High-Speed, Stable and Repeatable PMD Emulator with Tunable Statistics

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Abstract: Using three programmable DGD elements, we experimentally demonstrate a high-speed PMD emulator with tunable statistics and good stability and repeatability. By incorporating in-line polarimeters, a repeatable lookup-table of DGD and 2^{nd}-order PMD states can be created.

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Introduction

Polarization-mode-dispersion (PMD) presents a unique challenge for high-speed optical systems because the induced pulse spreading is a frequency-dependent statistical parameter that varies randomly over time [1][2]. To accurately characterize the outage probability of networks that may or may not incorporate PMD compensation, it is essential to have a PMD emulator that can quickly cycle through the various PMD states expected in an optical fiber.

Previously demonstrated PMD emulators are typically constructed using several randomly-coupled PM fibers [3,4] or birefringent crystals mounted on rotation stages [5]. Two major drawbacks of current emulators are: (i) the lack of stability and repeatability, and (ii) the inability to vary the PMD statistics (i.e., no tunable average DGD). In general, emulator repeatability is limited by the environmental sensitivity of the birefringent elements and/or the poor control certainty of any mechanical parts. Moreover, the average DGD of these emulators is fixed and cannot be reconfigured to emulate different fiber plants. We emphasize that the ability to repeatably "dial-in" any PMD value is extremely desirable, as it enables the user to quickly investigate system or compensator performance at any PMD state of interest.

Using three programmable DGD elements, we experimentally demonstrate a high-speed (<1 ms), stable and repeatable PMD emulator that can generate any desired Maxwellian DGD distribution, with an average up to 35ps, and corresponding 2^{nd}-order statistics.

The stability and repeatability of the emulator DGD and output state of polarization (SOP) are characterized and compared with other emulators. Our emulator maintains a given PMD state over several hours, whereas the output SOP of other emulators drifts dramatically within minutes. A PMD variation of <5% is obtained for 50 samples repeated 4 times. To create a truly repeatable emulator, in which any previously recorded set of PMD values can be dialed-in, we insert simple in-line polarimeters between sections with automatic feedback to the polarization controllers to facilitate the generation of a repeatable lookup table of input DGD values and polarization states versus output PMD values. This technique also enables deterministic control of the angles between the PMD vectors of each section. We demonstrate this by controlling the angles between sections to 0° to generate pure 1^{st}-order PMD values from 0 to 135ps, and to 90° to generate large 2^{nd}-order PMD values from 0 to 2600ps^2. This capability opens the door to experimentally implementing several advanced PMD emulation techniques that have only previously been performed using computer simulations [6-9].

PMD Emulation with Tunable Statistics

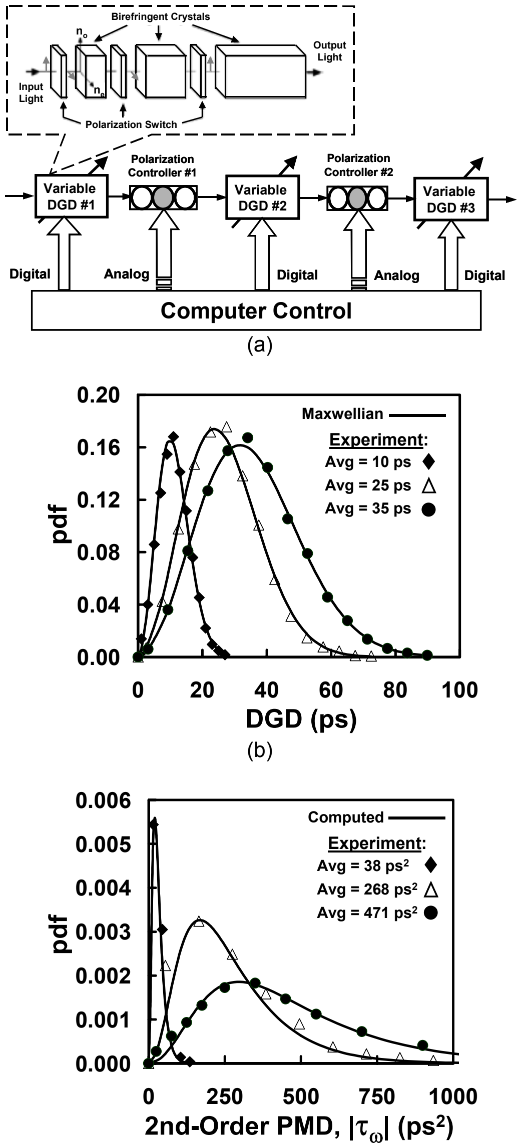
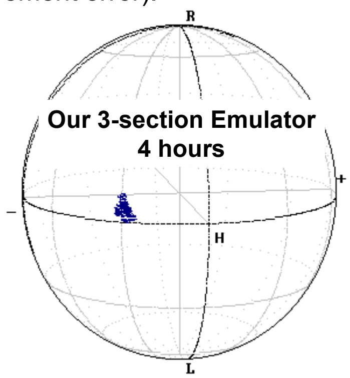


