Polarization effect in parametric amplifier

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Received February 3, 2005

Polarization effect in parametric amplifiers is studied. Coupled equations are derived from the basic propagation equations and numerical solutions are given for both one-wavelength-pump and two-wavelength-pump systems. Several parametric amplifiers driven by pumps at one wavelength and two wavelengths are analyzed and the polarization independent parametric amplifier is proposed.

OCIS codes: 060.2320, 190.4380.

With the rapid development of optical communication, wideband optical amplifier has always been the topic of intensive study. Optical parametric amplifier (OPA) is a potential candidate for future optical amplification due to its wide bandwidth outside the erbium-doped fiber amplifier (EDFA) amplification bandwidth[1]. Parametric amplification is based on four-wave-mixing (FWM) phenomenon and is polarization-dependent if it is not carefully configured. If the signal and the pumps do not share the same state of polarization (SOP), the gain will be polarization dependent. Unlike optical fiber Raman amplifier[2], the employment of orthogonally polarized pumps with equal power cannot solve the problem of polarization dependent gain (PDG). Instead, there will be a maximum gain point when the signal polarization state is circumrotated[3]. Only when the two orthogonal pumps, as well as the two orthogonal parts of the signal, propagate clockwise and counter-clockwise in a ring, the PDG can be eliminated[4]. So it is quite essential to study the polarization effect in OPA. In order to increase the bandwidth, two-wavelength-pump OPA has been implemented[5]. In comparison with one-wavelength-pump OPA, two-wavelength-pump OPA has much wider amplification range and higher gain. Subsequently the polarization effect is also more complicated than in one-wavelength-pump OPA. In Ref. [6], polarization-independent OPA with orthogonal pumps at different wavelengths was proposed. It requires careful control of the polarization state of pumps. Because of the random birefringence, the states may vary. To study the polarization effect in OPA, a compact formula can be derived by neglecting pump depletion due to the short fiber length as most theories analyzing OPA do.

In this paper, coupled equations governing the polarization effect in OPA are derived for both one pump wavelength and two pump wavelengths under undepleted pump assumption. The polarization states of the pumps of the OPA are not specific at the birefringence axis. Although there are several models about the two orthogonal pump OPA[7] and one-wavelength-pump OPA, the OPA with generally polarized pump has not been commonly studied. In practical system, it is very likely that the pump and signal will be neither be perfectly orthogonal nor parallel, the model provided in this paper will be of potential value in evaluating practical systems.

Several different OPAs with different pump configuration are studied in this paper. The numerical simulation results show that it is not polarization independent in a one-wavelength-pump OPA with two orthogonal pumps of equal power when they propagate in the same direction. Furthermore, the investigation of the polarization effects shows that in two-wavelength-pump OPA, the polarization-independent OPA can only be achieved via the method proposed in Ref. [6] when the pumps co-propagate with the signal.

The coupled equation is derived from the basic propagation equation[7] by assuming the amplitude:

$$A_x = A_{x1}\exp(j\beta_{x1}z-\omega_1 t) + A_{x3}\exp(j\beta_{x3}z-\omega_3 t) + A_{x4}\exp(j\beta_{x4}z-\omega_4 t),$$

$$A_y = A_{y1}\exp(j\beta_{y1}z-\omega_1 t) + A_{y3}\exp(j\beta_{y3}z-\omega_3 t) + A_{y4}\exp(j\beta_{y4}z-\omega_4 t),$$

where A is the amplitude and β is the propagation constant. The numbers 1, 3, 4 stand for the pump, signal and idler respectively, x and y stand for the polarization direction. Substituting the above expressions into the basic equation, neglecting pump depletion under the strong pump assumption and collecting the terms with same frequency under the condition of phase matching, we have

