Cross-Phase Modulation Instability with High-Order Dispersion*

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Abstract: Based on extended nonlinear Schrödinger equation, the effects of third-order and fourth-order dispersion on cross-phase modulation instability (XPM) are investigated, considering the fiber loss and high-order dispersion. The results show that the third-order dispersion does not affect modulation instability. But because of fourth-order dispersion, XPM occurs at two spectrum regions in both the normal and the anomalous dispersion regimes under certain conditions. Gain spectra of the two regions of anomalous dispersion regime are larger than those of normal dispersion regime, and gain spectrum of the second region of anomalous dispersion regime is near zero than that of normal dispersion regime. The research also shows that fiber loss reduces the frequency range of the gain spectrum, and the frequency range becomes smaller with the increasing of the propagation distance.

Key words: Cross-phase modulation instability; Fourth-order dispersion; Gain spectrum; Fiber loss

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0 Introduction

Many nonlinear systems exhibit the modulation instability (MI) as a result of an interplay between the nonlinear and dispersion effects, i. e., the exponential growth of the amplitude of continuously weak perturbation caused by the interaction between dispersion and the nonlinear[1]. When two or more optical waves propagate inside a fiber, one main effect to cause MI is XPM. XPM has an important impact on the performance of high-speed wavelength division multiplexing (WDM) optical fiber communication system[2-3]. It will cause crosstalk between simultaneously transmitted channels in WDM systems and lead to the pulse impairment and distortion, which seriously constrain the steady transmission of optical waves in fiber. There has been a considerable interest in the research of XPM[4-6]. So, the technologies to contain or suppress the pulse impairments due to XPM using dispersive management and compensation have attracted considerable attention since XPM significantly degrades the quality of communication. One of them, for example, is XPM suppressor for multispan dispersion managed WDM transmission[7]. Time domain phase conjugation (TDPC) and frequency domain phase conjugation (FDPC) are the other methods to improve the suppression and compensation for the distortion caused by XPM[8]. Reference [9] proposed a new asymmetrical pulse pair method to suppress the pulse walk-off effect during the process of pulse compression by XPM of pulse pair.

However, the past investigations mainly focused on the effect of XPM duo to the second dispersion (group velocity dispersion, GVD) with the high-order dispersion omitted. It is reasonable to neglect the high-order dispersion in ordinary transmission since its influence is very little comparing to that of GVD. But with the development of fiber communication, the emergence of large capacity, high bit-rate, high input optical power and multichannel in WDM systems, the XPM effect duo to the third and fourth-order dispersion should be taken into account since this effect is inevitable and strong enough. In fact, an experiment has been reported about the experimental observation of a new modulation instability spectral window induced by the fourth-order dispersion in a normally dispersive single-mode optical fiber[10].

Reference [11] studies XPM with high order dispersion of the ideal fiber ($\alpha=0$). However, the effect of the fiber loss to the transmission of optical waves is inevitable. In this paper, XPM caused by

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the high-order dispersion of two optical waves is studied, which is based on extended nonlinear Schrödinger equation with the fiber loss and high-order dispersion considered. The dispersion equation to describe XPM of high-order dispersion is obtained theoretically. The characteristics of gain spectra in both the normal and the anomalous dispersion regimes of fiber are studied by simulation. These provide a theoretically basis to minimize the effect of XPM duo to the high-order dispersion in WDM systems.

1 Theoretical model

If the effects of high-order dispersion and fiber loss to the properties of optical transmission are considered, the extended nonlinear Schrödinger equation of two optical waves can be written as[1]

$$\frac{\partial A_1}{\partial z}+\frac{1}{v_{g1}}\frac{\partial A_1}{\partial t}+\frac{i}{2}\beta_{21}\frac{\partial^2 A_1}{\partial t^2}+\frac{\alpha_1}{2}A_1=\frac{\beta_{31}}{6}\frac{\partial^3 A_1}{\partial t^3}-\frac{i\beta_{41}}{24}\frac{\partial^4 A_1}{\partial t^4}+i\gamma_1[|A_1|^2+2|A_2|^2]A_1 \quad (1)$$