Fig. 1 (a). PMD emulator with three programmable DGD elements separated by two electrically-driven polarization controllers. (b) Three output DGD distributions showing a good fit to the Maxwellian pdf for real fibers and (c) the corresponding 2nd-order PMD distributions.

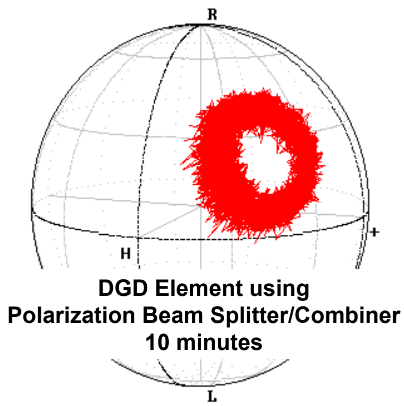
The emulator is constructed from three variable DGD elements separated by two fiber-squeezer-based polarization controllers (Fig. 1a). Each variable DGD element consists of several birefringent crystals whose lengths increase in a binary series and are separated by electrically driven polarization switches [10]. The elements can be digitally programmed to generate any DGD value from -45ps to +45ps with a tuning speed of <1ms and a resolution of 1.40ps. A computer is used to control the emulator to randomly generate any desired DGD distribution for each element and to uniformly scatter the polarization between sections. To obtain a Maxwellian DGD distribution at the emulator output, the DGD values of each element are varied according to a Maxwellian distribution with average $\Delta\tau$. This yields an average DGD of $3^{1/2}(\Delta\tau)$ for the total emulator and an average 2nd-order PMD distribution that has the correct shape but falls slightly short of that expected for a real fiber, as shown in a recent simulation result [11]. To demonstrate tunability of the PMD statistics, three different distributions are generated, as shown in Figs. 1(b) and (c) for <DGD> = 10, 25 and 35ps. As expected, the DGD values closely match the expected Maxwellian distribution. The corresponding 2nd-order PMD distributions have averages of 38, 268, and 471ps^2, which are ~30% lower than expected for a real fiber. All of our PMD measurements were performed using the Jones matrix method of a commercial PMD analyzer [12].

Emulator Stability and Repeatability

Stability and repeatability are highly desirable features for PMD emulators as they enable one to examine system performance at specific PMD conditions and to achieve deterministic control of the emulator state. To characterize stability, we observed the output SOP variation of our emulator compared with other, more traditional, emulators in a laboratory environment. SOP stability is important because it indicates that the direction of the PMD vector remains stable, which is a necessary condition for repeatability. Fig. 2(a) shows that the output SOP of our 3-section emulator remains nearly constant over a 4-hour period. For each individual section, we observed that the SOP varies negligibly over tens of hours. In contrast, the other PMD emulators show dramatic SOP variations within minutes, as shown in Figs. 2(b) and (c). Due to the remarkable stability of our emulator, generated PMD states remain stable over hours, e.g., with the emulator set to 72-ps DGD, the DGD varied <5% and the 2nd-order PMD varied <10% over 30 minutes (including measurement error).



