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保偏光纤中相近频率传输区域的调制不稳定性*

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利用激光脉冲在光纤中传播时所遵守的相干非线性薛定谔耦合方程,研究了保偏光纤中两相近频率的线偏振光,其偏振方向相互正交且平行于光纤的双折射轴,且偏振方向沿两个双折射轴的分量强度相等时,在同为反常色散区和正常色散区所产生的调制不稳定性.结果表明在反常色散区和正常色散区都能产生调制不稳定性;在正常色散区存在不同的调制不稳定性功率区域,对应不同的功率区域,导致增益谱表现出明显的不同,并且当输入功率一定时,波长差(或频率差)的变化导致增益谱的变化.

关键词:相近频率传输区域, 双折射, 保偏光纤, 调制不稳定性

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1. 引 言

当一连续波在非线性介质中传输时,由于非线性和色散的相互作用产生调制不稳定性.在弱的噪声和其他一些小的微扰存在下,由于振幅和相位的调制,连续波最终分裂成高重复率的超短脉冲,从而产生光孤子[1].在弱的双折射光纤中,当波长相同的两光脉冲沿着双折射轴传输时,由于光纤的双折射并通过光纤中的非线性发生相互作用,产生交叉相位调制(XPM),不仅在反常色散区,而且在正常色散区也能产生调制不稳定性[2—4].在强的双折射光纤中,同样由于双折射、非线性效应和色散的相互作用,同波长的两光脉冲在双折射光纤中传输时,由于 XPM,也可产生调制不稳定性[5—9].在保偏光纤中,固有双折射比由于应力、纤芯形状变化以及非线性效应引起的随机双折射大得多,光纤在整个长度上双折射为常数.本文主要讨论了在保偏光纤中,当入射两个不同波长的激光脉冲,其偏振方向相互正交且平行于光纤的双折射轴时,由于双折射、非线性效应和色散的相互作用产生 XPM,在正常色散区和反常色散区所产生调制不稳定性.

2. 理 论

当输入两束不同波长光的偏振方向相互正交且平行于光纤的双折射轴时,两束不同波长的光在保偏光纤中传输时所遵循的耦合薛定谔方程为

$$\frac{\partial E_1}{\partial z} - \frac{\delta}{2}\frac{\partial E_1}{\partial t} + \mathrm{i}\beta_{21}\frac{\partial^2 E_1}{\partial t^2} - \mathrm{i}\gamma_1\left(|E_1|^2 + \frac{2}{3}|E_2|^2\right)E_1 = 0, \tag{1a}$$

$$\frac{\partial E_2}{\partial z} + \frac{\delta}{2}\frac{\partial E_2}{\partial t} + \mathrm{i}\beta_{22}\frac{\partial^2 E_2}{\partial t^2} - \mathrm{i}\gamma_2\left(|E_2|^2 + \frac{2}{3}|E_1|^2\right)E_2 = 0, \tag{1b}$$

式中 E_1, E_2 为以波长 λ_1 和 λ_2(对应的频率为 ω_1, ω_2)沿着快轴和慢轴偏振的场的慢变包络,β_{21}, β_{22} 为不同波长的群速度色散.$\gamma_i = \frac{n_2\omega_i}{cA_i}$ $(i = 1,2)$, n_2 为非线性折射率系数,A_i 为有效截面,$\delta = \frac{1}{v_{gy}(\omega_2)} - \frac{1}{v_{gx}(\omega_1)}$ 为群速度失配,它依赖于光纤的双折射和传输频率.可近似表示为

$$\delta = \delta_0 + (\omega_2 - \omega_1)\beta, \tag{2}$$

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式中 $\beta=\frac{(\beta_{21}+\beta_{22})}{2}$，$\delta_0=\frac{B}{c}$，$B=n_y-n_x$ 为光纤的固有双折射，当两频率差（$\omega_2-\omega_1$）较小时，$\delta\approx\delta_0$.