$$\frac{\partial A_2}{\partial z}+\frac{1}{v_{g2}}\frac{\partial A_2}{\partial t}+\frac{i}{2}\beta_{21}\frac{\partial^2 A_2}{\partial t^2}+\frac{\alpha_2}{2}A_2=\frac{\beta_{32}}{6}\frac{\partial^3 A_2}{\partial t^3}-\frac{i\beta_{42}}{24}\frac{\partial^4 A_2}{\partial t^4}+i\gamma_2[|A_2|^2+2|A_1|^2]A_2 \quad (2)$$

where $A(z,t)$ is the amplitude of slow-varying envelop wave, t is time, z is transmission distance, v_{g1} is group velocity, β_{ij} is the i-th coefficient of the group velocity dispersion (GVD) of the j-th optical wave, α_j is the coefficient of fiber loss, γ_j is the nonlinear coefficient. In order to mathematically distinguish the two optical waves, the footnote 1 and 2 to is used describe them respectively. Supposing $A_1=u_1\exp(-\alpha_1 z/2)$ and $A_2=u_2\exp(-\alpha_2 z/2)$, Substituting them into Eq. (1) and Eq. (2), we obtain

$$\frac{\partial u_1}{\partial z}+\frac{1}{v_{g1}}\frac{\partial u_1}{\partial t}+\frac{i}{2}\beta_{21}\frac{\partial^2 u_1}{\partial t^2}=\frac{\beta_{31}}{6}\frac{\partial^3 u_1}{\partial t^3}-\frac{i\beta_{41}}{24}\frac{\partial^4 u_1}{\partial t^4}+i\gamma_1[u_1^2\exp(-\alpha_1 z)+2u_2^2\exp(-\alpha_2 z)]u_1 \quad (3)$$

$$\frac{\partial u_2}{\partial z}+\frac{1}{v_{g2}}\frac{\partial u_2}{\partial t}+\frac{i}{2}\beta_{22}\frac{\partial^2 u_2}{\partial t^2}=\frac{\beta_{32}}{6}\frac{\partial^3 u_2}{\partial t^3}-\frac{i\beta_{42}}{24}\frac{\partial^4 u_2}{\partial t^4}+i\gamma_2[u_2^2\exp(-\alpha_2 z)+2u_1^2\exp(-\alpha_1 z)]u_2 \quad (4)$$

In the condition of continuous and quasi-continuous waves, the amplitude u_j at $z=0$ is irrelative with time. If $A_j(z,t)$ is still irrelative with time during the transmission in fiber, the steady-state solutions of Eq. (3) and Eq. (4) are

$$\bar{u}_1(z,t)=\sqrt{P_1}\exp\{i\gamma_1\int_0^z[P_1\exp(-\alpha_1 z')+2P_2\exp(-\alpha_2 z')]dz'\} \quad (5)$$

$$\bar{u}_2(z,t)=\sqrt{P_2}\exp\{i\gamma_2\int_0^z[P_2\exp(-\alpha_2 z')+2P_1\exp(-\alpha_1 z')]dz'\} \quad (6)$$

where P_1 and P_2 are incident powers at $z=0$. To study the stability of the steady-state solution, perturbing the steady state slightly, and supposing the perturbation item $|a_1(z,t)|\ll P_1^{1/2}$ and $|a_2(z,t)|\ll P_2^{1/2}$, we have

$$u_1(z,t)=(\sqrt{P_1}a_1)\exp\{i\gamma_1\int_0^z[P_1\exp(-\alpha_1 z')+2P_2\exp(-\alpha_2 z')]dz'\} \quad (7)$$

$$u_2(z,t)=(\sqrt{P_2}a_2)\exp\{i\gamma_2\int_0^z[P_2\exp(-\alpha_2 z')+2P_1\exp(-\alpha_1 z')]dz'\} \quad (8)$$