(a)



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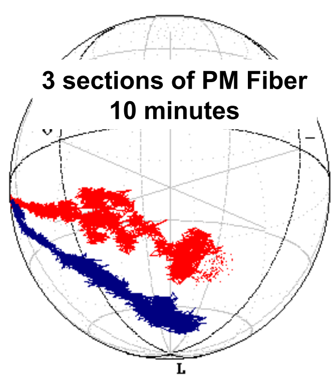
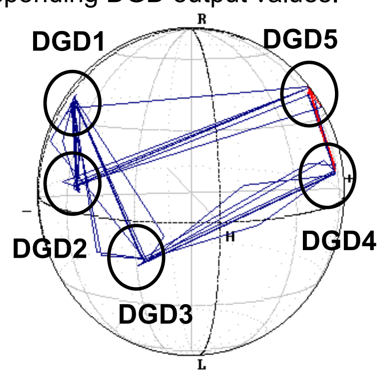


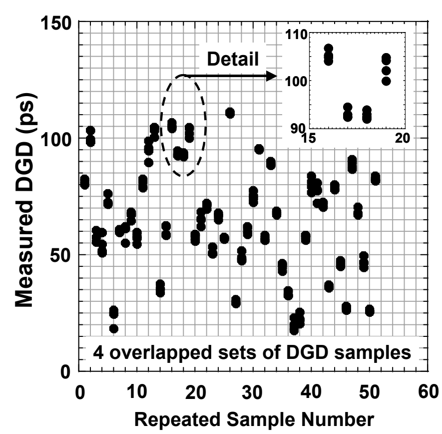
(c)

Fig.2 Output SOP stability of (a) our PMD emulator over 4 hours, (b) a DGD element using a polarization-beam-splitter/combiner and fiber-delay-line over 10 minutes, and (c) 3 cascaded PM fibers with DGD values of 20, 30 and 40ps over 10 minutes.

To characterize the SOP repeatability, the emulator was repeatedly cycled six times through five different DGD states at 1-minute intervals. Fig. 3(a) shows that the output SOP repeatedly returns to the same point on the Poincaré sphere for each DGD state. To characterize the DGD repeatability, the emulator was cycled through 50 different sets of control parameters four times. The total test time was ~ 1 hour. The 50 measured DGDs from the four tests are overlaid in Fig. 3(b). At each sample point, the DGD variation is typically <5%, indicating the ability to generate a look-up table of control parameters and corresponding DGD output values.



(a)



(b)

Fig. 3 (a) Repeatability of the output SOP as the emulator is repeatedly tuned to 5 DGD states. (b) Four repeated measurements of 50 DGD samples are overlaid to show the repeatability of the output DGD (variation is typically <5% at each sample point with some of this variation due to measurement error).

Although the above results indicate that this emulator is a highly promising candidate for applications that require the PMD state to remain stable over several hours, it is still possible for the output state to vary with large temperature changes (more than a few degrees), or if the single-mode fiber pigtails between the sections are perturbed. Therefore, a simple and effective method to achieve repeatability without concern about emulator drift would be highly desirable. To accomplish this, three in-line polarimeters are inserted after each section and a polarization controller is added after section three (Fig. 4). The polarimeters are used to record the SOP between sections for different emulator states. Since the DGD of each section is known and extremely stable (<0.1ps/80°C), the additional SOP information allows us to construct a lookup table of output first and second-order PMD vectors versus the six input DGD and SOP parameters. After recording the input and corresponding output parameters for each randomly-generated sample during a long system test, the operator can return to any previously recorded PMD state (e.g. one that caused high penalty) for further investigation by simply adjusting the DGD elements and polarization controllers to re-acquire the set of input values for that sample. Even after environmental or polarization-coupling perturbations, this table can always be used to re-acquire a desired PMD state using automatic feedback control of the polarization controllers to obtain the needed SOP coupling.

