization diversity technique is about 0.004 dB, which shows better performance of the latter scheme. Results of Kenneth K. Y.

Wong[18] and G. Kalogerakis[20] confirm the analyses and results in this paper.

Fig.5 shows the output signal power for different input power. The input power is -39.56 dBm, -29.56 dBm, -19.56 dBm, -9.56 dBm, 0.44 dBm and 2.48 dBm respectively. For the polarization-insensitive FOPA studied in this paper, when the input signal power is lower than -9.22 dBm, the output power is linear with the input, which is independent of the SoP. However, if the input signal power is higher than 0.44 dBm, the output almost remains constant which has little gain and is polarization-sensitive, that is to say, the FOPA reaches its saturation threshold.

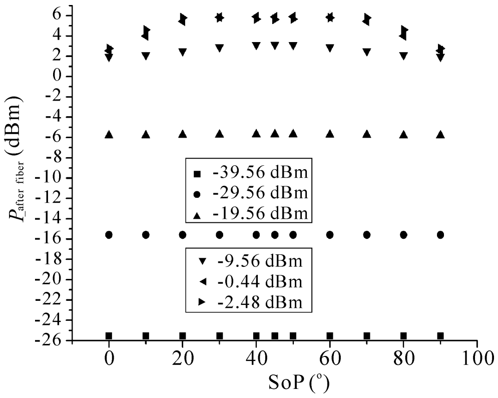

Fig.5 Output signal power for different inputs

In order to get the value of the saturation threshold, gain as a function of input power with SoP of the signal to be 45° and 90° is monitored by the system, which is shown in Fig.6. It shows that the gain can keep constant only when the power of the input signal is below -10.8 dBm, which means that the value of the saturation threshold is -10.8 dBm. What's more, in the saturated area, the signal gain is somehow related to the SoP. So the system has to work in its linear area to guarantee the polarization-insensitive performance.

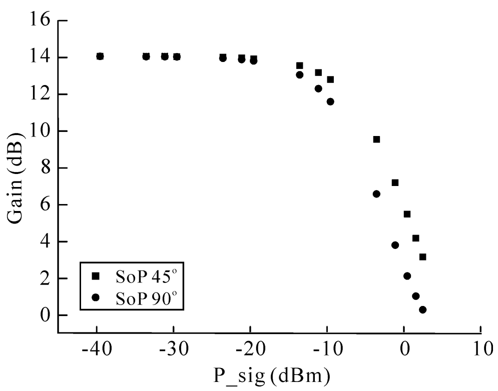

Fig.6 Gain as a function of input power for different SoPs

Assuming the SoP of input signal is 0°, the on-off keying (OOK) data of 10 Gb/s is modulated to the input optical signal. The electrical signal is obtained by optical-electrical conversion. After demodulation, the original data can be recovered.

Fig.7 compares the BERs of parallel-pump FOPA based on polarization diversity technique, parallel-pump FOPA and orthogonal-pump FOPA.

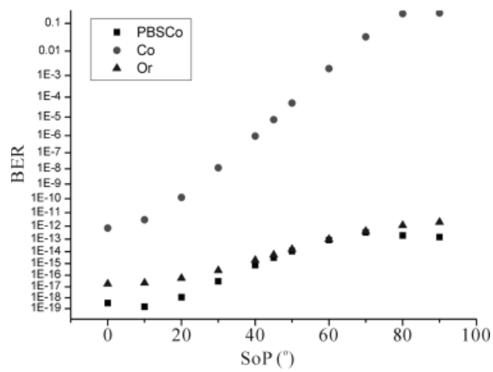

Fig.7 BER comparison of three schemes for dual-pump FOPA

Fig.7 shows that the minimum BERs of the three schemes are 1.0^{-19}, 1.0^{-17} and 1.0^{-12} respectively. The BER performance of parallel-pump FOPA based on polarization diversity technique is the best among the three schemes.

The polarization dependency of dual-pump FOPA is analyzed in the paper, which confirms that the signal gain of dual-pump FOPA is related to the SoPs of the fields. In order to solve the problem, this paper presents the scheme of parallel-pump FOPA based on polarization diversity technique to obtain the polarization-insensitive gain and investigates the system in some important aspects. Parallel-pump FOPA based on polarization diversity technique achieves the best performance of polarization insensitivity compared with parallel-pump or orthogonal-pump FOPA at the cost of sacrificing some gain. Gain of parallel-pump FOPA based on polarization diversity technique is smaller than the maximum gain of parallel-pump FOPA but higher than that of orthogonal-pump FOPA. This system has a saturation threshold when the input power reaches some level, and the polarization-insensitive gain can be only obtained when it works in the linear area. Parallel-pump FOPA based on polarization diversity technique has the best BER performance among the three schemes mentioned in the paper. In summary, the parallel-pump FOPA based on polarization diversity technique is an advanced scheme to obtain polarization-insensitive gain. Furthermore, the SoPs of the pumps are controlled by monitoring the power of them, which makes the scheme much easier to realize.

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