Time and Frequency Domain Characteristics of Polarization-Mode Dispersion Emulators

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***Abstract*—We investigate both experimentally and theoretically a new technique to realistically emulate polarization-mode dispersion (PMD). We propose and demonstrate a PMD emulator using rotatable connectors between sections of polarization-maintaining fibers that generates an ensemble of high PMD fiber realizations by randomly rotating the connectors. It is shown that: 1) the DGD of this emulator is Maxwellian-distributed over an ensemble of fiber realizations at any fixed optical frequency; and 2) the frequency autocorrelation function of the PMD emulator resembles that in a real fiber when averaged over an ensemble of fiber realizations. A realistic autocorrelation function is required for proper emulation of higher order PMD and indicates the feasibility of using this emulator for wavelength-division-multiplexing (WDM) systems.**

***Index Terms*—Optical communication, polarization, polarization-mode dispersion, wavelength-division multiplexing.**

I. INTRODUCTION

POLARIZATION-MODE DISPERSION (PMD) has recently emerged as one of the next critical hurdles in achieving high-performance optical transmission systems. PMD is caused by an optical fiber's randomly varying birefringence. To first order, PMD can be represented by a differential group delay (DGD) between two principal states of polarization (PSP) of the optical fiber [1]. For a fixed PMD, DGD is a random variable that has a Maxwellian probability density function (pdf) [2].

Although present-day fibers have PMD values $\sim$0.1 ps/km$^{1/2}$, much of the previously installed fiber has higher PMD values. A critical problem for designers of high-performance systems is to measure performance degradations due to high-PMD fiber spans [3], [4]. Unfortunately, high-PMD fiber is not commercially available. Moreover, even if it was available, it would be hard to use it to rapidly explore a large number of different fiber ensembles, as is required to determine the distribution of penalties due to PMD.

A fairly well-known technique of quasi-PMD emulation is to splice several short sections of polarization-maintaining (PM) fiber with some randomly chosen (but thereafter fixed) angular offset between the polarization axes of each section [5]. This approach results in a fixed PMD vector (DGD and PSP) at each wavelength. Therefore, it is impossible to set up any experiment to emulate an ensemble of fiber realizations in order to obtain PMD statistics at a specific wavelength.

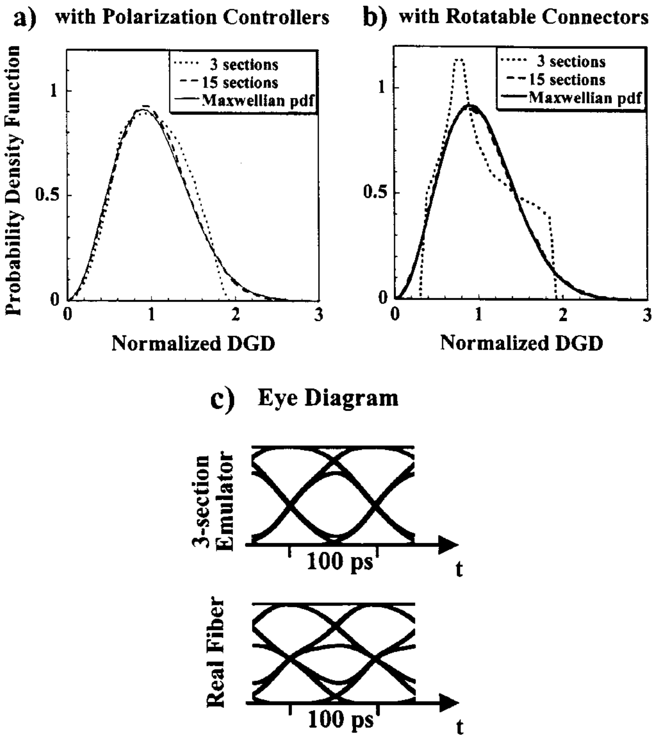

Fig. 1. (a) DGD distribution for a three- and 15-section PMD emulator with a polarization controller between each section (unequal lengths of PM fiber), (b) with a polarization rotation between each section, (c) the worst case eye diagram (with probability 0.001) of a 10-Gb/s signal with 30-ps average DGD, for a real fiber and a three-section PMD emulator (simulation results).