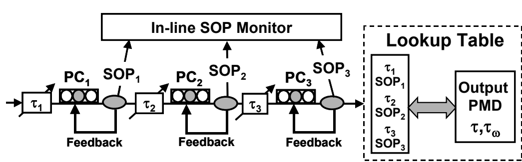
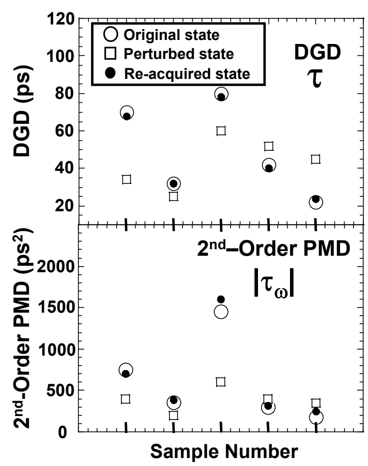


Fig. 4 Emulator setup incorporating simple, in-line polarimeters with automatic feedback to control the SOP between sections. This enables the generation of a lookup table of input DGD and SOP values versus the corresponding output 1st (τ) and 2nd-order PMD (τ_ω).

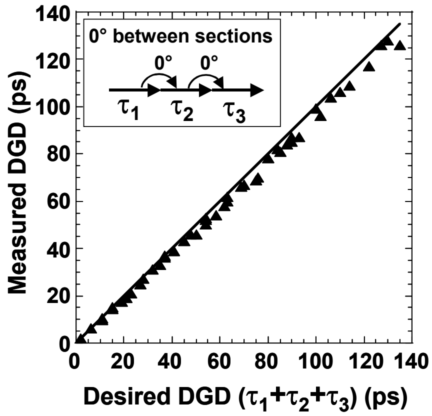
The effectiveness of this concept is shown in Fig. 5(a). The input parameters were recorded for five "original" PMD states. The fiber pigtails were then perturbed between sections, causing the SOPs, and therefore, the output values, to change. The polarization controllers were then adjusted to re-acquire the previously recorded SOPs for each sample, causing the output DGD and 2nd-order PMD values to return to their original states.

This setup may also be used to easily control the PMD vectors of the three sections to obtain any desired PMD state. For example, in order to generate pure first-order PMD, a one-point calibration is performed to measure the three SOPs that maximize the output DGD for a set of three input DGD values. As the DGD elements are varied, the SOPs can be controlled back to this calibration point to re-align the vectors and obtain the maximum output DGD (and negligible 2nd-order PMD) as shown in Fig 5(b). This same concept is used to set fixed 90° angles between the PMD vectors of each section to generate large values of 2nd-order PMD (Fig. 5c).

This approach of using polarimeters to control the polarization coupling between sections could be useful for applications requiring deterministic control of the PMD vectors between sections. These include importance sampling [6-7] and the generation of accurate higher-order statistics with only three sections by dialing-in the desired first and 2nd-order PMD vectors, instead of randomly generating these samples [8-9].



(a)



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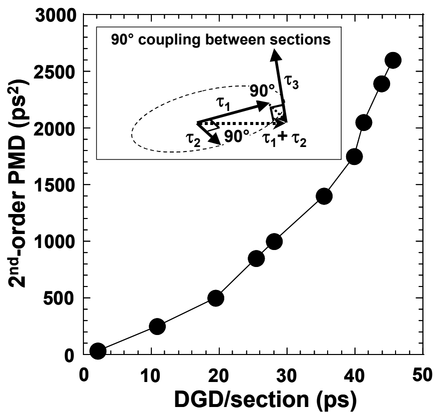

(c)

Fig. 5 (a) Using polarimeters and feedback control to dial-in previously recorded PMD states regardless of environmental perturbations (lookup table concept). (b) Coupling angle between sections set to 0° to align the PMD vectors and obtain any desired, pure 1st-order PMD and (c) setting the angle to 90° between sections to obtain large 2nd-order PMDs.

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