Substituting Eq. (7) and Eq. (8) into Eq. (3) and Eq. (4), and making a_1 and a_2 linear, we get

$$\frac{\partial a_1}{\partial z}+\frac{1}{v_{g1}}\frac{\partial a_1}{\partial t}+\frac{i}{2}\beta_{21}\frac{\partial^2 a_1}{\partial t^2}=\frac{\beta_{31}}{6}\frac{\partial^3 a_1}{\partial t^3}-\frac{i\beta_{41}}{24}\frac{\partial^4 a_1}{\partial t^4}+i\gamma_1[P_1\exp(-\alpha_1 z)(a_1+a_1^*)+2(P_1P_2)^{1/2}\cdot\exp(-\alpha_2 z)(a_2+a_2^*)] \quad (9)$$

$$\frac{\partial a_2}{\partial z}+\frac{1}{v_{g2}}\frac{\partial a_2}{\partial t}+\frac{i}{2}\beta_{22}\frac{\partial^2 a_2}{\partial t^2}=\frac{\beta_{32}}{6}\frac{\partial^3 a_2}{\partial t^3}-\frac{i\beta_{42}}{24}\frac{\partial^4 a_2}{\partial t^4}+i\gamma_2[P_2\exp(-\alpha_2 z)(a_2+a_2^*)+2(P_1P_2)^{1/2}\cdot\exp(-\alpha_1 z)(a_1+a_1^*)] \quad (10)$$

Supposing the solutions of the set of equations are

$$a_j=U_j\cos(kz-\Omega T_j)+iV_j\sin(kz-\Omega T_j) \quad (j=1,2) \quad (11)$$

where k is the wave number, Ω is the angular frequency of disturbance, $T_j=t-z/v_{gj}(j=1,2)$ is delay time. Substituting Eq. (11) into Eq. (9) and Eq. (10), let the real and imaginary parts of each equation be zero respectively, one can obtain a set of equations about U_1, V_1, U_2 and V_2. The enough and essential condition with nontrivial solution of this set is the determinant of the coefficient should be zero, i. e.

$$\left[(k-\frac{\beta_{31}}{6}\Omega^3)^2-f_1\right]\left[(k-\frac{\beta_{32}}{6}\Omega^3)^2-f_2\right]=C_{XPM} \quad (12)$$

where

$$f_j=(\frac{1}{2}\beta_{2j}\Omega^2-\frac{1}{24}\beta_{4j}\Omega^4)(\frac{1}{2}\beta_{2j}\Omega^2-\frac{1}{24}\beta_{4j}\Omega^4+2\gamma_jP_j\exp(-\alpha_j z)) \quad (j=1,2)$$

$$X_{XPM}=16\gamma_1\gamma_2P_1P_2\exp[-(\alpha_1+\alpha_2)z](\frac{1}{2}\beta_{21}\Omega^2-\frac{1}{24}\beta_{41}\Omega^4)(\frac{1}{2}\beta_{22}\Omega^2-\frac{1}{24}\beta_{42}\Omega^4)$$

Equation (12) is very complicated when fiber loss and high-order dispersion are considered. To simplify the problem, supposing the third-order dispersions of two lights with little difference, i. e. $\beta_{21}\approx\beta_{22}=\beta_2$, $\beta_{31}\approx\beta_{32}=\beta_3$, $\beta_{41}\approx\beta_{42}=\beta_4$, $\gamma_1\approx\gamma_2=\gamma$, $\alpha_1\approx\alpha_2=\alpha$. The solution of Eq. (12) is

$$(k-\frac{\beta_3}{6}\Omega^3)^2=\frac{1}{2}\{(f_1+f_2)\pm[(f_1+f_2)^2+4(C_{XPM}-f_1f_2)]^{1/2}\} \quad (13)$$

