Pulse Distortion Occasioned by High-Order Polarization Mode Dispersion

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Abstract: - We show waveform distortion induced by fiber polarization mode dispersion (PMD) on high-speed pulses. Since the mean differential group delay of the fiber is three times the pulse width, high-order PMD plays a significant role. Knowledge of this PMD-induced waveform distortion is important to system designers who require accurate pulse models and descriptions.

Key-Words: - polarization mode dispersion PMD lightwave system *CSCC'99 Proceedings,* Pages:6481-6484

1 Introduction

Polarization-mode dispersion (PMD)[1-3] currently attracts much interest. This is partially in anticipation of the deployment of lightwave communication systems operating at a channel rate of 40 Gb/s and partially the result of a desire to transmit 10 Gb/s over legacy fiber exhibiting unacceptable levels of PMD.

If reasonable care is taken in the specification of individual components in a lightwave transmission system, its PMD arises from a stochastic combination of birefringence distributed throughout the fiber. To lowest order, PMD behaves like simple birefringence. The transmission time through the system depends on the polarization of the light entering the system. Light with polarization aligned with one axis will be delayed by the differential group delay (DGD) relative to light having the orthogonal polarization. PMD can be characterized[4] by a vector $\mathbf{\Omega}$ in Stokes space pointing in the direction of the fast birefringent axis and of length equal to the differential group delay (DGD). The fast and slow birefringent axes are called the principal states of polarization (PSP). In the first-order approximation of PMD, $\mathbf{\Omega}$ is independent of wavelength. In a useful second-order description of PMD, $\mathbf{\Omega}$ varies with changes in optical frequency or wavelength. The derivative of the magnitude of $\mathbf{\Omega}$ with respect to wavelength is known as polarization-dependent chromatic dispersion (PCD) because it provides signal distortion similar to that provided by chromatic dispersion, with a sign that depends on the signal state of polarization relative to the PSP's [5,6].

Since $\mathbf{\Omega}$ varies with wavelength, one can investigate the fiber transmission distortions induced by various amounts of PMD and PCD in a system by merely changing wavelength. In the work described here, we measured the wavelength dependence of the magnitude of $\mathbf{\Omega}$. From this we knew the DGD and the PCD. However the depolarization component of second-order PMD, which characterizes changes in the direction of $\mathbf{\Omega}$, was not measured. Therefore, although the fiber data shown below was taken at wavelengths for which PCD was small, the depolarization component of second-order PMD and other, higher-order components were not necessarily small.

2 Measurements

In order to understand the effects of PMD on pulses, we transmitted short pulses through fiber having known, large amounts of first-order PMD. We first measured the spectral dependence of the magnitude of first-order PMD of a test fiber. This measurement used a commercially-available PMD analyzer employing the Jones-Matrix Eigenvalue technique[7]. From the spectrum of the PMD magnitude, we could determine the PCD spectrum. We next selected a wavelength providing some desired PMD and PCD, and recorded the pulse waveforms at the output of the test fiber for various states of input polarization. We then repeated the

PMD measurement. The two PMD measurements allowed interpolation of the drift in PMD.

The apparatus shown in Fig. 1. was used to observe pulse distortion. The external-cavity laser and wavemeter were used to provide light at the selected wavelength. An electro-absorption modulator carved the light into a 12-ps, 20 Gb/s pulse train, which was amplified and then filtered to remove amplified spontaneous emission noise. A lithium niobate Mach-Zehnder modulator impressed onto the pulse train an 8-bit pattern containing an isolated "one". Transmitter constraints limited the isolation on one side of the isolated pulse to a single "zero" bit. The drive signals to the modulators and the center frequency of the filters were adjusted to minimize frequency chirp in the pulse. After passing through a polarization controller, the pulse train was split, with one part passing into a polarization analyzer and the other part passing through an attenuator and thence into the test fiber. Since there is an isomorphic mapping between the polarization at the input of the fiber under test and that entering the polarization analyzer, the latter can be used to noninvasively monitor changes in the polarization entering the fiber.

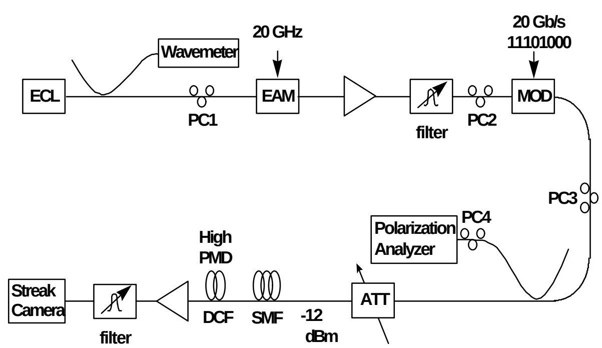

Figure 1. Apparatus used to observe pulse distortion containing a tunable external-cavity laser, ECL; polarization controllers, PC1-PC4; an electro-absorption modulator, EAM; a Mach-Zehnder modulator, MOD; an optical attenuator, ATT; single-mode fiber, SMF; and dispersion-compensating fiber, DCF.