Any PMD emulator that realistically emulates transmission through communication fiber should have two key properties: 1) the DGD should be Maxwellian-distributed over an ensemble of fiber realizations at any fixed optical frequency; and 2) averaged over an ensemble of fiber realizations, the frequency autocorrelation function of the PMD emulator should resemble that in a real fiber, i.e., it should tend quadratically to zero outside a limited frequency range [6]. Ideally, a PMD emulator should also have the property that the DGD is Maxwellian-distributed over an ensemble of frequencies for nearly all fiber realizations. However, we have found theoretically that obtaining this property requires a large number of sections in the emulator—far in

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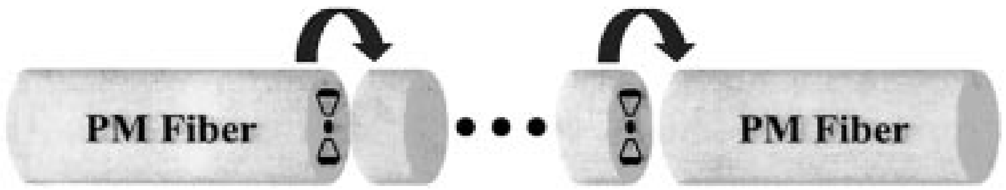

Fig. 2. Experimental setup of the PMD emulator with 15 sections of PM fibers of unequal lengths with rotatable connectors. The fiber lengths are 5.1, 6.8, 8.6, 7.4, 6.3, 6.7, 10.0, 8.6, 5.4, 7.2, 6.9, 7.1, 6.1, 7.4, and 4.6 m.

excess of 15. At the same time, it is not necessary to impose this criterion to accurately reproduce the correct statistics for second-order PMD.

We propose and investigate, both experimentally and theoretically, a new technique to accurately emulate PMD using multiple sections of PM fiber with rotatable connectors. This technique makes it possible for us to generate different fiber realizations at any specific wavelength by randomly rotating the connectors. We demonstrate that three sections of PM fiber cannot realistically emulate PMD. By contrast, an emulator with 15 sections of PM fiber and randomly rotatable connectors appears to be adequate.

II. THEORY OF PMD EMULATORS

A PMD emulator could in principle be constructed by using polarization controllers between sections of PM fibers. The polarization controllers produce arbitrary rotation on the Poincaré sphere after each section of PM fiber. We have obtained an iterative analytical expression for the pdf of the DGD distribution for any number of sections of any length for this type of PMD emulators, as shown in (1):

$$f_{\Delta\tau_{n+1}}(\Delta\tau_{n+1}) = \frac{\Delta\tau_{n+1}}{2a}\int_{|\Delta\tau_{n+1}-a|}^{\Delta\tau_{n+1}+a} \frac{f_{\Delta\tau_n}(\Delta\tau_n)}{\Delta\tau_n}\, d\Delta\tau_n \tag{1}$$

where

$f_{\Delta\tau_n}(\Delta\tau_n)$	pdf of the $\Delta\tau$ (DGD) for the n-section PMD emulator;
$f_{\Delta\tau_{n+1}}(\Delta\tau_{n+1})$	the same pdf for an $(n+1)$-section PMD emulator;
a	DGD of section $n+1$.

Fig. 1(a) shows density functions for three- and 15-section emulators with polarization controllers between each section of PM fiber. We observed that utilizing unequal lengths of PM fibers increases the rate of convergence of DGD to a Maxwellian distribution [7].

