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FM-AM Conversion Induced by Polarization Mode Dispersion in Fiber Systems *

HUANG Xiao-Dong(黄小东)[1,2], WANG Jian-Jun(王建军)[2]**, LI Ming-Zhong(李明中)[2], XU Dang-Peng(许党朋)[2], LIN Hong-Huan(林宏奂)[2], ZHANG Rui(张锐)[2], DENG Ying(邓颖)[2], ZHANG Xiao-Min(张小民)[2], ZHAO Sheng-Zhi(赵圣之)[1]

[1]*School of Information Science and Engineering, Shandong University, Jinan 250100*
[2]*Research Center of Laser Fusion, China Academy of Engineering Physics, PO Box 919-988, Mianyang 621900*

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The conversion of the frequency modulated pulse induced from frequency modulation (FM) to amplitude modulation (AM) by the polarization mode dispersion (PMD) is theoretically and experimentally investigated. When there is no polarizer at the output end of a fiber system, the amplitude modulation depth is stable by 8%. Random amplitude modulation is observed when a polarizer is placed at the output end of the fiber system. The observed minimum and maximum modulation depths in our experiment are 5% and 80%, respectively. Simulation results show that the amplitude modulation is stable by 4% induced mainly by group velocity dispersion (GVD) when there is no polarizer, and the amplitude modulation depth displays the random variation character induced by the GVD and PMD. Lastly, a new fiber system scheme is proposed and little amplitude modulation is observed at the top of the output pulse.

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Frequency modulated laser was widely used in most front end systems of the high power laser facility for two main purposes.[1,2] First, it could suppress the buildup of stimulated Brioullin scattering (SBS) in the large aperture laser optics. Second, it was required for smoothing the illuminated speckle pattern of the target by spectral dispersion method (SSD). A large number of effects could bring the FM-AM conversion.[3−8] All these effects belong to non-uniform spectral transmission. So far, most works contributed to FM-AM conversion were focused on the characters of these effects. Especially in the fiber front end system, the effects of group velocity dispersion (GVD), the connection of polarization-maintaining fibers, and the gain narrowing were theoretically and experimentally investigated, but little work was mentioned about the polarization mode dispersion (PMD) in the single mode fiber (SMF). It is well known that the polarization of the pulse could change randomly due to the PMD, which has been widely studied in the communication field.[9−14] Because the frequency modulated pulse is very sensitive to the polarization perturbation, then FM-AM conversion would occur when the frequency modulated pulse passed the polarizer.

In this Letter, we theoretically and experimentally investigate the PMD effect of the single mode fiber. The results indicate that random polarization mode coupling occurs due to the PMD effect, and weak FM-AM conversion induced by GVD can be obtained when the frequency modulated pulse transmits through a long single mode fiber. However, strong FM-AM conversion occurs when the pulse passes through the polarizer successively, and this amplitude modulation is random, which is detrimental to the fiber system.

Polarization mode dispersion was widely studied for its limitation to the optical fiber communication systems, and many models were used to describe the PMD effect of single mode fibers.[15−17] In this study, we choose the nonlinear Schrödinger equation because of its several effects in the fibers, such as PMD, GVD, and nonlinearity. Taking all these effects into account, we have

$$i\frac{\partial \boldsymbol{A}}{\partial z} + b\sum \boldsymbol{A} + ib'\sum \frac{\partial \boldsymbol{A}}{\partial t} - \frac{1}{2}\beta''\frac{\partial^2 \boldsymbol{A}}{\partial t^2} + n_2 k_0\left[\frac{5}{6}|\boldsymbol{A}|^2\boldsymbol{A} + \frac{1}{6}(\boldsymbol{A}^+\sigma_3\boldsymbol{A})\sigma_3\boldsymbol{A} + \frac{1}{3}\boldsymbol{B}\right] = 0. \quad (1)$$