The test fiber was a concatenation of 40.1 km of standard fiber and dispersion compensating fiber with a mean PMD of 35 ps. The dispersion compensating fiber provided the PMD while the standard fiber was used to reduce the influence of background chromatic dispersion on the pulse distortion. The net chromatic dispersion of the entire test fiber was near -60 ps/nm in the absence of PCD. In the absence of polarization effects, this dispersion would broaden our chirp-free pulses to 22 ps at full-width half maximum. The influence of nonlinearity was reduced to negligible levels by setting the peak pulse power to -3 dBm at the fiber entrance and by placing the standard fiber before the fiber having the high PMD. After the fiber, the distorted pulse was amplified and filtered and then entered a streak camera having a resolution of 3 ps.

3 Results

At each wavelength, the pulse distortion was measured for several different input polarizations having a known relationship between them. This was accomplished by first adjusting polarization controller PC4 so that the polarization analyzer read linear polarization at an angle of 45°. The distorted waveform at the end of the test fiber was recorded. Then, without adjusting polarization controller PC4, the polarization at the input to the fiber was changed by adjusting polarization controller PC3. This change was monitored on the polarization analyzer, and at convenient polarizations we recorded the distorted waveform at the end of the test fiber. We typically used left and right circular polarization, horizontal and vertical linear polarization and linear polarization at -45° and +45°. The latter measurement, which duplicated the first measurement, served to calibrate drift in the propagation time of the apparatus. This facilitated correction of the time offsets in the recorded waveforms. No attempt was made to preserve the orientation of the polarization coordinate system when the wavelength was changed.

As a test of the technique, we looked at pure first-order PMD. The test fiber was replaced with a PMD emulator consisting of a polarization beam splitter, differential delay, and polarization beam recombiner. The results for a 26.2-ps differential delay shown in Fig. 2 confirm our expectations. Here, polarization controllers PC3 and PC4 were adjusted so that when the polarization analyzer read linear polarization at +45°, the input polarization was aligned along the slow axis of the emulator. Under these conditions, a single output pulse is observed. Similarly, -45° linear polarization corresponded to alignment along the fast axis of the emulator. Here we obtain a single output pulse with a total propagation delay 26.2 ps less than that observed for the orthogonal input polarization. Any other state of input polarization results in pulse splitting into two pulses separated by 25 ps. Fig. 2 shows that an input of horizontal linear polarization to the emulator causes two equal power pulses to appear at the output. As expected, the output pulse shapes for input polarizations of vertical linear polarization, right circular polarization and left circular polarization are identical to the output observed for horizontal polarization since all of these states launch equal power into each of the two birefringence axes of the emulator. For symmetric input pulses and purely first-order PMD, launch polarizations that are mutually orthogonal will result in output waveforms that are mirror images of each other.

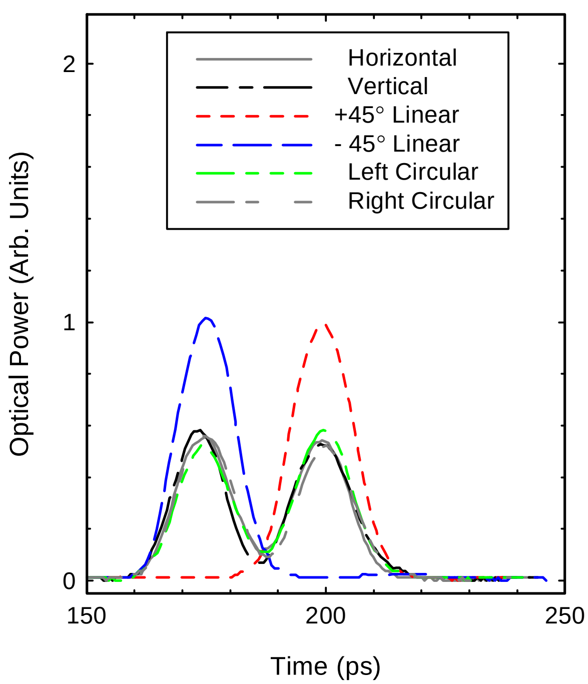

Figure 2. Output pulses after propagation through 26.2 ps of first-order PMD generated in a PMD emulator for various input polarizations. The principal states of the emulator corresponded to linear input polarizations at +45° and -45°. The solid line shows the split-peak output observed for input polarizations of horizontal and vertical linear polarization and right and left circular polarization.

