Programmable Differential-Group-Delay (DGD) Elements Based Polarization-Mode-Dispersion (PMD) Emulator with Tunable Statistics

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Abstract

A programmable DGD elements based PMD emulator with tunable statistics is demonstrated, exhibiting good stability and repeatability in a laboratory environment. More importantly, this emulator is the first one for the experimentally realization of importance sampling technique.

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]. It is caused by slight asymmetries in the core of the fiber that cause the light polarized in one axis to travel faster than light polarized in the orthogonal axis. The instantaneous PMD of a fiber is characterized by a vector, τ, whose direction determines the fiber's two principle states of polarization and whose magnitude is the differential-group-delay (DGD). The DGD follows a Maxwellian distribution that falls off to low probabilities at ~3 times the average value and extends out to infinity. It is the occasional events in the tail of the distribution that are likely to cause system outages. 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.

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Previously demonstrated PMD emulators are typically constructed using several randomly-coupled polarization maintaining (PM) fibers [2][3] or birefringent crystals mounted on rotation stages [4], as illustrated in Figure 1(a) to (c). Two major drawbacks of current emulators are: (i) the lack of stability or 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.

System designers typically require that system outages (penalty >1dB) due to PMD occur with a probability of 10^{-6} or less (<1 min/yr) [1]. To assess the effects of PMD on a system, both with and without compensation, PMD emulators are used to cycle through different PMD states. However, it is very difficult to characterize system outage probabilities using previously reported PMD emulators, or even with computer simulations, because of the extremely large number of randomly generated PMD states that must be explored to obtain a reliable estimate.

Importance sampling (IS) is a powerful tool for obtaining very low probability events with relatively few sample points [5]. This is accomplished by altering the method of obtaining the random samples to concentrate the measured results in the area of interest in the sample space. This will distort the probability distribution of the measured results, so each sample must then be appropriately weighted to map the measured values back onto the proper distribution function.

Thus far, importance-sampling techniques for PMD emulation have only been accomplished using computer simulations [5-7]. This is because a critical drawback of most previously reported PMD emulators is that they do not possess the programmability, or stability, required to perform IS. To perform IS

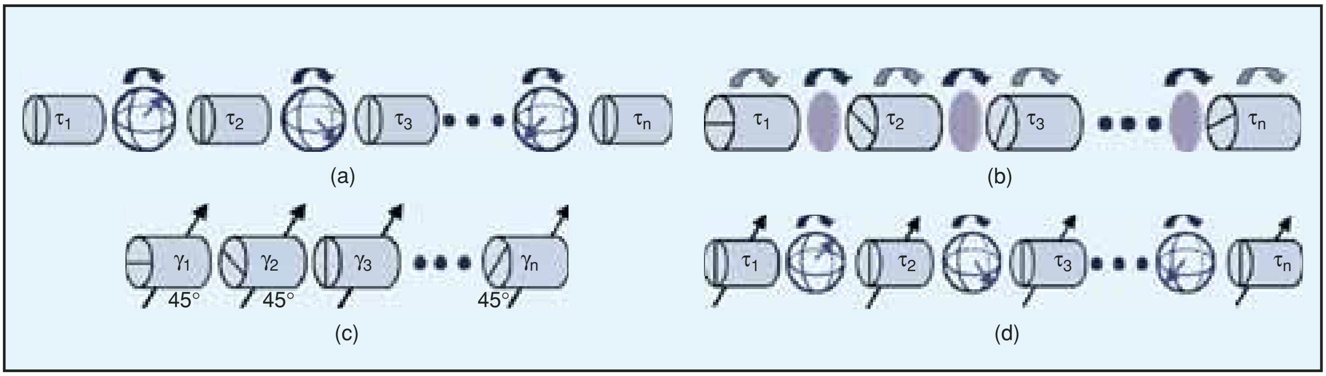


Figure 1 Typical configurations for constructing PMD emulators (a) fixed DGD elements with polarization scattering between sections (b) rotatable DGD elements separated by polarization rotators (c) variable birefringence on sections (d) variable DGD elements with polarization scattering between sections

with these emulators requires deterministic control of the coupling angle between the PMD vectors of adjacent sections in order to preferentially align them to obtain rare PMD events. This is extremely difficult to accomplish because the environmental sensitivity of the birefringent elements causes the direction of the PMD vectors to drift over time (even if the DGD remains constant, tiny variations in the birefringence will cause large changes in the PMD vector's direction). Furthermore, even with highly stable elements, it would still be a significant challenge to determine the PMD vector between sections and accurately produce the desired coupling angles for each sample. One recent PMD source approach may be a good candidate for such applications, though it has not yet been demonstrated for importance sampling [8], and the source exists periodic behavior that is unrealistic in real systems.