Equation (1) is suitable for a single mode fiber with randomly varying birefringence orientation. Here $\boldsymbol{A} = (A_1, A_2)^t$ is a column vector with elements, A_1 and A_2 are the complex envelopes of the two polarization components. The vector $\boldsymbol{B}$ is defined as $(A_1^* A_2^2, A_1^2 A_2^*)^t$, where the asterisks designate the complex conjugation. The z-coordinate measures the distance along the fiber axis, while the t-coordinate represents the retarded time-the time relative to the moving center of the signal. The matrix $\sum = \sigma_3\cos(2\alpha) + \sigma_1\sin(2\alpha)$, and σ_1, σ_2, σ_3 are Pauli's matrices defined as

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},\ \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix},\ \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (2)$$

It is assumed that the orientation of the axes of birefringence is only a weak function of the frequency by

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**Email: wjjcaep@126.com

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using the matrix $\sum$ in the second and third terms of Eq. (1), n_2 is the nonlinear Kerr coefficient and k_0 represents the wave-number in the vacuum, it is assumed that $\beta_1'' \approx \beta_2'' = \beta''$. The birefringence $b = (\beta_1 - \beta_2)/2$, β_1, β_2 are the propagation constant for A_1 and A_2; $b' = db/d\omega = (\beta_1' - \beta_2')/2$ represents the group delay per length.

We numerically solve Eq. (1) by the split-step operator technique. The linear parts of Eq. (1) can be expressed as

$$i\frac{\partial \boldsymbol{A}}{\partial z} + b\sum \boldsymbol{A} + ib'\sum \frac{\partial \boldsymbol{A}}{\partial t} - \frac{1}{2}\beta''\frac{\partial^2 \boldsymbol{A}}{\partial t^2} = 0. \quad (3)$$

The nonlinear parts are

$$i\frac{\partial \boldsymbol{A}}{\partial z} + n_2 k_0\left[\frac{5}{6}|\boldsymbol{A}|^2\boldsymbol{A} + \frac{1}{6}(\boldsymbol{A}^+\sigma_3\boldsymbol{A})\sigma_3\boldsymbol{A} + \frac{1}{3}\boldsymbol{B}\right] = 0. \quad (4)$$

Equation (3) can be numerically solved by using the Jones matrices, and Eq. (4) can be solved by split-step Fourier transform. The frequency modulated pulse is linearly polarized and can be expressed as

$$A_1 = \exp\Big[-\Big(\frac{t}{t_0}\Big)^{2m} + im\sin(2\pi f_m t)\Big]. \quad (5)$$

Thus the input linearly polarized optical field vector can be described as $\boldsymbol{A} = (A_1, 0)^t$, where t_0 is the pulse width, m is the modulation depth of the frequency modulator, f_m is the modulation frequency of the frequency modulator.

The PMD effect in the single mode fiber and the FM-AM conversion are numerically simulated. In our fiber system, the pulse width t_0 is 3 ns, the modulation frequency of the frequency modulator f_m is 2 GHz, and the bandwidth of the pulse is 0.3 nm, the GVD coefficient β'' is 15 $\mathrm{ps}^2/\mathrm{km}$, the nonlinear Kerr coefficient $n_2 \approx 2.6 \times 10^{-20}\,\mathrm{m}^2/\mathrm{W}$, the PMD parameters $D_p = 2\,\mathrm{ps}/\mathrm{km}^{1/2}$, the beat length and fiber correlation length are 50 m and 100 m, respectively.[17] Figure 1 shows the relative pulse intensities of A_1 and A_2 after the frequency modulated pulse transmitting 150 m in a single mode fiber. We can find two independently simulation results under the same boundary condition and parameters. Figures 1(a) and 1(c) show the output optical fields with the polarization as the same as A_1. Figures 1(b) and 1(d) shows the optical fields at the polarization of A_2. It is apparent that the amplitude modulation and the power proportion of the two orthogonal fileds are different, and their difference is inevitable if there are more simulation results. Here we just list the arbitrary two simulation results to show the random character of the PMD in the single mode fiber. When there is no polarizer at the output of the single mode fiber, the combination optical field is shown in Fig. 2, in which the calculation times are also 50, and the parameters are the same as Fig. 1. It is shown that the amplitude modulation depth of the output pulse is stable, which is about 4%.