方程（1）的稳态解为

$$E_1=\sqrt{P}\exp\left[\mathrm{i}\left(\frac{5}{3}\gamma_1 Pz\right)\right],\quad E_2=\sqrt{P}\exp\left[\mathrm{i}\left(\frac{5}{3}\gamma_2 Pz\right)\right],\tag{3}$$

式中 P 为输入功率、z 为传输距离，假定两偏振模有相同的输入功率 p. 在稳态解（3）中引入一阶振幅微扰项 u 和 v 得

$$E_1=(\sqrt{P}+u)\exp\left[\mathrm{i}\left(\frac{5}{3}\gamma_1 Pz\right)\right],\quad E_2=(\sqrt{P}+v)\exp\left[\mathrm{i}\left(\frac{5}{3}\gamma_2 Pz\right)\right].\tag{4}$$

将（4）式代入（1）式，并且线性化得到有关 u 和 v 的方程

$$\frac{\partial u}{\partial z}+\frac{\delta}{2}\frac{\partial u}{\partial t}+\mathrm{i}\beta_{21}\frac{\partial^2 u}{\partial t^2}-\mathrm{i}\gamma_1 P(u+u^*)-\mathrm{i}\gamma_1 P\frac{2}{3}(v+v^*)=0,\tag{5a}$$

$$\frac{\partial v}{\partial z}+\frac{\delta}{2}\frac{\partial v}{\partial t}+\mathrm{i}\beta_{22}\frac{\partial^2 v}{\partial t^2}-\mathrm{i}\gamma_2 P(v+v^*)-\mathrm{i}\gamma_2 P\frac{2}{3}(u+u^*)=0.\tag{5b}$$

设

$$u=u_s\exp[\mathrm{i}(\Omega t-Kz)]+u_a\exp[\mathrm{i}(-\Omega t+Kz)],\tag{6a}$$

$$v=v_s\exp[\mathrm{i}(\Omega t-Kz)]+v_a\exp[\mathrm{i}(-\Omega t+Kz)].\tag{6b}$$

将（6）式代入（5）式，得到有关 u_s，u_a，v_s，v_a 的线性方程，我们可以得到如下色散关系：

$$((K-b)^2-f_1)((K+b)^2-f_2)=C_{\mathrm{XPM}}^2,\tag{7}$$

式中

$$b=\frac{1}{2}\delta\Omega,$$

$$f_1=\gamma_1|\beta_{21}|\mathrm{sgn}(\beta_{21})P\Omega^2+\frac{1}{4}\beta_{21}^2\Omega^4,$$

$$f_2=\gamma_2|\beta_{22}|\mathrm{sgn}(\beta_{22})P\Omega^2+\frac{1}{4}\beta_{22}^2\Omega^4,$$

$$C_{\mathrm{XPM}}^2=\left(\frac{2}{3}\right)^2\gamma_1\gamma_2|\beta_{21}|\mathrm{sgn}(\beta_{21})|\beta_{22}|\times\mathrm{sgn}(\beta_{22})P^2\Omega^4.$$

方程（7）可展开为

$$K^4-(f_1+f_2+2b^2)K^2-2b(f_1-f_2)K+f_1f_2-b^2(f_1+f_2)+b^4-C_{\mathrm{XPM}}^2=0.\tag{8}$$

当沿着快轴和慢轴的两偏振模有相同的功率 P，色散性质相同，沿着快轴和慢轴的波长差 $|\lambda_1-\lambda_2|\leqslant 10\mathrm{nm}$ 时，$f_1-f_2\approx0$. 所以当忽略方程（8）中 K 的一次项，方程（8）可化简为

$$K^4-(f_1+f_2+2b^2)K^2+f_1f_2-b^2(f_1+f_2)+b^4-C_{\mathrm{XPM}}^2=0.\tag{9}$$

方程（9）的解为

$$K^2=\frac{(f_1+f_2+2b^2)}{2}\pm\frac{1}{2}((f_1+f_2+2b^2)^2+4(C_{\mathrm{XPM}}^2+b^2(f_1+f_2)-f_1f_2-b^4))^{1/2}.\tag{10}$$