In this paper, another PMD emulation approach as shown in Figure 1(d), is demonstrated using programmable DGD elements. The key advantages of this approaches include (i) high-speed (<1 ms), (ii) stable and repeatable in the lab environments; (iii) can generate any desired Maxwellian DGD distribution and corresponding 2nd-order statistics; and more significantly, (iv) the first emulator that can realize experimental importance sampling technique.

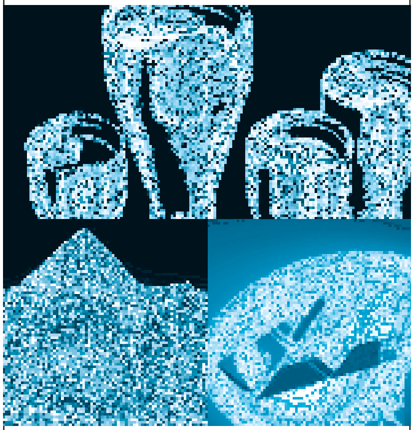
We present a new method to readily enable experimental importance sampling to produce low-probability events without the need to determine and control the direction of the PMD vector between sections. The IS technique is accomplished by simply biasing the distribution of DGD values applied to each element, as opposed to controlling the coupling angles between sections. As such, only uniform scattering of the polarization coupling between sections is required, which is easily accomplished with electrically driven polarization controllers. Here we experimentally use importance sampling to efficiently obtain rare, Maxwellian distributed DGD events with probabilities as low as 10^{-24} (for <DGD>=15 ps) and correspondingly rare 2nd-order PMD events after taking only 1,000 samples.

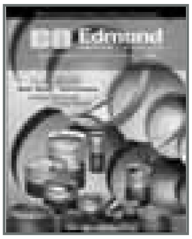
PMD Emulation with Tunable Statistics

Figure 2 shows the related information about this emulator. The emulator is constructed from three variable DGD elements separated by two fiber-squeezer-based polarization controllers (Figure 2b). Several variable DGD generation approaches have been proposed [9], and here we employ a very practical approach that was described recently in [10]. As shown in Figure 2(a), each variable DGD element consists of several birefringent crystals whose lengths increase in a binary series and are separated by electrically driven polarization switches. The elements can be digitally programmed to generate any DGD value from -45 ps to +45 ps with a tuning speed of <1 ms and a resolution of 1.40 ps. This resolution is a consequence of the structure of the DGD of sections included in each variable DGD element. 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 [11]. 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, $\Delta\tau$ [12]. 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 [13]. To demonstrate tunability of the PMD statistics, three different distributions are generated, as shown in Figure 2(c) and (d) for <DGD> = 10, 25 and 35 ps. As expected, the DGD values closely match the expected Maxwellian distribution. The corresponding 2nd-order PMD distributions have averages of 31, 174, and 322 ps^2, which are ~30% lower than expected for a real fiber, and also lower than the expected values in the recent simulations [13]. Thus in order to emulate higher-order effects more accurately, more sections may be required, although deterministic control may improve the higher-order statistics.

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's state. To characterize stability, we observed the output SOP variation of our emulator 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. 3(c) 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 varied negligibly over tens of hours. As a comparison, the other conventional emulators show dramatic drifting over short period (Figure 3a and 3b). The generated DGD and 2nd-order PMD also remain stable over hours. In addition to the superior stability, the repeatability of the emulator is also remarkable in the laboratory environment.

Importance Sampling using Programmable DGD Elements

Importance sampling (IS) is a well-known technique for biasing the method of obtaining random samples such that the statistical results are concentrated in an area of interest in the sample space. This allows one to more effectively study the effects of a random phenomena, such as PMD, with fewer trials than would ordinarily be required by using conventional Monte Carlo techniques. Using the emulator described in the previous section, we are able to apply this powerful technique to physical fiber systems so that the impairments due to rare PMD events can be quickly and experimentally characterized and provide a comparison for results obtained previously via computer simulations.

The importance sampling technique we employed is conceptually illustrated in Figure 4. We exploit the programmability of the DGD elements to perform IS by applying randomly selected DGD values from a probability density function (pdf) other than a Maxwellian. Any pdf may be used, but the best choices are those that will tend to generate more output samples in the region of interest with the fewest possible measurements. For our first case, we chose to apply a uniform distribution of DGD values to each element over their full 45-ps range. In contrast to conventional importance sampling techniques, deterministic polarization coupling (i.e. biased polarization coupling) between sections is not required in this new approach. Here we still only apply uniform polarization coupling between sections.