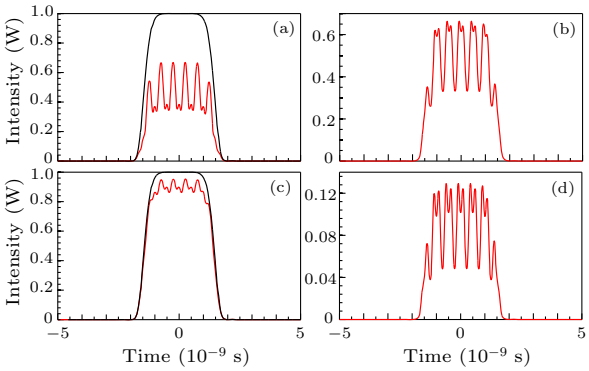


Fig. 1. Random polarization coupling and amplitude modulation of the two orthogonal optical field at the output of 150 m single mode fiber. (a) and (c) Input linear polarized pulse A_1 (black line) and the output pulse (red line) withthe same polarization as A_1. (b) and (d) Output pulse withthe same polarization as A_2 (red line) and input $A_2 = 0$.

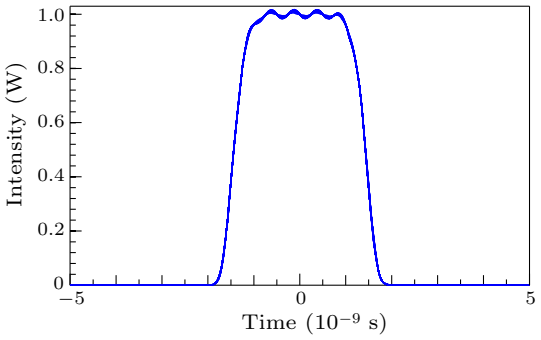


Fig. 2. Combination of A_1 and A_2 for independent simulation of 50 times.

The modulation depth is much larger than that under the only effect of GVD (about 1.4%), and the amplitude modulation at the top of the pulse displays random distortion, as shown in Fig. 2. This is because the transfer-function for the single mode fiber can be expressed as[11]

$$\boldsymbol{T}(\omega) = e^{-\alpha L}e^{-j\overline{\beta}(\omega)L}\boldsymbol{M}(\omega), \quad (6)$$

where $\boldsymbol{M}(\omega) = \boldsymbol{R}^{-1}(\omega)\boldsymbol{D}(\omega)\boldsymbol{R}(\omega)$, which is the combination of PMD matrices $\boldsymbol{D}(\omega)$ and rotation matrices $\boldsymbol{R}(\omega)$; $\overline{\beta}(\omega)$ represents the dispersion, and α is the fiber loss. The matrices for $\boldsymbol{M}(\omega)$ can be expressed as

$$\boldsymbol{M}(\omega) = \begin{pmatrix} u_1(\omega) & u_2(\omega) \\ -u_2^*(\omega) & u_1^*(\omega) \end{pmatrix}, \quad (7)$$

$$u_1(\omega) = \cos(\Delta\phi/2) + i\sin(\Delta\phi/2)\cos(2\theta)\cos(2\varepsilon), \quad (8)$$

$$u_2(\omega) = \sin(\Delta\phi/2)[\sin(2\varepsilon) + i\sin(2\theta)\cos(2\varepsilon)], \quad (9)$$

where $\Delta\phi(\omega) = \Delta\phi + \Delta\phi_1\omega + \Delta\phi_2\frac{\omega^2}{2} + \cdots$ is the different phase delay (DGD) of the fiber induced by PMD, and $\Delta\phi_n = \frac{\partial^n(\beta_x - \beta_y)}{\partial\omega^n}$. The parameters θ and

ε represent the random ellipticity angle and elliptical azimuth angle of the principle states of polarization (PSP), respectively, which are also the function of ω. Thus the output optical field can be described as

$$\boldsymbol{A}_{\rm out} = \boldsymbol{T} \cdot \boldsymbol{A}_{\rm in}. \tag{10}$$