（10）式解表明，当 $C_{\mathrm{XPM}}^2+b^2(f_1+f_2)-f_1f_2-b^4>0$ 时，K^2 有负值（K 有复数解），稳态解变的不稳定，由

$$C_{XPM}^2+b^2(f_1+f_2)-f_1f_2-b^4>0,\tag{11}$$

得

$$(\Omega^2-\Omega_+^2)(\Omega^2-\Omega_-^2)\leq\frac{64\gamma_1\gamma_2}{9|\beta_{21}||\beta_{22}|\mathrm{sgn}(\beta_{21})\mathrm{sgn}(\beta_{22})}P^2,\tag{12}$$

$$\Omega_+^2=\frac{\delta^2}{\beta_{21}^2}-\frac{12\gamma_1 P}{3|\beta_{21}|\mathrm{sgn}(\beta_{21})},\tag{12a}$$

$$\Omega_-^2=\frac{\delta^2}{\beta_{22}^2}-\frac{12\gamma_2 P}{3|\beta_{22}|\mathrm{sgn}(\beta_{22})}.\tag{12b}$$

解（12）有关 Ω 的方程得

$$\Omega_1^2\leqslant\Omega^2\leqslant\Omega_2^2,\tag{13}$$

其中

$$\Omega_1^2=\frac{1}{2}\Bigg\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|\mathrm{sgn}(\beta_{21})}+\frac{\gamma_2}{|\beta_{22}|\mathrm{sgn}(\beta_{22})}\right)-\Bigg[\Bigg(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|\mathrm{sgn}(\beta_{21})}-\frac{\gamma_2}{|\beta_{22}|\mathrm{sgn}(\beta_{22})}\right)\Bigg)^2+\frac{4\times64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|\mathrm{sgn}(\beta_{21})\mathrm{sgn}(\beta_{22})}\Bigg]^{1/2}\Bigg\},\tag{13a}$$

$$\Omega_2^2=\frac{1}{2}\Bigg\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|\mathrm{sgn}(\beta_{21})}+\frac{\gamma_2}{|\beta_{22}|\mathrm{sgn}(\beta_{22})}\right)+\Bigg[\Bigg(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|\mathrm{sgn}(\beta_{21})}-\frac{\gamma_2}{|\beta_{22}|\mathrm{sgn}(\beta_{22})}\right)\Bigg)^2+\frac{4\times64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|\mathrm{sgn}(\beta_{21})\mathrm{sgn}(\beta_{22})}\Bigg]^{1/2}\Bigg\}.\tag{13b}$$

定义：$g(\Omega)=2\mathrm{Im}(K)$，$g(\Omega)$ 代表频率 $\omega_0\pm\Omega$ 处对于原始频率 ω_0 的偏移 Ω 后的扰动的增益. 当 Ω 满足(13)式时，调制不稳定性存在，对应的增益为

$$\begin{aligned}g(\Omega)&=2\mathrm{Im}(K)\\&=(f_1+f_2+2b^2)-((f_1+f_2+2b^2)^2\\&\quad+4(C_{\mathrm{XPM}}^2+b^2(f_1+f_2)-f_1f_2-b^4))^{1/2}.\end{aligned}\quad(14)$$

显然产生调制不稳定性的区域和对应的增益与色散区的性质($\mathrm{sgn}(\beta_{21})$，$\mathrm{sgn}(\beta_{22})$)、输入频率($\gamma_i=\frac{n_2\omega_i}{cA_i}$ $(i=1,2)$)、群速度失配(δ)和输入功率 P 有关.

2.1. 两者同为正常色散区

当两偏振模同为正常色散区时($\mathrm{sgn}(\beta_{21})=1$，$\mathrm{sgn}(\beta_{22})=1$)，即沿着快轴偏振场的慢变包络和沿着慢轴偏振场的慢变包络同处在正常色散区，则由(13)式得

$$\begin{aligned}\Omega_1^2&=\frac{1}{2}\Bigg\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)\\&\quad-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}+\frac{\gamma_2}{|\beta_{22}|}\right)\\&\quad-\Bigg[\Bigg(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)\\&\quad-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}-\frac{\gamma_2}{|\beta_{22}|}\right)\Bigg)^2\\&\quad+\frac{4\times64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|}\Bigg]^{1/2}\Bigg\},\end{aligned}\quad(15\mathrm{a})$$

$$\begin{aligned}\Omega_2^2&=\frac{1}{2}\Bigg\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)\\&\quad-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}+\frac{\gamma_2}{|\beta_{22}|}\right)\\&\quad+\Bigg[\Bigg(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)\\&\quad-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}-\frac{\gamma_2}{|\beta_{22}|}\right)\Bigg)^2\\&\quad+\frac{4\times64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|}\Bigg]^{1/2}\Bigg\}.\end{aligned}\quad(15\mathrm{b})$$