In Eq. (13), when the sign '±' is minus and

$C_{XPM} > f_1 f_2$, we have $(k - \frac{\beta_3}{6}\Omega^3) < 0$, and k is imaginary number at this time. Then the disturbance a_1 and a_2 increase exponentially according to Eq. (11), which lead to MI phenomena when $C_{XPM} > f_1 f_2$.

$$k = \frac{\beta_3}{6}\Omega^3 + \frac{\sqrt{2}}{2}\mathrm{i}\{[(f_1+f_2)^2 + 4(C_{XPM} - f_1 f_2)]^{1/2} - (f_1+f_2)\}^{1/2} \quad (14)$$

Since β_3 does not appear in the imaginary part of k, the third-order dispersion is useless to XPM, which is consistent with the past researches[1]. The definition of gain is[1]: $g(\Omega) = 2\mathrm{Im}(k)$. From Eq. (14), we get

$$g(\Omega) = \sqrt{2}\{[(f_1+f_2)^2 + 4(C_{XPM} - f_1 f_2)]^{1/2} - (f_1+f_2)\}^{1/2} \quad (15)$$

Substituting the expressions of C_{XPM}, f_1 and f_2 into $C_{XPM} > f_1 f_2$, we can rewrite the condition of MI as

$$16\gamma^2 P_1 P_2 \exp(-2\alpha z) > (\frac{1}{2}\beta_2\Omega^2 - \frac{1}{24}\beta_4\Omega^4 + 2\gamma_1 P_1 \exp(-\alpha z)\frac{1}{2}\beta_2\Omega^2 - \frac{1}{24}\beta_4\Omega^4 + 2\gamma P_2 \cdot \exp(-\alpha z))$$

Expanding and arranging it, we have

$$\Omega^8 - \frac{24\beta_2}{\beta_4}\Omega^6 - \left[\frac{48\gamma}{\beta_4}(P_1+P_2)\exp(-\alpha z) - \frac{144\beta_2^2}{\beta_4^2}\right]\Omega^4 + \frac{576\gamma\beta_2}{\beta_4^2}(P_1+P_2)\exp(-\alpha z)\Omega^2 - 6912\,\frac{\gamma^2 P_1 P_2}{\beta_4^2}\exp(-2\alpha z) < 0 \quad (16)$$

The above equation can be written as

$$(\Omega^2 - \Omega_1^2)(\Omega^2 - \Omega_2^2)(\Omega^2 - \Omega_3^2)(\Omega^2 - \Omega_4^2) < 0 \quad (17)$$

When Eq. (17) is satisfied, XPM can occur and the four parameters in Eq. (17) are

$$\Omega_{1,2,3,4}^2 = \frac{6\beta_2}{\beta_4} \pm \frac{1}{\beta_4}\{36\beta_2^2 + 24\gamma\beta_4(P_1+P_2) \cdot \exp(-\alpha z) \pm 24\gamma\beta_4 \exp(-\alpha z)[(P_1+P_2)^2 + 12P_1P_2]^{1/2}\}^{1/2} \quad (18)$$

when the former and later sign '±' being pluses corresponds Ω_1^2; former plus later minus Ω_2^2; former minus later plus Ω_3^2; both minuses Ω_4^2.

2 Results and analysis

2.1 The effect of fourth-order dispersion to XPM in anomalous dispersion region

In the anomalous dispersion region of fiber, $\beta_2 < 0$ and $\beta_4 < 0$. So $\Omega_2^2 < 0$ and $\Omega_4^2 > 0$. To get $\Omega_1^2 > 0$, from Eq. (18) we should have

$$3\beta_2^2 - 2\gamma|\beta_4|\exp(-\alpha z)\{(P_1+P_2) + [(P_1+P_2)^2 + 12P_1P_2]^{1/2}\} > 0 \quad (19)$$

Now we can obtain $\Omega_3^2 > 0$ from Eq. (18) and Eq. (19). So to produce MI, the relations among β_2, β_4, γ, P_1, P_2 and α should satisfy Eq. (19) with the fiber loss and high-order dispersion considered.