In practice, an emulator with polarization controllers is hard to build and control. Thus, in our experiments we used rotatable connectors that change the polarization orientations but not their relative phases. Although utilizing rotatable connectors slightly reduces the convergence rate of the DGD distribution to being Maxwellian, it greatly simplifies the structure of the PMD emulators.

We obtained DGD density functions using Monte Carlo simulations based on the coarse step method [8]. Fig. 1(b) shows the DGD pdfs of three- and 15-section PMD emulators. The shape of the DGD density function converges to a Maxwellian pdf for the PMD emulators with more than ten sections of PM fiber. Note that higher DGD values, which appear in the tail of the distribution, can generate more severe signal degradation and is usually the cause of link outages. It is therefore very important that the tail of the DGD density function closely resembles the fiber's Maxwellian distribution. Fig. 1(c) shows the worst case eye diagram (with probability 0.001) of a 10-Gb/s signal with 30-ps average DGD, for a real fiber and a three-section PMD emulator. It is apparent that a three-section PMD emulator cannot reproduce realistic PMD degradation. We have numerically verified that with 15 sections of PM fiber, a Maxwellian pdf is achieved out to three times of the average DGD on the tail of the pdf.

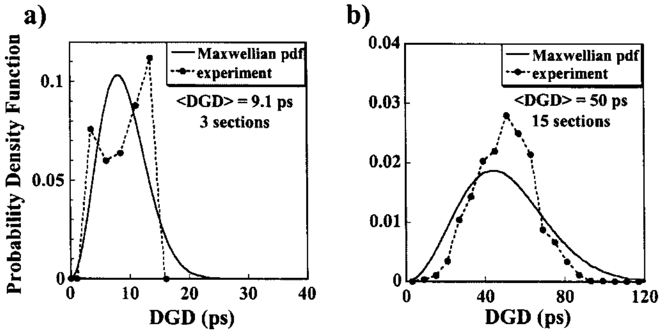

Fig. 3. DGD distribution of (a) three- and, (b) 15-section PMD emulators obtained by an optical frequency sweep over a 20-nm range.

III. EXPERIMENT AND COMPARISON TO THEORY

Fig. 2 shows the experimental setup of our PMD emulator. We used 15 sections of PM fiber connected by rotatable-key connectors. Rotatable connectors allow the polarization axes of any two adjacent fibers to be rotated with respect to each other. The length of the PM fibers are chosen randomly, with an average of ~7 m and a 20% Gaussian deviation [9]. The beat length of the PM fiber is ~3.1 mm at 1550 nm. Therefore, 15 sections of PM fiber generates ~40 ps of PMD [10]. Although the total loss of our emulator is 6–10 dB and varies with the angles between the PM fiber sections, it can be made more uniform by careful consideration of the connectors themselves. The polarization-dependent loss has been measured to be less than 0.2 dB, and the DGD values are measured using the Jones matrix method [11].

In order to obtain a collection of DGD values, it is possible to emulate different fiber realizations either by changing the wavelength of the optical carrier (frequency sweep) after fixing the angles between the PM fiber sections, or by rotating the angles between each section of PM fiber. In Fig. 3, we show