对应的增益为

$$\begin{aligned}g(\Omega)_+&=2|\mathrm{Im}(K)|\\&=\Bigg(\frac{1}{4}\beta_{21}^2\Omega^4+\gamma_1|\beta_{21}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\\&\quad+\frac{1}{4}\beta_{22}^2\Omega^4+\gamma_2|\beta_{22}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\\&\quad-\Bigg(\Bigg(\frac{1}{4}\beta_{21}^2\Omega^4+\gamma_1|\beta_{21}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\\&\quad+\frac{1}{4}\beta_{22}^2\Omega^4+\gamma_2|\beta_{22}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\Bigg)^2\\&\quad-\frac{1}{36}\Omega^4\Big((3\beta_{21}^2\Omega^2-3\delta^2+12\gamma_1\beta_{21}P)\\&\quad\times(3\beta_{22}^2\Omega^2-3\delta^2+12\gamma_2\beta_{22}P)\\&\quad-64\gamma_1\gamma_2\beta_{21}\beta_{22}P^2\Big)\Bigg)^{1/2}.\end{aligned}\quad(16)$$

我们只考虑频率相对于原始频率的偏移 $+\Omega$ 后的扰动的增益谱，由 $\Omega_1^2=0$ 和 $\Omega_2^2=0$ 得

$$\begin{aligned}&\frac{1}{2}\Bigg\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}^2|}+\frac{\gamma_2}{|\beta_{22}^2|}\right)\\&-\Bigg[\Bigg(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)-\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}-\frac{\gamma_2}{|\beta_{22}|}\right)\Bigg)^2\\&+\frac{4\times64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|}\Bigg]^{1/2}\Bigg\}=0.\end{aligned}\quad(17)$$

解(17)式有关 P 的方程得

$$P=P_{\mathrm{C1}}\text{ 或 }P=P_{\mathrm{C2}},$$

其中

$$\begin{aligned}P_{\mathrm{C1}}&=\frac{9}{40}\left(\frac{\delta^2}{\gamma_2\beta_{22}}+\frac{\delta^2}{\gamma_1\beta_{21}}\right)\\&\quad-\frac{1}{2}\Bigg\{\Bigg[\frac{9}{20}\left(\frac{\delta^2}{\gamma_2\beta_{22}}+\frac{\delta^2}{\gamma_1\beta_{21}}\right)\Bigg]^2\\&\quad-\frac{9}{200}\frac{\delta^4}{\gamma_1\gamma_2\beta_{21}\beta_{22}}\Bigg\}^{1/2},\\P_{\mathrm{C2}}&=\frac{9}{40}\left(\frac{\delta^2}{\gamma_2\beta_{22}}+\frac{\delta^2}{\gamma_1\beta_{21}}\right)\\&\quad+\frac{1}{2}\Bigg\{\Bigg[\frac{9}{20}\left(\frac{\delta^2}{\gamma_2\beta_{22}}+\frac{\delta^2}{\gamma_1\beta_{21}}\right)\Bigg]^2\\&\quad-\frac{9}{200}\frac{\delta^4}{\gamma_1\gamma_2\beta_{21}\beta_{22}}\Bigg\}^{1/2}.\end{aligned}$$

所以，当 $P\leqslant P_{\mathrm{C1}}$ 时，$\Omega_2^2>0$，$\Omega_1^2>0$，沿着快轴偏振场的慢变包络产生调制不稳定性的频率区域为

$$\Omega_1^2\leqslant\Omega^2\leqslant\Omega_2^2.\quad(18\mathrm{a})$$

当 $P_{\mathrm{C1}}\leqslant P\leqslant P_{\mathrm{C2}}$ 时，$\Omega_1^2<0$，$\Omega_2^2>0$，产生调制不稳定性的频率区变为

$$0<\Omega^2<\Omega_2^2.\quad(18\mathrm{b})$$

当 $P\geqslant P_{\mathrm{C2}}$ 时，$\Omega_2^2<0$，$\Omega_1^2<0$，不产生调制不稳定性.

