Gaussian pulse transmission over ultra-high PMD fiber

NING Tigang (宁提纲), TAN Zhongwei (谭中伟), LI Tangjun (李唐军), FU Yongjun (傅永军), LIU Yan (刘 艳), PEI Li (裴 丽) & JIAN Shuisheng (简水生)

Institute of Lightwave Technology, Northern Jiaotong University, Beijing 100044, China
Correspondence should be addressed to Jian Shuisheng (email: ntigang@163.com)

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Abstract Experiment was conducted to study Gaussian pulse transmission over ultra-high PMD fiber. Gaussian pulse is broken into a series of deformed pulses when it transmits over ultra-high PMD fiber. It is indicated that the walk-off deformed pulses were caused by ultra-high PMD. Transmitted experiment has been done using fiber with PMD coefficient 237.95ps/km$^{1/2}$. The result of the experiment is consistent with the simulated one.

Keywords: polarization mode dispersion, ultra-high PMD fiber, optical fiber communication, coupled nonlinear Schrödinger equations, Monte Carlo simulation.

The increasing demand for bandwidth is driving most telecommunication operators to use large capacity transmission systems. When chromatic dispersion and loss in optical fiber no longer limit the data-rate transmission systems, polarization mode dispersion (PMD) could become the key factor to update high-performance optical transmission and networks. In high bit rate optical communication systems beyond 10 Gbps, signal distortion caused by PMD is a major limitation to transmission distance[1—3]. PMD is a distortion arising from unwanted birefringence in optical fiber. Real fibers are never perfect, of course, and have slight asymmetries or other perturbations that bring the degeneracy, leading to two polarization states with slightly different phases and velocities, a phenomenon known as PMD. Since the birefringence of a fiber changes randomly along a fiber link and time-dependent variation, polarization mode dispersion is a statistically random quantity. Polarization mode dispersion represents the major impairment for high bit-rate systems resulting in pulse broadening and distortion, which in turn lead to system performance degradation[4].

Present-day fibers have a 0.1 ps/km$^{1/2}$ PMD coefficient, while many of the installed fibers before the 1990s had higher PMD coefficient, say, more than 10ps/km$^{1/2}$, so the PMD had 200 ps when light pulse transmitted over 400km[5,6]. Gauss pulses must go through high PMD when optical link PMD is compensated by using nonlinear fiber Bragg grating, for nonlinear fiber Bragg gratings written by polarization maintaining fiber have PMD beyond 300 ps. Therefore, it is necessary to study transmission effect over high PMD fibers in order to update optical fiber network to high bit rate system. We simulate Gaussian pulse transmission over high PMD fiber by coupled nonlinear Schödinger equation (CNLS). The simulated result shows that Gaussian pulse gets deformed when they go through high-PMD fiber. Then we carry out a PMD experiment using fiber with 237.95 ps/km$^{1/2}$ PMD coefficient. The result of the experiment is consistent with the simulated one.

1 Background of theory

Poole and Wagner[4] introduced a phenomenological model of polarization mode dispersion in long optical fiber in which two orthogonal input and output principal states of polarization were identified in an analogous way in the eigenmodes of an uncoupled system. This theory is a useful tool for studying polarization mode dispersion. PMD of fiber is a stochastic variable, which is affected by temperature, environment, and time. In the simplest birefingence model[5] it is assumed that the birefingence strength $\delta\beta$ remains constant and the orientation angle φ is driven by the white-noise process. In other words, the fiber is modeled by dividing it into m segments, each of which is characterized by a local differential group delay τ_i or the local birefingence strength $\delta\beta$, with axes of given orientation angle φ (wavelength is assumed to be independent). The Jones matrices J, which consists of the Jones matrices B_i and R_i at the angular frequency ω correspond to the ith delay element and rotation respectively[7,8]:

$$J(\omega)=\prod_{i=m}^{1}B_i(\omega)R(\varphi_i)=\prod_{i=m}^{1}\begin{bmatrix}\exp(jw_i) & 0\\ 0 & \exp(-jw_i)\end{bmatrix}\begin{bmatrix}\cos(\varphi_i) & \sin(\varphi_i)\\ -\sin(\varphi_i) & \cos(\varphi_i)\end{bmatrix}, \tag{1}$$

where $w_i=\sqrt{3\pi/8}\sqrt{\delta z_i}\,\delta\beta\omega/4$, δz_i is the length of the ith segment, and B_i is the birefringence matrix of length δz_i. We can study the PMD of optical fiber using formula (1). The coupled nonlinear Schrödinger equation (CNLS) can describe the effect of PMD on light pulse when it transmits over optical fiber with PMD. The CNLS[7] is