$$\frac{\partial A_{3x}}{\partial z} = j\gamma\left(2\left|A_{1x}^2\right| + \frac{2}{3}\left|A_{1y}^2\right|\right)A_{3x} + j\gamma\left(2A_{1x}^2A_{4x}^* + \frac{2}{3}A_{1x}A_{1y}A_{4y}^*\right)\exp(-j\Delta\beta z),$$

$$\frac{\partial A_{3y}}{\partial z} = j\gamma\left(2\left|A_{1y}^2\right| + \frac{2}{3}\left|A_{1x}^2\right|\right)A_{3y} + j\gamma\left(2A_{1y}^2A_{4y}^* + \frac{2}{3}A_{1x}A_{1y}A_{4x}^*\right)\exp(-j\Delta\beta z),$$

$$\frac{\partial A_{4x}}{\partial z} = j\gamma\left(2\left|A_{1x}^2\right| + \frac{2}{3}\left|A_{1y}^2\right|\right)A_{4x}$$

$$+j\gamma\left(2A_{1x}^2A_{3x}^*+\frac{2}{3}A_{1x}A_{1y}A_{3y}^*\right)\exp(-j\Delta\beta z),$$

$$\frac{\partial A_{4y}}{\partial z}=j\gamma\left(2\left|A_{1y}^2\right|+\frac{2}{3}\left|A_{1x}^2\right|\right)A_{4y}$$

$$+j\gamma\left(2A_{1y}^2A_{3y}^*+\frac{2}{3}A_{1x}A_{1y}A_{3x}^*\right)\exp(-j\Delta\beta z), \tag{1}$$

where γ is the nonlinear coefficient and $\Delta\beta$ is the phase mismatch. First part of the right side of the equations is the phase contribution of the pumps to the signal and idler. The second part is the amplification effect of the co-polarization pump and the third part represents the effect of the orthogonal-polarized pump. We assume that the fiber used is of constant high birefringence and high nonlinearity, such that the slow axis and fast axis do not vary randomly.

When OPA is driven by two pump wavelengths, for simplicity, only non-degenerated FWM is considered, for degenerated FWM has been investigated in one pump wavelength situation. By assuming

$$A_x=A_{x1}\exp(j\beta_{x1}z-\omega_1t)+A_{x2}\exp(j\beta_{x2}z-\omega_2t)$$
$$+A_{x3}\exp(j\beta_{x3}z-\omega_3t)+A_{x4}\exp(j\beta_{x4}z-\omega_4t),$$
$$A_y=A_{y1}\exp(j\beta_{y1}z-\omega_1t)+A_{y2}\exp(j\beta_{y2}z-\omega_2t)$$
$$+A_{y3}\exp(j\beta_{y3}z-\omega_3t)+A_{y4}\exp(j\beta_{y4}z-\omega_4t),$$

one can similarly derive the following equations (there is one assumption that in the two polarization direction, the fiber shares the same dispersion and dispersion slope):

$$\frac{\partial A_{3x}}{\partial z}=j\gamma\left(2\left|A_{1x}^2\right|+2\left|A_{2x}^2\right|+\frac{2}{3}\left|A_{1y}^2\right|+\frac{2}{3}\left|A_{2y}^2\right|\right)A_{3x}$$
$$+j\gamma\left(2A_{1x}A_{2x}A_{4x}^*+\frac{2}{3}A_{1x}A_{2y}A_{4y}^*+\frac{2}{3}A_{1y}A_{2x}A_{4y}^*\right)$$
$$\times\exp(-j\Delta\beta z),$$

$$\frac{\partial A_{3y}}{\partial z}=j\gamma\left(2\left|A_{1y}^2\right|+2\left|A_{2y}^2\right|+\frac{2}{3}\left|A_{1x}^2\right|+\frac{2}{3}\left|A_{2x}^2\right|\right)A_{3y}$$
$$+j\gamma\left(2A_{1y}A_{2y}A_{4_y}^*+\frac{2}{3}A_{1x}A_{2y}A_{4x}^*+\frac{2}{3}A_{1y}A_{2x}A_{4x}^*\right)$$
$$\times\exp(-j\Delta\beta z),$$