图 1 为正常色散区输入临界功率(P_{C1}，P_{C2})与波长差(或频率差)的关系，(其中选取 $\lambda_1=532\mathrm{nm}$，$\gamma_1=44.9/\mathrm{W}\cdot\mathrm{Km}$，$\beta_{21}=65.69\mathrm{ps}^2/\mathrm{Km}$，$\delta=1.9\mathrm{ps/m}$，$|\lambda-\lambda_1|\leqslant10\mathrm{nm}$，以下各图参数相同)并且认为在这一小范围内群速度色散(β_{22})随频率增加(或波长减

小)线性增加.从图可以看出,随着波长差(或频率差)的增加输入临界功率增大,当两波长相同时输入临界功率最小.

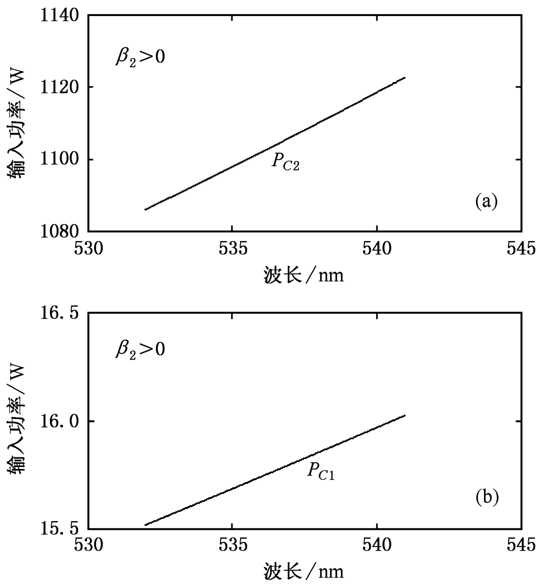

图 1 输入临界功率与波长的变化关系

图 2 为当 $P \leqslant P_{C1}$,输入功率一定时($P = 10W$),增益谱随波长差(或频率差)的变化关系.从图可以看出,随着波长差(或频率差)的增加增益谱的宽度变宽、强度增加,增益谱中心频率逐渐离开原始频率(ω_0).

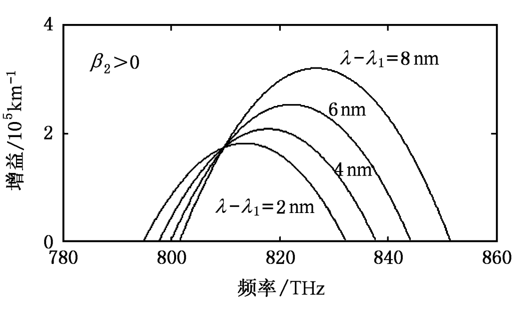

图 2 输入功率($P = 10W$)一定时不同波长差(或频率差)的调制不稳定性增益

图 3 为波长差一定时($\lambda - \lambda_1 = 2nm$)调制不稳定性增益随输入功率的关系,图 3 表明随着输入功率的增加增益谱的宽度加宽、强度增强,增益谱中心频率逐渐接近原始频率(ω_0).

图 4 为 $P_{C1} \leqslant P \leqslant P_{C2}$ 时,当波长差一定时($\lambda - \lambda_1 = 2nm$)调制不稳定性增益随输入功率的变化关系,从图 4 可以看出最初增益谱有两个增益谱旁瓣,

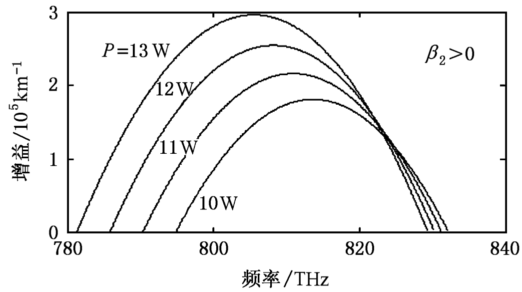

图 3 当波长差一定时($\lambda - \lambda_1 = 2nm$)调制不稳定性增益随输入功率的关系

并且,第一增益谱旁瓣的强度和宽度大于第二增益谱旁瓣的强度和宽度,当输入功率增大时,第一增益谱旁瓣的强度相对减弱和宽度相对变小;第二增益谱旁瓣的相对强度增强、相对宽度变大,但小于第一增益谱旁瓣的强度和宽度.随着输入功率的增大,第一增益谱旁瓣的强度继续减弱和宽度继续变小;第二增益谱旁瓣的相对强度增强、相对宽度变大,最后第一增益谱消失.以后随着输入功率的增强,增益谱强度增强、宽度变大,当输入功率达到一定数值时,增益谱强度达到最大,随着输入功率的进一步增大,增益谱强度减小、宽度变窄,增益谱中心频率逐渐接近原始频率(ω_0).