$$\begin{aligned}&i\frac{\partial A}{\partial z}+\frac{1}{2}\delta\beta\ \Xi A+i2\delta\beta'\ \Xi\frac{\partial A}{\partial t}-\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial t^2}\\&+n_2k_0\left[\frac{5}{6}|A|^2A+\frac{1}{6}(A^+p_3A)p_3A+\frac{1}{3}(A^+p_2A)p_2A^*\right]=0,\end{aligned} \tag{2}$$

where $A=(A_x\quad A_y)^t$ is column vector with elements A_x and A_y, the complex envelopes of the two polarization components. The z-coordinate measures distance along the optical fiber axis, while t-coordinate represents retarded time——the time relative to the moving center of the signal; $*$ designates complex conjugation; β_2 is the fiber group velocity delay (GVD), with the assumption $\beta_2^x\approx\beta_2^y=\beta_2$; n_2 is the nonlinear Kerr coefficient. The wavenumber is expressed as $k_0=2\pi/\lambda$, where λ is the vacuum wavelength of light. The specific group delay per unit length is represented by $\delta\beta'\equiv\left(\dfrac{\partial\beta}{\partial\omega}\right)_{\omega_0}=\beta_x'-\beta_y'$, where ω_0 is the center frequency of transmitted light. The matrix is

$$\Xi = \begin{pmatrix} \cos(2\varphi) & \sin(2\varphi) \\ \sin(2\varphi) & -\cos(2\varphi) \end{pmatrix} = p_3 \cos(2\varphi) + p_1 \sin(2\varphi) \ . \tag{3}$$

The p_i (i = 0—3) is represented by Pauli's matrices:

$$p_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad p_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad p_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad p_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} . \tag{4}$$

Therefore, we can simulate the effect of polarization mode dispersion on transmitted pulse using formulae (1)—(4).

2 Numerical simulation and experiment

Usually present-day fibers have PMD 0.1 ps/km$^{1/2}$, but many of the installed fibers before the 1990s had high PMD, say, more than 10ps/km$^{1/2}$, so the PMD have 200 ps when light pulse transmits over 400 km. But some present-day fibers have PMD more than 1.5 ps/km$^{1/2}$, so it is important to study light pulse transmission over high PMD fiber. The simulated parameters are selected according to the fiber we used in experiment. The length of optical fiber is 1.18 km, the fiber dispersion is –102ps/nm.km, measured by CD400 EG&G. The effective area is 15.23 µm^2, measured by NR9200 EXFO. The nonlinear factor n_2 is 3.2×10^{-20}m^2/W. The coefficient of high-PMD fiber is 237.95ps/km$^{1/2}$, which is measured by HP 8509B polarization lightwave analyzer. The full width at half maximum of light pulse is 24.35 ps. The light pulse is narrower than 40Gb/s. The input power is 10 dBm. The signal wavelength is 1550 nm.

The coupled nonlinear Schrödinger equation is solved by split-step operator technique. The PMD is simulated by DRWM. The input power is 50:50 for fast axis vs. slow axis. The transmission over 1.18 km high-PMD fiber has been numerically studied. The two simulated results are shown in fig. 1. Fig. 1 shows the light pulse transmission over 1.18 km high-PMD fiber, with light pulse deformed badly. We cannot find what is the original pulse in fig. 1.

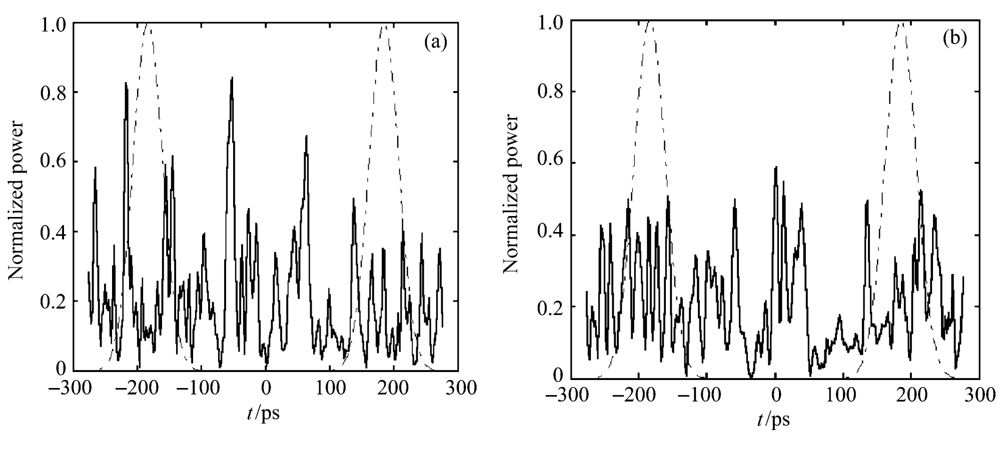

Fig. 1. The two simulated results about Gaussian pulse transmission on high PMD fiber. — • — • , Original pulse; ——, deformed pulse.