Furthermore, from Eq. (18) we can get $\Omega_4^2 > \Omega_3^2 > \Omega_1^2 > 0$. So when Ω is in $0 < |\Omega| < |\Omega_1|$ or $|\Omega_3| < |\Omega| < |\Omega_4|$, Eq. (18) is satisfied. That is, XPM can occur in two spectrum regions. It shows that the fourth-order dispersion leads to a new spectrum region of XPM in the anomalous dispersion region.

2.2 The effect of fourth-order dispersion to XPM in normal dispersion region

In the normal dispersion region of fiber, $\beta_2 > 0$ and $\beta_4 > 0$. So $\Omega_1^2 > 0$ and $\Omega_3^2 < 0$. To get $\Omega_2^2 > 0$ and $\Omega_4^2 > 0$, we should have

$$3\beta_2^2 + 2\gamma\beta_4 \exp(-\alpha z)\{(P_1+P_2) - [(P_1+P_2)^2 + 12P_1P_2]^{1/2}\} > 0 \quad (20)$$

Under this condition, one can obtain $\Omega_1^2 > \Omega_2^2 > \Omega_4^2 > 0$. XPM occurs in two regions $0 < |\Omega| < |\Omega_4|$ and $|\Omega_2| < |\Omega| < |\Omega_1|$. It indicates that in normal dispersion the fourth-order dispersion also makes XPM appear in two spectrum regions: one is closer to zero, the other is far from zero. From Eq. (20), we know that the fiber loss decreases the width of spectrum region.

For common fiber, the conditions, i. e., Eq. (19) and Eq. (20), can usually be satisfied. Supposing the spectrum region closer zero point is called the first spectrum region and the far from zero one called the second spectrum region. The following figures can explicitly illustrate the effects of the four-order dispersion to XPM. The parameters are selected as $\beta_2 = \pm 20\ \mathrm{ps^2/km}$, $\beta_4 = \pm 0.02\ \mathrm{ps^4/km}$ (the normal and anomalous dispersion regions correspond plus and minus respectively), $\gamma = 2\ \mathrm{W^{-1}\,km^{-1}}$, $\alpha = 0.2$ dB/km, $z = 10$ km and $P_1 = P_2 = 30$ W.

Fig. 1 and 2 show the first spectrum region is far from the second spectrum region, and the spectrum width of the second spectrum region is very small. In order to compare them explicitly, we amplify these two spectrum regions, shown as in Fig. 3 and Fig. 4.

Fig. 3 and Fig. 4 show that the fiber loss decreases the amplitude and width of the gain spectrum greatly. Comparing Fig. 3 and Fig. 4, it is found that the first and second spectrum regions in the anomalous dispersion region are wider than those in the normal dispersion region, and the second spectrum region in anomalous dispersion region is closer to zero. Although there are a high and a low peaks in both normal and