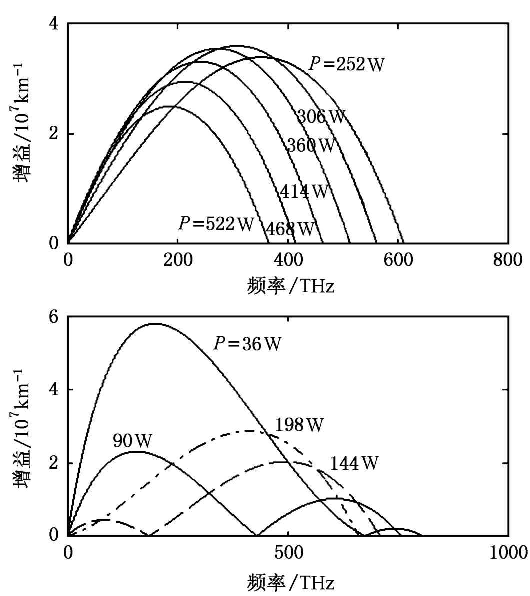

图 4 正常色散区,当波长差一定时($\lambda - \lambda_1 = 2nm$)调制不稳定性增益随输入功率的变化关系

图 5 表示 $P_{C1} \leqslant P \leqslant P_{C2}$,当输入功率一定时,调制不稳定性增益谱随不同波长差(或频率差)的变化

关系,图中波长差的变化间隔同图 2 相同,其中包含四条曲线,由于彼此靠的很近形成一个带,但仍可看出,随着波长差(或频率差)的增加增益谱的强度和宽度略有增加,增益谱中心频率基本保持一致.

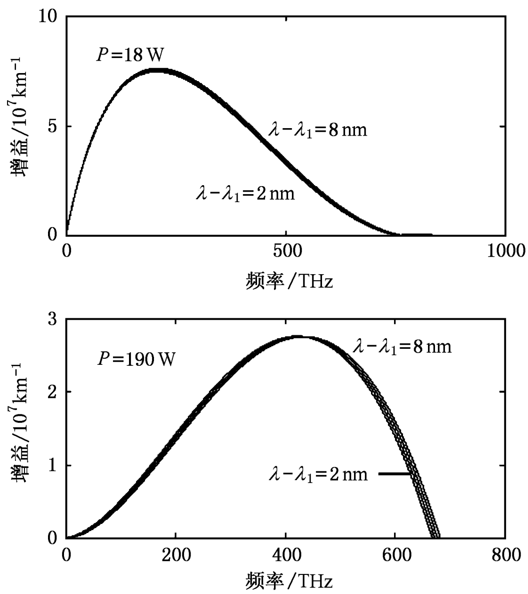

图 5 正常色散区输入功率一定时不同波长差(或频率差)的调制不稳定性增益

2.2. 两者同为反常色散区

当两偏振模同为反常色散区($\mathrm{sgn}(\beta_1) = -1$, $\mathrm{sgn}(\beta_2) = -1$),即沿着快轴偏振场的慢变包络和沿着慢轴偏振场的慢变包络同处在反常色散区,则由(13)式得

$$\Omega_3^2 = \frac{1}{2}\left\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)+\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}+\frac{\gamma_2}{|\beta_{22}|}\right)\right.$$
$$-\left[\left(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)+\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}-\frac{\gamma_2}{|\beta_{22}|}\right)\right)^2$$
$$\left.+\frac{4\times 64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|}\right]^{1/2}\right\}, \tag{19a}$$

$$\Omega_4^2 = \frac{1}{2}\left\{\delta^2\left(\frac{1}{\beta_{21}^2}+\frac{1}{\beta_{22}^2}\right)+\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}+\frac{\gamma_2}{|\beta_{22}|}\right)\right.$$
$$-\left[\left(\delta^2\left(\frac{1}{\beta_{21}^2}-\frac{1}{\beta_{22}^2}\right)+\frac{12P}{3}\left(\frac{\gamma_1}{|\beta_{21}|}-\frac{\gamma_2}{|\beta_{22}|}\right)\right)^2$$
$$\left.+\frac{4\times 64\gamma_1\gamma_2P^2}{9|\beta_{21}||\beta_{22}|}\right]^{1/2}\right\}. \tag{19b}$$