Thus, for linearly polarized pulse $\varepsilon = 0$, using Eq. (5) and Eqs. (6)–(10), the output optical field becomes

$$\begin{pmatrix} A_{1\rm out}(\omega) \\ A_{2\rm out}(\omega) \end{pmatrix} = \begin{pmatrix} a_1 \exp(i\phi - i\overline{\beta}(\omega)L)A_1(\omega) \\ a_2 \exp(i\pi - i\overline{\beta}(\omega)L)A_1(\omega) \end{pmatrix}, \tag{11}$$

$$a_1 = \sqrt{\cos^2\frac{\Delta\phi}{2} + \sin^2\frac{\Delta\phi}{2}\cos^2 2\theta},$$

$$a_2 = \sin\frac{\Delta\phi}{2}\sin 2\theta, \quad \phi = \arctan\left(\tan\frac{\Delta\phi}{2}\cos 2\theta\right),$$

where $A_1(\omega)$ is the Fourier transformation of Eq. (5). Equation (11) shows that the two orthogonal optical fields contain the effect of GVD, the random amplitude and the phase related to the DGD and the random rotation of PSP.

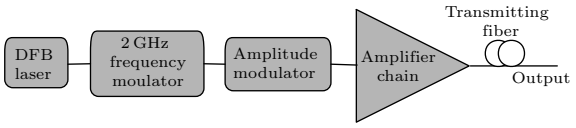


Fig. 3. The initial experimental scheme.

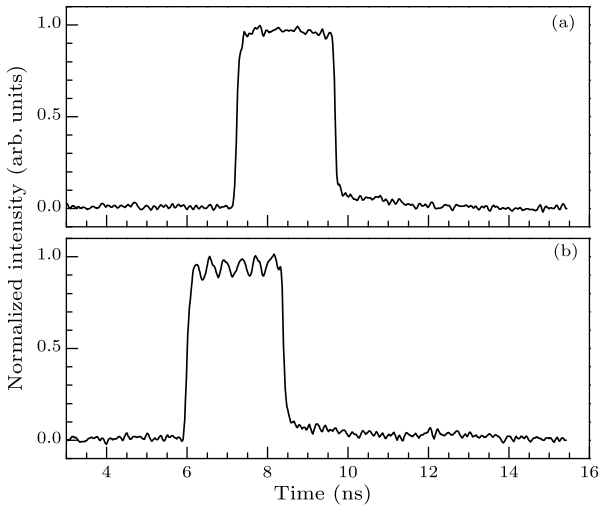


Fig. 4. Experimental results: (a) output pulse from the frequency modulator, (b) output pulse from the fiber system.

The fiber most used in our fiber front end systems is a single mode fiber, so we have experimentally studied the FM-AM conversion induced by PMD. The experimental scheme is shown in Fig. 3. The continuous laser with single frequency was frequency-modulated by a 2 GHz wave guide frequency modulator, then the frequency modulated laser transitted into an amplitude modulator. The output pulse was modulated as a pulse train and the single pulse width is 3 ns with repetition of 1 KHz. The pulse train was amplified by the amplifier chain, and transmitted by a 50-m-long single mode fiber before entering. The peak intensity of the output pulse train is 1 W, and the total fiber length in the system is about 150 m. The nonlinear coefficient for the single mode fiber is $\gamma \approx 2\,\mathrm{W}^{-1}\mathrm{km}^{-1}$, and the nonlinear length $L_{\rm NL} = 1/\gamma P$. Thus the nonlinear length is far larger than the total fiber length in our system, and the nonlinear effect can be ignored.

The output pulse from the amplitude modulator is shown in Fig. 4(a). We can find that no amplitude modulation appears. The gain bandwidth of the fiber amplifier in the amplifier chain is about 20 nm, and the total gain in the system is about 60 dB, so the amplitude modulation induced by the gain narrowing is less than 1%.[6] The pulse output from the fiber system is shown in Fig. 4(b). When there is no polarizer at the output end of the fiber system, the amplitude modulation on the pulse is stable by 8% for long-time observation, which is about 30 min. The little differences between the experimental results and simulation may be induced by the acousto-optic switch in the amplifier chain for suppressing ASE.