A common misconception is that, with sufficient fiber PMD, a splitting similar to that shown in Fig. 2 will be observed and that the pulse separation will be equal to the DGD of the fiber. However, the first-order approximation illustrated in Fig. 2 breaks down as the fiber DGD approaches and exceeds the width of the pulse being affected by the PMD. In this case, a higher-order description of PMD must be employed. Consequently, fiber PMD distortion rarely exhibits the complete pulse bifurcation depicted in Fig. 2. More typical fiber PMD distortions can be seen in Fig. 3, which shows the output waveforms recorded using a wavelength where the fiber DGD was 26.2 ps and the PCD was near zero. An input polarization of +45° results in a single pulse on a 10% pedestal. However, changing the input to the orthogonal state does not generate an output pulse separated by 26.2 ps from this pulse, but rather produces a double-peaked pulse. Other input polarizations result in other single or double lobed output waveforms, usually with a pedestal and some broadening. In no case do pairs of orthogonal launch polarizations result in mirror-image pairs of output waveforms as would be expected if only first-order PMD were present. The superposition of waveforms in Fig. 3 suggests a predilection for optical power to experience two different transmission delays. The separation between these two delays is close to the first-order PMD magnitude.

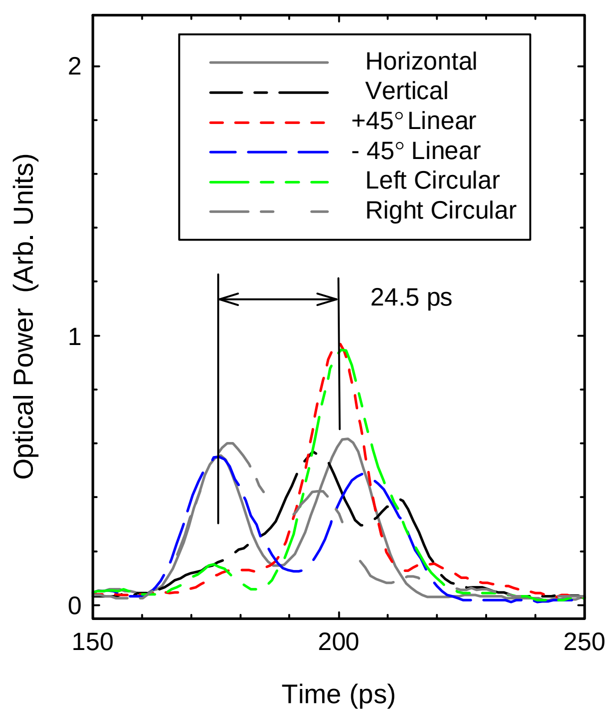

Figure 3. Output waveforms for six different launch polarization states of a 12-ps pulse. The DGD was 26.2 ps, the PCD was near zero, and the residual chromatic dispersion was -57 ps/nm.

The vestigial first-order behavior was not always so evident, even at wavelengths for which the fiber had low first-order PMD. With a mean DGD of 35 ps, the test fiber could have large higher-order PMD even at wavelengths for which the DGD was low. The complex waveforms shown in Fig. 4 are presumably caused by higher-order PMD. Here the DGD is 64 ps and the PCD is near zero. Once again, an input polarization of +45° results in a fairly well defined pulse, but in this case, a third of the total waveform energy is contained in a broad precursor. Changing the input polarization to the orthogonal state provides a waveform with three or four peaks. It can be seen from Fig. 4 that other states of input polarization yield a variety of waveforms, which suggest, if anything, a predilection for a delay spacing of 30 ps. As in the case shown in Fig. 3, orthogonal launch polarizations do not generate mirror image output waveforms.

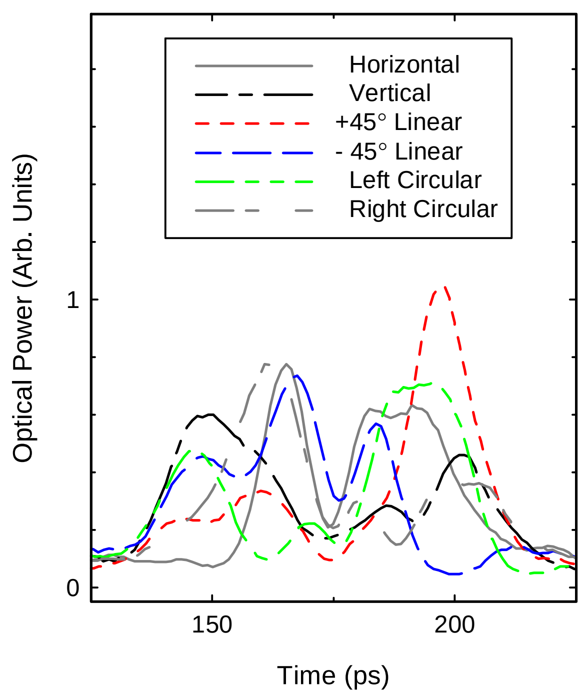

Figure 4. Output waveforms for six different launch polarization states of a 12-ps pulse. The DGD was 64 ps, the PCD was near zero, and the residual chromatic dispersion was -65 ps/nm.

4 Conclusion

We have shown samples of the waveform distortion that arises when pulses are transmitted through fiber having a mean first-order PMD magnitude that is three times the width of the pulses. As expected, under these conditions, first-order PMD does not accurately describe the fiber transfer function. Knowledge of this PMD-induced waveform distortion is important to the system designers who require accurate pulse models and descriptions.

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