对应的增益为

$$g(\Omega)_- = 2|\mathrm{Im}(K)|$$
$$=\left(\frac{1}{4}\beta_{21}^2\Omega^4-\gamma_1|\beta_{21}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\right.$$
$$+\frac{1}{4}\beta_{22}^2\Omega^4-\gamma_2|\beta_{22}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2$$
$$-\left(\left(\frac{1}{4}\beta_{21}^2\Omega^4-\gamma_1|\beta_{21}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\right.\right.$$
$$\left.+\frac{1}{4}\beta_{22}^2\Omega^4-\gamma_2|\beta_{22}|P\Omega^2+\frac{1}{4}\delta^2\Omega^2\right)^2$$
$$-\frac{1}{36}\Omega^4\left((3\beta_{21}^2\Omega^2-3\delta^2-12\gamma_1\beta_{21}P)\right.$$
$$\times(3\beta_{22}^2\Omega^2-3\delta^2-12\gamma_2\beta_{22}P)$$
$$\left.\left.\left.-64\gamma_1\gamma_2\beta_{21}\beta_{22}P^2\right)\right)^{1/2}. \tag{20}$$

我们只考虑频率相对于原始频率的偏移 $+\Omega$ 后的扰动的增益谱,其中选取 $\lambda_1 = 532\mathrm{nm}$,$\gamma_1 = 44.9/\mathrm{W\cdot Km}$,$\beta_{21} = 65.69\mathrm{ps^2/Km}$,$\delta = 1.9\mathrm{ps/m}$,$|\lambda-\lambda_1| \leqslant 10\mathrm{nm}$,以下各图参数相同)并且认为在这一小范围内群速度色散(β_{22})随频率增加(或波长减小)线性减小.由(19a)和(19b)式可以看出,对于任何输入功率 P,$\Omega_3^2>0$,$\Omega_4^2>0$ 所以对于任何输入功率 P,当 $\Omega_3<\Omega<\Omega_4$ 时,产生调制不稳定性;对应的增益为(20)式.

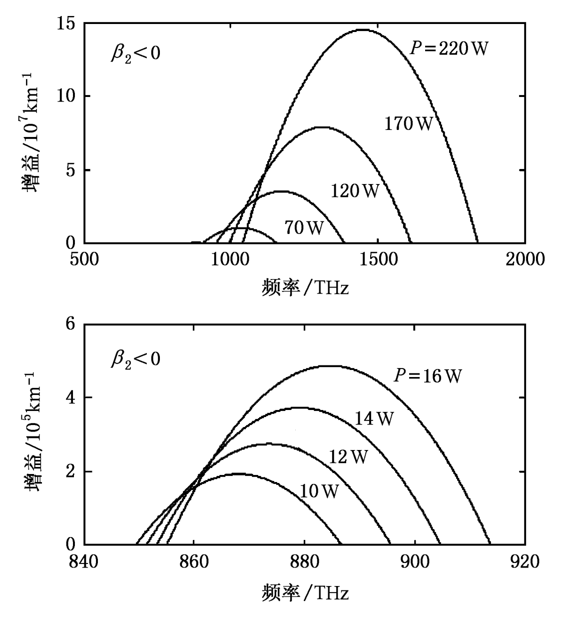

图 6 当波长差一定时($\lambda-\lambda_1 = 2\mathrm{nm}$)调制不稳定性增益随输入功率的关系

图 6 为 波长差一定时($\lambda-\lambda_1 = 2\mathrm{nm}$)调制不稳定性增益随输入功率的变化关系,图中显示当输入功率增加时,增益谱强度增强、宽度变宽,并且中心频率远离原始频率 ω_0.