$$\frac{\partial A_{4x}}{\partial z}=j\gamma\left(2\left|A_{1x}^2\right|+2\left|A_{2x}^2\right|+\frac{2}{3}\left|A_{1y}^2\right|+\frac{2}{3}\left|A_{2y}^2\right|\right)A_{4x}$$
$$+j\gamma\left(2A_{1x}A_{2x}A_{3x}^*+\frac{2}{3}A_{1x}A_{2y}A_{3y}^*+\frac{2}{3}A_{1y}A_{2x}A_{3y}^*\right)$$
$$\times\exp(-j\Delta\beta z),$$

$$\frac{\partial A_{4y}}{\partial z}=j\gamma\left(2\left|A_{1y}^2\right|+2\left|A_{2y}^2\right|+\frac{2}{3}\left|A_{1x}^2\right|+\frac{2}{3}\left|A_{2x}^2\right|\right)A_{4y}$$
$$+j\gamma\left(2A_{1y}A_{2y}A_{3y}^*+\frac{2}{3}A_{1x}A_{2y}A_{3x}^*+\frac{2}{3}A_{1y}A_{2x}A_{3x}^*\right)$$
$$\times\exp(-j\Delta\beta z). \tag{2}$$

In Eq. (2), when $A_{1y}=0$ and $A_{2x}=0$, the similar equations in Ref. [6] appear and it is reduced to two sets of decoupled equations. When one considers the polarization effect in x direction only, Eq. (2) is transformed into equations in Refs. [5] and [6]. This shows the validity of our derivation. It is quite hard to derive analytical expressions for Eqs. (1) and (2) generally. To solve the equations, fourth order Runge-Kouta method is implemented.

In our simulation, a 1-km high birefringent high nonlinear fiber is used. The nonlinear coefficient of the fiber γ is 18 $W^{-1}\cdot km^{-1}$, and the dispersion slope is 0.03 ps/($nm^2\cdot km$). The zero dispersion wavelength is 1562.5 nm.

The one-wavelength-pump OPA with two orthogonal pumps is firstly simulated. The pump wavelength is 1564.6 nm and the signal is at 1571.54 nm with different polarization states. In Fig. 1, we can see that when the powers of the two pumps are equal to 22 dBm, the signal still experienced polarization dependent gain.

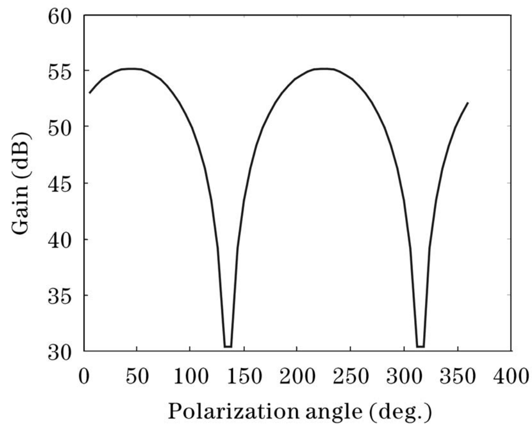

Fig. 1. The polarization dependent gain of one-wavelength-pump OPA.

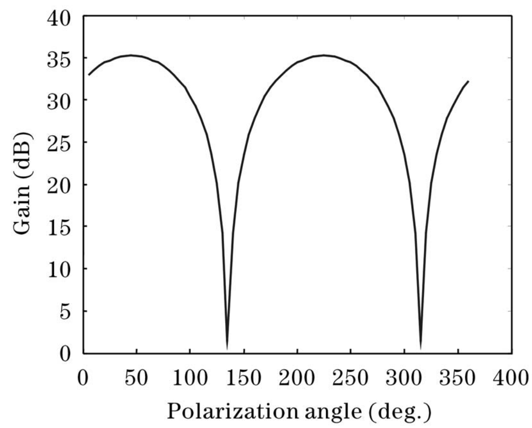

Fig. 2. Two-wavelength-pump OPA polarization dependent gain.

