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Raman effect on the polarization state in low-birefringence fiber

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Abstract. In low birefringence fiber, by solving the coupled nonlinear Schrodinger equations contained the Raman effect for satisfy right- and left-handed circularly polarized light in the quasi-CW case, the relationship between the effective polarization beat length and changes of input power have been studied emphatically in low- and high input power situation considering the Raman effect or not. The results showed that the polarization state evolution cycles of the incident light can be changed and meanwhile the transmission distance of the incident light also can be changed due to Raman effect, regardless of the polarization of the incident light was along the slow axis or along the fast axis.

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Key words: low-birefringence optical fiber, Raman effect, state of polarization

1 Introduction

Since the polarization instability of optical fiber was first observed in experiments, which has been attracted the interests in the research quickly. In the same year, H. G. Winful made qualitative explanation about polarization instability, and described the instability of polarization coupled equations and the phase-plane method in 1993. Then the articles on the polarization instability and nonlinear effects in related fields domestic and abroad have been published constantly [1], while the relationship between the polarization instability and Raman effect instead. According to this background, this article set the main body for Raman effect is how to influence the effective polarization beat length and changes of the input power.

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For some non-coherent communication applications, the polarization state should maintain stability when pulse propagating in optical fiber. In such requirements, polarization maintaining fiber [2] emerges as the times require including high birefringence fiber and low birefringence fiber. Compared to the ordinary optical fiber, low birefringence optical fiber [3-6] has good polarization properties. Application prospects are brighter in communication field, as well as in the non-communication field, such as optical fiber sensor [7-10] and fiber laser [11].

However, a series of new nonlinear effects are produced with the increase of input power in low birefringence fiber, for example, Raman effect generated by light and optical phonon interaction. The Raman effect will cause the polarization instability, which will bring a lot of trouble. The instability of polarization not only makes the signal amplitude changes, but also causes the signal waveform distortion. Even it can damage the quality of optical communication and the reliability of signals when serious. So the study of Raman effect has important realistic significance to the state of polarization.

In this paper, in low birefringence fiber, by solving the coupled nonlinear Schrodinger equations contained the Raman effect for satisfy right- and left-handed circularly polarized light in the quasi-CW case, the relationship between the effective polarization beat length and changes of input power have been studied emphatically in low- and high input power situation considering the Raman effect or not.

2 Theoretical model

In low birefringence fiber, the coupled nonlinear Schrodinger equations contained the Raman effect for satisfy right- and left-handed circularly polarized light in the quasi-CW case

$$\frac{\partial A_+}{\partial z}=\frac{i\Delta\beta}{2}A_-+\frac{2}{3}i\gamma'[\|A_+\|^2+2\|A_-\|^2]A_+, \tag{1}$$

$$\frac{\partial A_-}{\partial z}=\frac{i\Delta\beta}{2}A_++\frac{2}{3}i\gamma'[2\|A_+\|^2+2\|A_+\|^2]A_-, \tag{2}$$

where $\Delta\beta=2\pi/L_B$ and $\gamma'=\gamma-\frac{3}{32}g''*(\Omega)$.$\Delta\beta$ is related to the modal birefringence of the fiber, and γ is the nonlinear coefficient of electrons, $g''*(\Omega)$ is parallel Raman gain [12-13]. The A_+ and A_- represent right- and left-handed circularly polarized states.

Consider first the low-power case and neglect the nonlinear effects, the solution is given by

$$A_+(z)=\sqrt{P_0}\cos(\pi z/L_B), \tag{3}$$

$$A_-(z)=\sqrt[i]{P_0}\sin(\pi z/L_B), \tag{4}$$

when the nonlinear effect can not be ignored, we get the normalized power p_+, p_- and the phase difference $\Psi=\phi_+-\phi_-$, we use [14]

$$A_\pm=(\frac{3\Delta\beta}{2\gamma'})^{\frac{1}{2}}\sqrt{P_\pm}\exp(i\phi_\pm), \tag{5}$$

and obtain the following three equations

$$\frac{dp_+}{dz} = 2_K\sqrt{p_+p_-}\sin\Psi, \tag{6}$$
$$\frac{dp_-}{dz} = -2_K\sqrt{p_+p_-}\sin\Psi, \tag{7}$$
$$\frac{d\Psi}{dz} = K(\frac{p_- - p_+}{\sqrt{p_+p_-}})\cos\Psi + 2_K(p_- - p_+), \tag{8}$$

these equations have the following two quantities that remain constant along the fiber [15]