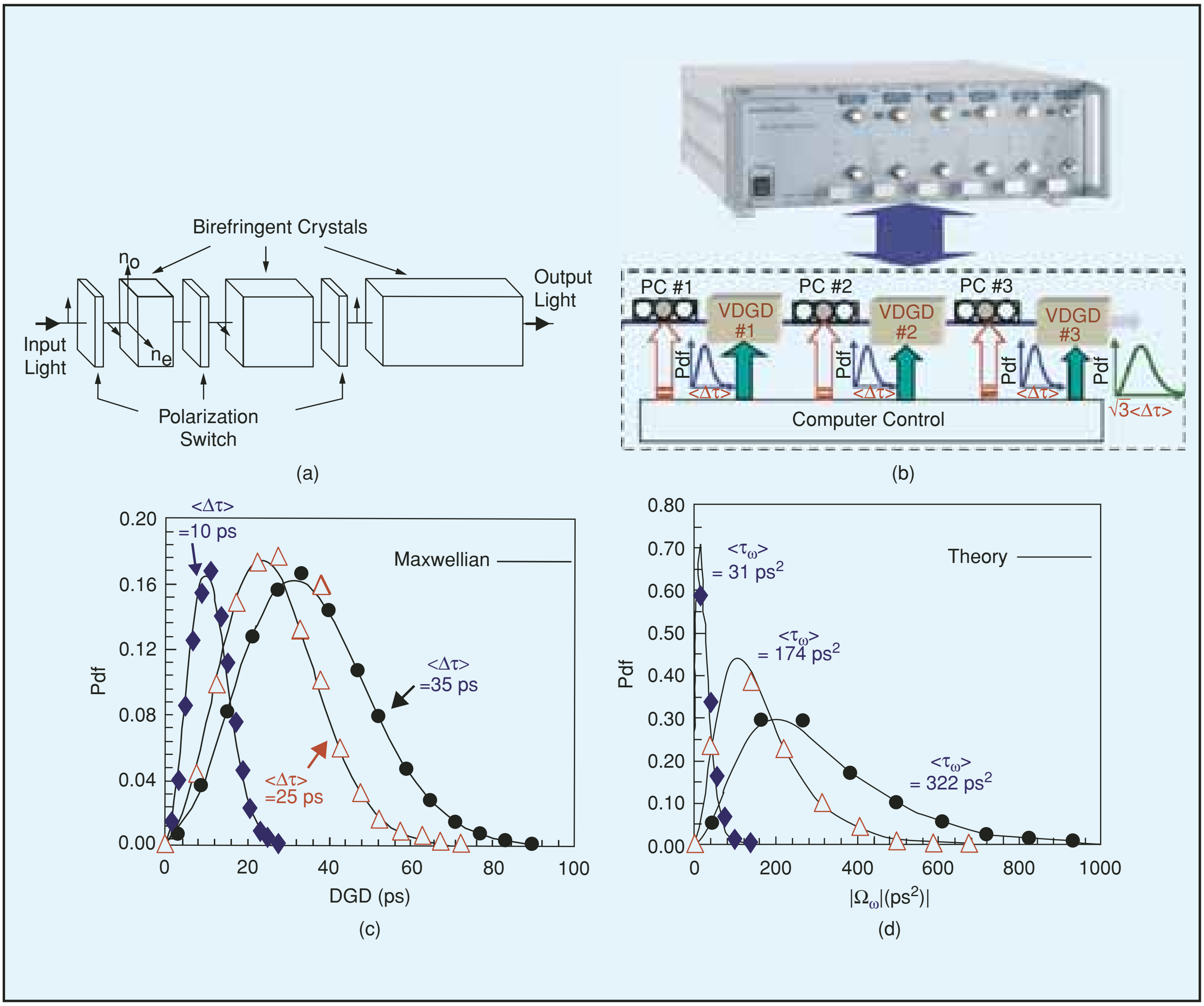


Figure 2 (a) Configuration of programmable DGD element (b) Programmable DGD elements based PMD emulator and generated tunable statistics (c) first-order (DGD) distribution and (d) second-order PMD (SOPMD) distribution

The DGD applied to each element and the corresponding output DGD and 2nd-order PMD are recorded for each sample. As expected, the measured output values will not follow the desired Maxwellian distribution and must be properly weighted to adjust their probabilities to match the desired Maxwellian statistics. For each DGD section, let $p(x_i)$ be the probability of obtaining DGD x_i using the desired Maxwellian pdf (with an average DGD of $\Delta\tau = \langle DGD \rangle/(3^{1/2})$) and $p^*(x_i)$ be the probability using the uniform pdf. For each sample, i, three likelihood ratios, $p(x_i)/p^*(x_i)$, are computed using the three applied DGD values for the x_is. The three ratios are multiplied together and divided by the total number of samples to determine the "weight" for each sample. The output DGD values are then sorted, while keeping track of the corresponding weights. The DGDs and corresponding weights are grouped into DGD bins and the weights in each bin are summed to obtain the probability for that bin. These probabilities are then plotted alongside a Maxwellian, integrated over each bin, for comparison. Note that, since the programmable ability plays a key role for importance sampling using biased distributions, the stability and repeatability of programmable DGD elements, which are highly desirable in conventional PMD emulators to facilitate long-term system evaluation, are not crucial for this application.