The two-wavelength-pump OPA with four orthogonal pumps is also simulated. The pump wavelengths are 1447.4 and 1474.7 nm and the signal is at the wavelength of 1560 nm. In Fig. 2, we can see that even if the four pumps have equal power of 19.5 dBm, the signal experienced polarization dependent gain. As Ref. [5] suggested, when two pumps with equal power of 22.5 dBm at different wavelengths with orthogonal polarization state are employed, the output signal power (1560 nm) is polarization independent (Fig. 3), and the gain spectrum of the signal (Fig. 4) agrees quite well with the experimental results shown in Ref. [5], the error between our results and the experimental data is less than 0.5 dB.

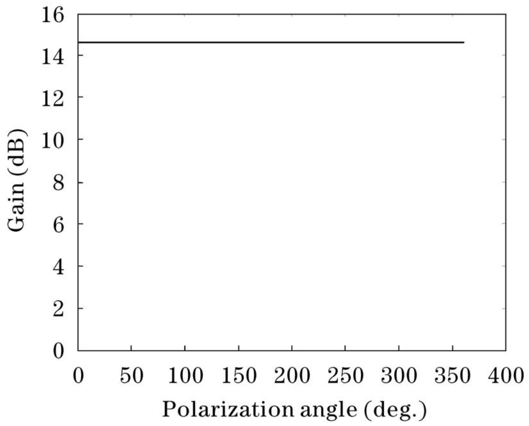

Fig. 3. Two-wavelength-pump OPA polarization independent gain.

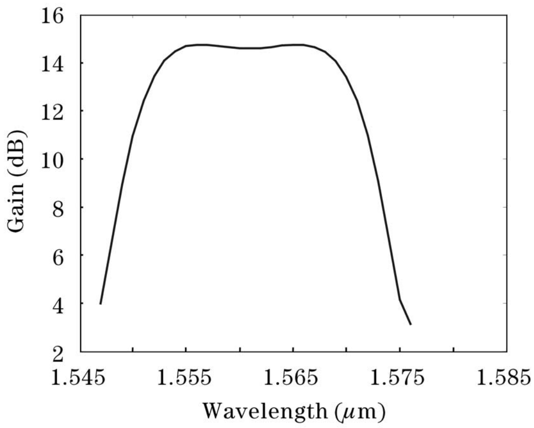

Fig. 4. Two-wavelength-pump OPA polarization independent gain spectrum.

As suggested above, polarization independent OPA can be realized by applying two orthogonal pumps with same power at different wavelength. It is the only method when the signal co-propagates with the pumps. This is because that the coupling part of the four equations can only be eliminated under such situations and become two decoupled sets of equations. To ensure the polarization independent amplification, polarization controller (PC) should be used to achieve the fine performance.

In conclusion, we have investigated the polarization effects in one- and two-wavelength-pump OPAs. The equations governing the amplification process including the polarization effects are derived and numerically solved. As results, polarization effects in several OPAs are investigated and compared. Conclusion is drawn based on these comparisons. The polarization independent OPA can only be realized with two strictly orthogonal pumps at different wavelengths when the signal co-propagates with the pumps and the results of our solution agree well with the experimental results of Ref. [5]. The equations and their solutions can also be used to inspect the polarization effects in OPA. In practice, the fiber is not highly birefringent and the random variation of the slow and fast axes may smooth the polarization dependent gain. One can still use the equations derived to evaluate the polarization effect in general OPA.

This work was supported by the National Natural Science Foundation of China (No. 90204006, 60377013), and the Natural Science Foundation of Ministry of Education of China (No. 20030248035, 2003034258). J. Zhou's e-mail address is scott@sjtu.edu.cn.

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