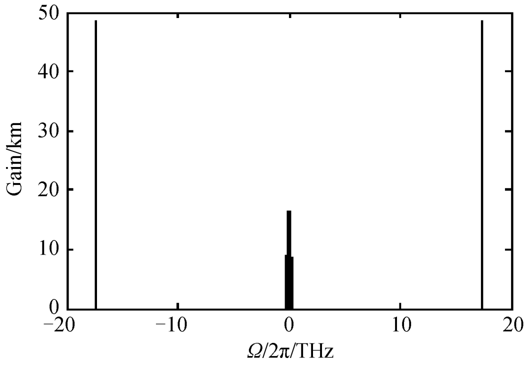

Fig. 1 The gain in anomalous dispersion region

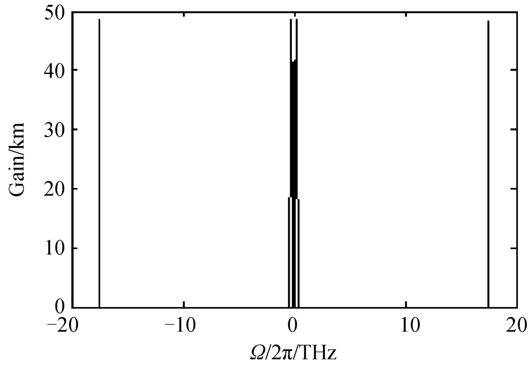

Fig. 2 The gain in normal dispersion region

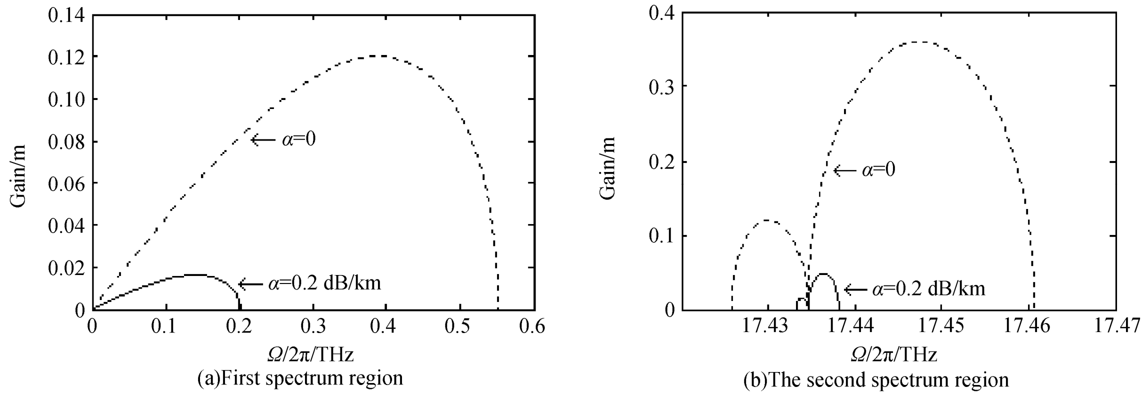

Fig. 3 The gain of the first and second spectrum regions in normal dispersion region

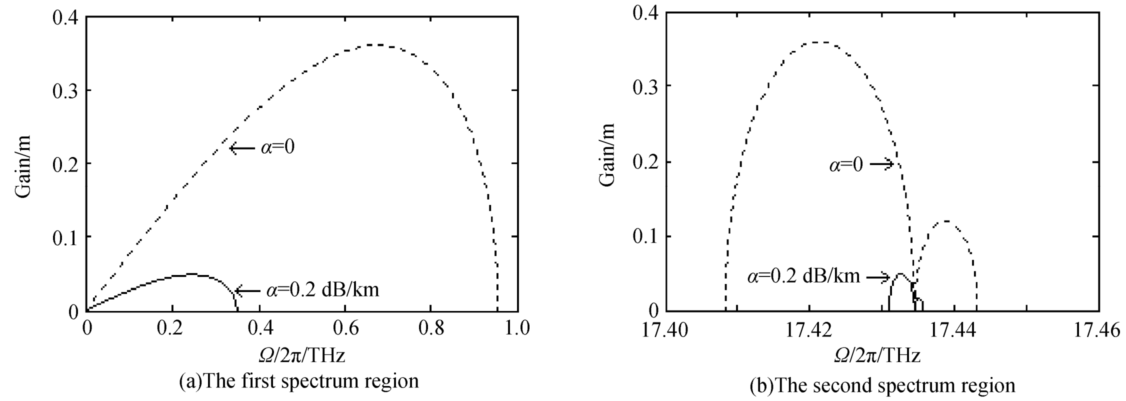

Fig. 4 The gain of the first and second spectrum regions in anomalous dispersion region

anomalous dispersion regions, the high peak in anomalous dispersion region is closer to zero. These indicate XPM in fiber occurs more easily in anomalous dispersion region.