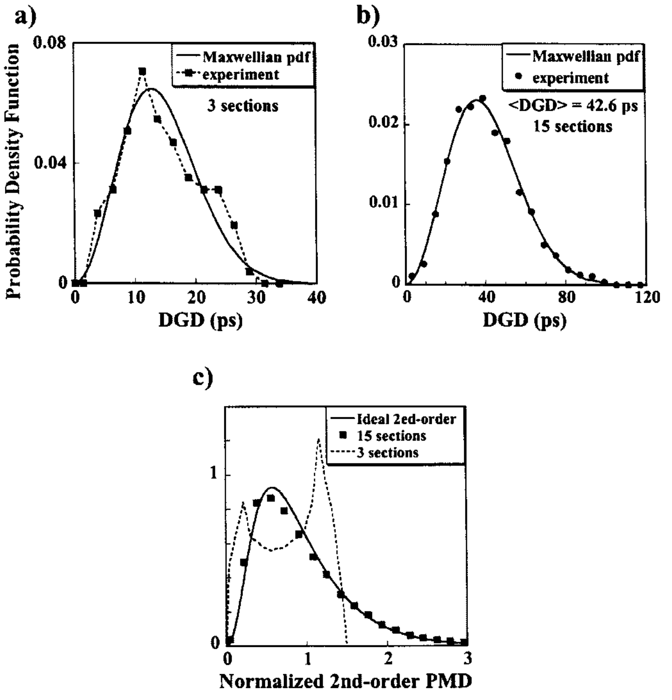

Fig. 4. (a), (b) DGD distribution of three- and 15-section PMD emulators with rotatable connectors at 1555 nm (experiment). (c) Normalized second-order PMD (simulation).

the DGD distribution from a frequency sweep using three- and 15-section PM fibers. Even with 15 sections, the results are not accurate in many cases and may provide a false measurement. However, some cases—e.g., when the angles between different sections are close to 45°—may resemble a Maxwellian pdf. In addition, the average DGD obtained by a frequency sweep with 15 sections was far from our intended 40 ps in many cases. Furthermore, in most of the practical systems—especially wavelength-division-multiplexing (WDM) systems—it is not feasible to change the optical frequency over a wide range.

Fig. 4(a) and (b) show the DGD density function for a three-section and a 15-section emulator at a **fixed** wavelength (1555 nm) by randomly rotating the angles between the fibers over 1000 times. We swept the wavelength 1 nm with 0.02 nm steps for each set of angles to obtain DGD pdf at 50 different wavelengths. Good distributions are obtained at other wavelengths as well, and the average DGD was very close to 40 ps at all wavelengths. In addition to the Maxwellian DGD distribution, as shown in Fig. 4(c), a 15-section emulator has a second-order PMD distribution, which is close to the ideal second-order PMD distribution.

In WDM systems, not only should the DGD pdf of each channel be Maxwellian, but also the PMD characteristics of channels with sufficiently large frequency spacing from each other should be statistically independent—i.e., the PMD vectors should be uncorrelated [6]. For 40 ps of PMD, a real fiber shows negligible correlation between PMD vectors when the spacing is more than 0.2 nm. Fig. 5 shows the autocorrelation function of the PMD vector for emulators with a different number of sections. For a 15-section unequal length PMD emulator, an average level of 10% correlation remains between well-spaced wavelengths. To avoid periodicity in the autocorrelation function and to decrease the residual correlation, it is preferable to employ unequal length PM fibers in PMD emulators. In addition, we have theoretically found that the use of polarization controllers rather than rotators only slightly reduces the residual correlation.

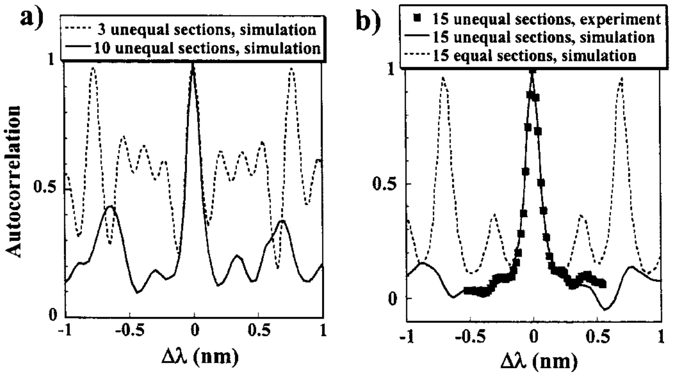

Fig. 5. Autocorrelation function of PMD vector for (a) three- and ten-section PMD emulators with unequal lengths of PM fibers (simulation), and (b) a 15-section emulator with equal and unequal lengths of PM fibers (simulation and experiment).

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