The experiment was done using high-PMD fiber too. Fig. 2 shows the measured fiber PMD. The light source is Santec TSL-210 tunable wavelength laser with output power 10 dBm. The output pulse is compressed to 24.35 ps. Then the light pulse transmits over high-PMD fiber. The transmitted pulse is detected by a Tektronix CSA 803A communication signal analyzer. The experimental result is shown in fig. 3. Fig. 3(b) shows the badly deformed light pulse transmission over 1.18km high-PMD fiber. We cannot find what is the original pulse from fig. 3(b) either.

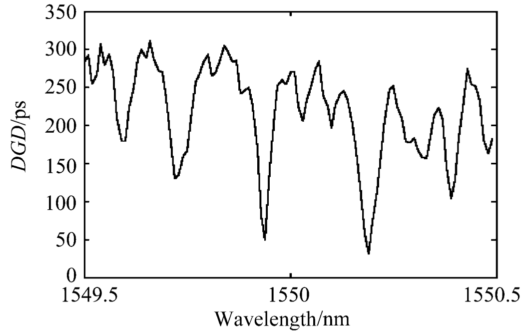

Fig. 2. Measured result of high-PMD fiber using JME. Step=0.01 nm.

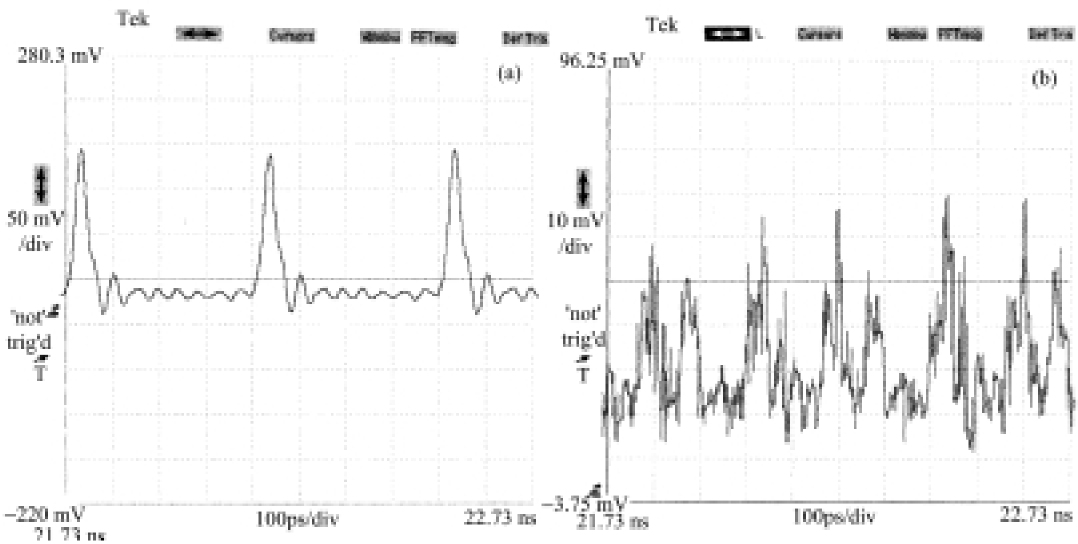

Fig. 3. Transmitted experiment over high-PMD fiber. (a) Original pulse; (b) deformed pulse.

The simulation is consistent with the experimental result (figs. 2 and 3). Why is the light pulse deformed so badly? The input mode LP_{01} consists of two orthogonal vectors HE_{11}^{x} and HE_{11}^{y}. They get mixed together if the transmitted link has no polarization mode dispersion. On the contrary, if the transmitted link has polarization mode dispersion, the two orthogonal vectors HE_{11}^{x} and HE_{11}^{y} can produce walk-off (fig. 4). Fig. 4 only shows the visual walk-off pulse, without

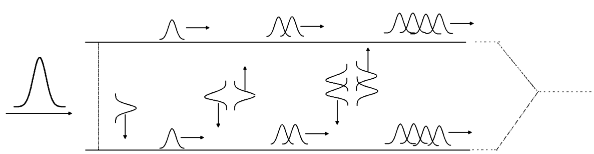

Fig. 4. Schematic configuration of the walk-off pulse generated when Gaussian pulse transmits over high PMD coefficient fiber.

taking into consideration the stochastic coupled-phase. The walk-off is very poor when the transmitted link's polarization mode dispersion is very high. The transmitted link's polarization mode dispersion is so high that the walk-off pulse becomes two self-governed pulses. Then the two self-governed pulses split into self-governed pulses, which in turn split into 8 self-governed pulses, and the same process continues. At last we can see deformed walk-off pulses at the end of transmitted link.

3 Conclusion

As far as we know, the experiment is the first ever tried to study Gaussian pulse transmission over ultra-high PMD fiber. The simulation and experiment have been carried out using coefficient of polarization mode dispersion with 237.95ps/nm · $km^{1/2}$. The numerical result agrees with that of the experiment. The walk-off pulse is observed.

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