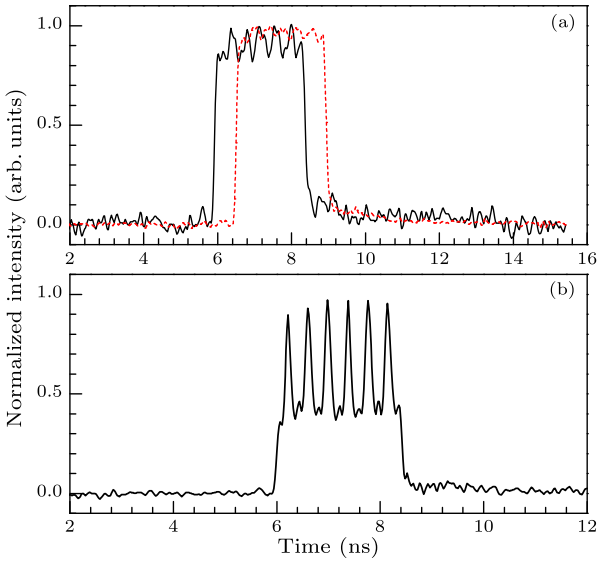


Fig. 5. Output pulse from the fiber system with a polarizer placed at the output end: (a) random amplitude modulation induced by PMD, (b) strong amplitude modulation induced by fiber distortion.

When a polarizer is placed at the output end of the fiber system, the pulse is displayed with random amplitude modulation, as shown in Fig. 5. The modulation depth randomly varies between 5% and 20%, as shown in Fig. 5(a). However, when there is fiber distortion at the output end of the fiber system, the modulation depth is enhanced to 80%, as shown in Fig. 5(b).

As mentioned above, the frequency modulated pulse could not transmit in the single mode fiber for

a long length, and the random PMD can induce the random FM-AM conversion. Thus we improve our fiber system as shown in Fig. 6. The frequency modulator is placed later, which is behind the amplifier chain, and the output of the frequency modulator is connected with polarization-maintaining fiber (PMF). One PMF of about 3 m is used as the transmitting fiber to avoid the PMD in the single mode fiber, then the polarizer is placed at the output end of the PMF with the same polarization orientation. There is little amplitude modulation at the top of the output pulse (< 1%), which may be induced by the imperfect matching between the polarization orientation of the PMF and the polarizer,[6] as shown in Fig. 7.

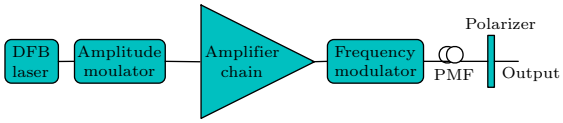


Fig. 6. The improved fiber system scheme.

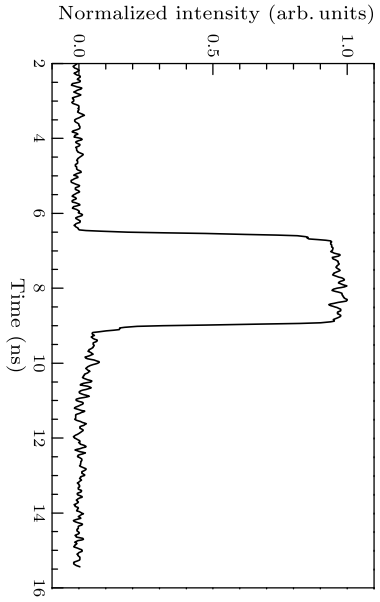


Fig. 7. The output pulse from the fiber system shown in Fig. 6.

We theoretically and experimentally study the character of frequency modulated pulse transmitting in the single mode fiber. When there is no polarizer placed at the output end of the fiber system, stable amplitude modulation depth is observed at the top of the pulse. However, when a polarizer is placed at the output of the fiber system, the amplitude modulation presents a random fluctuation as a result of the PMD in the single mode fiber. To our knowledge, it is the first time to investigate the effect of PMD on the frequency modulated pulse. The random amplitude modulation could induce the power imbalance among the beams irradiating on the target in high power laser facility. Lastly, we propose a new fiber system scheme to avoid the frequency modulated pulse transmitting in the single mode fiber, and the output pulse after the polarizer from the fiber system has little amplitude modulation (<1%).

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