$$p = p_+ + p_-, \tag{9}$$
$$\Gamma = \sqrt{p_+p_-}\cos\Psi + p_+p_-. \tag{10}$$

Where p is the normalized input power and P_{cr} is critical power and given by

$$P_{cr} = \frac{3|\Delta\beta|}{2\gamma'}. \tag{11}$$

q is defined as

$$q = 1 + p\exp(i2\theta_0), \tag{12}$$

here $\theta_0 = \frac{1}{2}\Psi_0$. The solution for p_+ is [15]

$$p_+(z) = \frac{1}{2}\left(p - 2[|q| - Re(q)]^{\frac{1}{2}}cn(x|m)\right) \tag{13}$$

where is a Jacobi elliptic function with the argument

$$x = 2_{KZ}|q|^{\frac{1}{2}} + K(m), \tag{14}$$

$K(m)$ is the quarter period, and m is defined as

$$m = \frac{1}{2}[1 - Re(q)/|q|]. \tag{15}$$

Both p_- and Ψ can be obtained in terms of $p_+(z)$ using Eq. (9) and Eq. (10). One can use the analytic solution to find the "fixed points" in the phase space. A fixed point represents a polarization state that does not change as light propagates inside the fiber. Below the critical power ($p<1$), light polarized linearly (e_p=0) along the slow and fast axes $\theta = 0$ and $\theta = \frac{\pi}{2}$ represents two stable fixed points. At the critical power (p=1) the fast-axis fixed point exhibits a pitchfork bifurcation. Beyond this power level, the linear-polarization state along the fast axis becomes unstable, but two new elliptically polarized states emerge as fixed points [14]. The period of the elliptic function in Eq. (12) determines the effective beat length as

$$L_p = \frac{2K(m)}{\sqrt[\pi]{|q|}}L_0, \tag{16}$$

where L_0 is the low-power beat length.

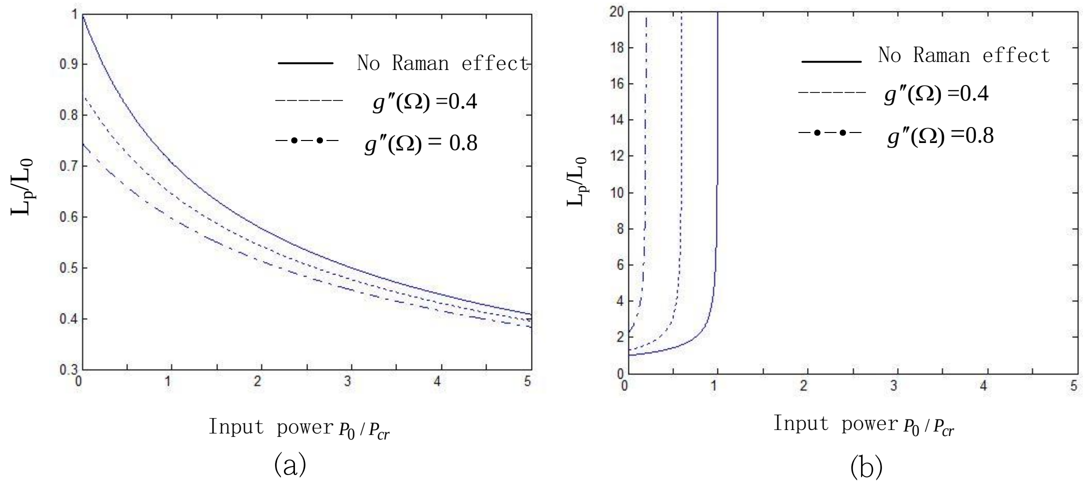

Figure 1: (a) The relationship between the effective polarization beat length and the input power when the parallel Raman gains are 0, 0.4, 0.8 respectively. (b) The relationship between the effective polarization beat length and the input power when the parallel Raman gains are 0, 0.4, 0.8 respectively.

3 Result Analysis and Discussion

3.1 The incident light polarized close to the slow axis when polarization angle is 0°

When polarization angle is 0°, the effective polarization beat length becomes $(1+p)^{\frac{1}{2}}L_0$. Fig. 1 shows the relationship between the effective polarization beat length and the input power using the parameter values $\Delta\beta$=4.0515$\times10^3 M^{-1}$, P_0=65KW, and the parallel Raman gain are 0, 0.4, 0.8 respectively.