图 7 为输入功率($P = 20\mathrm{W}$)一定时不同波长差

(或频率差)的调制不稳定性增益谱,从图 7 可以看出,随着波长差(或频率差)的增加增益谱的强度和宽度增加,增益谱中心频率趋向原始频率 ω_0.

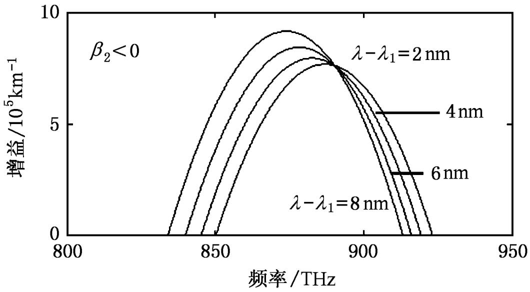

图 7 输入功率($P=20$W)一定时不同波长差(或频率差)的调制不稳定性增益

3. 结 论

在保偏光纤相近频率传输区,在反常色散区和正常色散区都能产生调制不稳定性.

在反常色散区对于任何输入功率 P,当 $\Omega_3<\Omega<\Omega_4$ 时,产生调制不稳定性,当波长差一定时($\lambda-\lambda_1=2$nm),其增益随输入功率的增加强度增强、宽度变宽,并且中心频率远离原始频率 ω_0;当输入功率一定时,随着波长差(或频率差)的增加增益谱的强度和宽度增加,增益谱中心频率趋向原始频率 ω_0.

在正常色散区,当 $P\leqslant P_{C1}$ 时,产生调制不稳定性的频率区域为 $\Omega_1^2\leqslant\Omega^2\leqslant\Omega_2^2$,输入功率一定时,增益谱随随着波长差(或频率差)的增加增益谱的宽度变宽,增益谱强度增加,增益谱中心频率逐渐离开原始频率(ω_0).波长差一定时($\lambda-\lambda_1=2$nm)增益随输入功率的增加增益谱的宽度加宽、强度增强,增益谱中心频率逐渐接近原始频率(ω_0).当 $P_{C1}\leqslant P\leqslant P_{C2}$ 时,产生调制不稳定性的频率区变为 $0<\Omega^2<\Omega_2^2$;当波长差一定时($\lambda-\lambda_1=2$nm)调制不稳定性增益随输入功率的变化最初增益谱有两个增益谱旁瓣,并且,第一增益谱旁瓣的强度和宽度大于第二增益谱旁瓣的强度和宽度,当输入功率增大时,第一增益谱旁瓣的强度相对减弱和宽度相对变小;第二增益谱旁瓣的相对强度增强、相对宽度变大,但小于第一增益谱旁瓣的强度和宽度.随着输入功率的增大,第一增益谱旁瓣的强度继续减弱和宽度继续变小;第二增益谱旁瓣的相对强度增强、相对宽度变大,最后第一增益谱消失.以后随着输入功率的增强,增益谱强度增强、宽度变大,当输入功率达到一定数值时,增益谱达到最大,随着输入功率的进一步增大,增益谱强度减小、宽度变窄,增益谱中心频率逐渐接近原时频率(ω_0).当输入功率一定时,调制不稳定性增益谱随着波长差(或频率差)的增加增益谱的强度和宽度略有增加,增益谱中心频率基本保持一致.当 $P\geqslant P_{C2}$ 时,不产生调制不稳定性.

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Modulation instability of near frequency propagation regime in polarization-maintaining fibers*

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Abstract

The coherently coupled nonlinear Schrödinger (NLS) equation of the propagation of a light pulse in a fiber has been utilized. We have studied modulation instability of linearly polarized lights with near frequency not only in anomalous dispersion regime but also in normal dispersion regime in polarization-maintaining fibers, when the polarization direction along the two birefringence axes are orthogonal and the intensities along the two birefringence axes are equal. The results show that modulation instability can be produced both in anomalous and normal dispersion regimes. The input pulses have obviously different gain spectra when input power regime is different in normal dispersion regime. Furthermore, the gain spectra are different for different wave lengths (or different frequencies) when the power of input pulse is kept constant.

Keywords: near frequency propagation regime, birefringence, polarization-maintaining fibers, modulation instability

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