2.3 The effect of fiber loss to XPM

In order to study the effect of fiber loss to XPM, we compare the gain widths in the two dispersion regions of the ideal fiber ($\alpha=0$) with those in the common fiber ($\alpha\neq 0$). Suppose the gain width of the ideal fiber is $\Delta\Omega_1$ and the gain width of the common fiber is $\Delta\Omega_2$. Since the effects of fiber loss to XPM in the normal and anomalous dispersion regions have the same law, only the first spectrum region in the normal dispersion region is considered. From Eq. (18), we have

$$\Delta\Omega_1=\frac{6\beta_2}{\beta_4}+\frac{1}{\beta_4}\{36\beta_2^2+24\gamma\beta_4(P_1+P_2)+24\gamma\beta_4[(P_1+P_2)^2+12P_1P_2]^{1/2}\}^{1/2} \tag{21}$$

$$\Delta\Omega_2=\frac{6\beta_2}{\beta_4}+\frac{1}{\beta_4}\{36\beta_2^2+24\gamma\beta_4(P_1+P_2)\cdot\exp(-\alpha z)+24\gamma\beta_4\exp(-\alpha z)[(P_1+P_2)^2+12P_1P_2]^{1/2}\}^{1/2} \tag{22}$$

Because α and z are always larger than, by comparing the above equations, it is known that $\Delta\Omega_2<\Delta\Omega_1$. That is, with the same initial peak power and transmission distance, the fiber loss decreases the width of the gain spectrum greatly and its influencing degree is increasing as the transmission distance increases. Fig. 5 shows the change curve of critical perturbation frequency with initial peak power with and without the fiber loss considered. From the figure, it is found that with the increase of the initial peak power, the degree of the influence of the fiber loss to the spectrum width (double the critical perturbation frequency) becomes larger. When the fiber loss is considered, the optical power and the nonlinear effect become smaller with the increment of transmission distance. So the XPM becomes more and more inconspicuous.

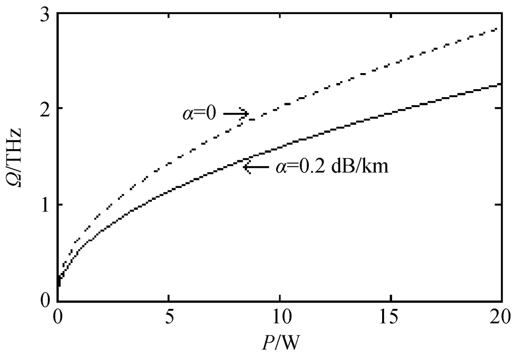

Fig. 5 The change of critical perturbation frequency with initial peak power

3 Conclusions

This paper investigates the effects of high-order dispersion on XPM. The results show that the third-order dispersion has no effect on modulation instability, but because of fourth-order dispersion, XPM occurs at two spectrum regions in both the normal and the anomalous dispersion regime of fiber under certain conditions. Gain spectra of the two regions of anomalous dispersion regime are larger than those of normal dispersion regime, and gain spectra of the second region of anomalous dispersion regime is near zero than that of normal dispersion regime. These indicate XPM in fiber occurs more easily in anomalous dispersion region. The fiber loss reduces the frequency range of the gain spectrum, and the frequency range becomes smaller with the increase of the propagation distance. When the fiber loss is considered, the optical power and the nonlinear effect become smaller with the increment of transmission distance. So the XPM becomes more and more inconspicuous.

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高阶色散导致的交叉相位调制不稳定性

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摘　要: 在考虑光纤损耗及高阶色散的情况下, 以三、四阶色散项的耦合非线性薛定谔方程为基础, 研究高阶色散对交叉相位调制不稳定性的影响. 研究表明: 三阶色散对调制不稳定性不起作用; 由于四阶色散的影响, 在光纤的正常、反常色散区, 交叉相位调制不稳定性均发生在两个频谱区. 且反常色散区两频谱区都比正常色散区的宽, 反常色散区第二频谱区比正常色散区的更靠近零点. 光纤损耗对增益谱的谱宽有较大影响, 它使增益的谱宽变窄, 且随传输距离的增大谱宽变得更窄.

关键词: 交叉相位调制不稳定性; 四阶色散; 增益谱; 光纤损耗

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