In all three cases shown in Fig. 1, the effective polarization beat length L_p decreases monotonously as the input power p increases, if Raman effect is neglected. While considering the Raman effect, with the increase of parallel Raman gain $g''(\Omega)$ and the input power p, the effective polarization beat length L_p also decreases monotonically, but the amplitude tends to level out. At the same input power p, the effective polarization beat length L_p decreases with the increase of parallel Raman gain $g''(\Omega)$, compared with Raman effect is ignored. The results show that considering the Raman effect, the effective polarization beat length L_p decreases, and accelerates the periodic change of polarization state of the incident light, at the same time the transmission distance of the incident light reduces in a cycle when the polarization angle $\theta=0°$, the incident light polarized close to the slow axis.

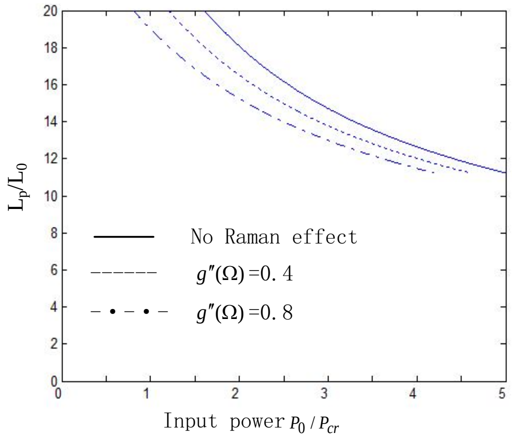

Figure 2: The relationship between the effective polarization beat length and the input power when the parallel Raman gains are 0, 0.4, 0.8 respectively.

3.2 The incident light polarized close to the fast axis when polarization angle is L_p

When polarization angle is 90° and the input power $p<1$, the effective polarization beat length becomes $(1-p)^{\frac{1}{2}}L_0$. Fig. 2 shows the relationship between the effective polarization beat length and the input power using the parameter values $\Delta\beta$=4.0515×$10^3 m^{-1}$, P_0=65KW, and the parallel Raman gain $g''(\Omega)$ are 0, 0.4, 0.8 respectively.

In all three cases shown in Fig. 2, the effective polarization beat length L_p becomes longer with the increase of input power p in a situation Raman effect is ignored. When the input power p reaches a critical value, the effective polarization beat length L_p becomes infinite. Considering the Raman effect, with the increase of parallel Raman gain $g''(\Omega)$, the effective polarization beat length L_p becomes infinite as the corresponding input power threshold becomes smaller. When the input power p is less than the critical value, the effective polarization beat length L_p increases under the same input power p with the increase of the parallel Raman gain $g''(\Omega)$. The results show that the polarization state evolution cycle is retarded by Raman effect when the incident light polarized close to the fast axis, meanwhile the transmission distance is increased in a period.

If the input power $p>1$, the effective polarization beat length becomes $(p\text{-}1)^{\frac{1}{2}}L_0$. Fig. 3 shows that the relationship between the effective polarization beat length and the input power using the parameter values $\Delta\beta$=4.0515×$10^3 m^{-1}$, P_0=65KW, and the parallel Raman gain $g''(\Omega)$ are 0, 0.4, 0.8 respectively.

In all three cases shown in Fig. 3, the effective polarization beat length L_p is reduced with the increase of input power p, whether the Raman effect is neglected or not. Considering Raman effect, the effective polarization beat length L_p decreases more quickly with the increase of parallel Raman gain $g''(\Omega)$ than the situation that Raman effect is ignored. However, if the parallel Raman gain $g''(\Omega)$ is constant, with the increase of input power p, the effective polarization beat length L_p decreases. When the input power p is relatively smaller, increasing the parallel Raman gain $g''(\Omega)$, the effective polarization beat length L_p decreases greatly compared with Raman effect is ignored. The results show that with the further increase of input power p, whether considering the Raman effect or not, the effective polarization beat length L_p is reduced when the polarization angle θ=90°, and the incident light polarized close to the fast axis. When considering the Raman effect, the Raman effect exhibits with the incident light polarized close to the slow axis similar circumstance, Raman effect accelerates the polarization state evolution cycles of the incident light, and the transmission distance decreases during a period.

4 Conclusion

Considering the Raman effect in low birefringence fiber, Raman effect accelerates the polarization state evolution cycles of the incident light and the transmission distance decreases in a cycle when the incident light polarized close to the slow axis (θ=0°). Raman effect slows down the polarization state evolution cycles of the incident light, and makes the transmission distance of the incident light increases in a period when the incident light polarized close to the fast axis (θ=90°), and the input power $p<1$. However, at power levels such that $p>1$, the polarization evolution is similar to incident light is polarized close to the slow axis case. In a word, not only the polarization state evolution period but also the transmission distance of the incident light can be changed due to Raman effect, whether the incident light is polarized along the slow axis or the fast axis.

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