Experimental Importance Sampling Results

The resulting DGD and 2nd-order PMD probability distributions when 1000 uniformly distributed DGDs are applied to the three

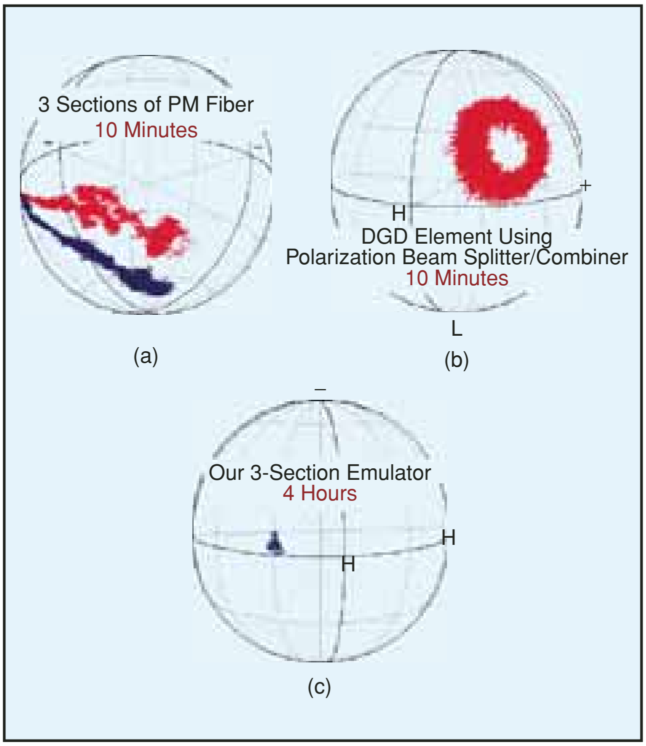


Figure 3 Comparison of the stability performance for different emulators (a) 3-section PM fiber based emulator in ten minutes; (b) a single stage emulator based on polarization beam splitting/combining in ten minutes; (c) our emulator over 4 hours

sections are shown in Figure 5. Figs. (a) and (c) show the distributions of the unprocessed, measured values. Clearly, numerous large DGD and 2nd-order PMD values result, relative to the unbiased case. In Figs. (b) and (d), the measured samples have been renormalized as described above, where $p(x_i)$ is a Maxwellian distribution with $\Delta\tau = 8.7$ ps/section. As expected, the experimental points for the total DGD closely approximate a Maxwellian with <DGD> = $3^{1/2}(8.7) = 15$ ps and rare events down to 10^{-24} are obtained, whereas conventional sampling would only reach 10^{-3} probabilities with 1000 trials. The experimental 2nd-order PMD pdf (Fig. 5d) has the correct shape, but falls short of the theoretical pdf for a real fiber because only three sections are used. However,

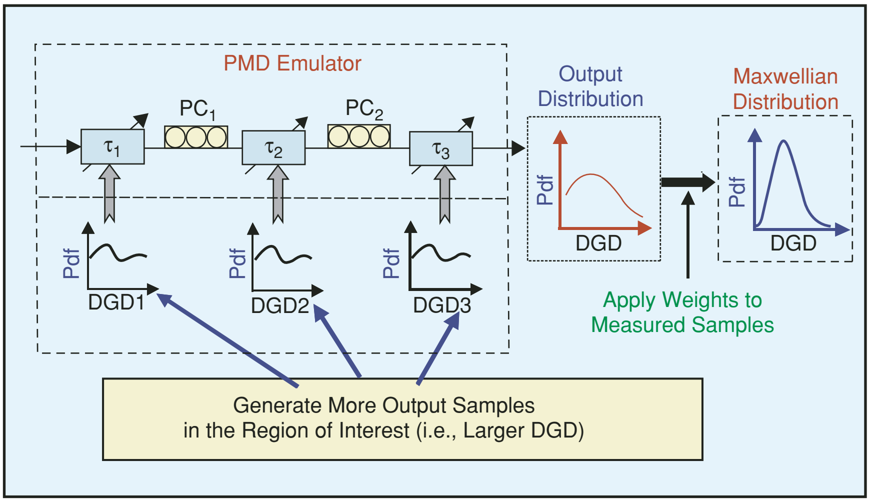


Figure 4 Conceptual diagram of PMD emulation using importance sampling, which is accomplished by applying a biased DGD distribution to each section (chosen to emphasize the region of interest) and then appropriately weighting the results to obtain the desired pdf.

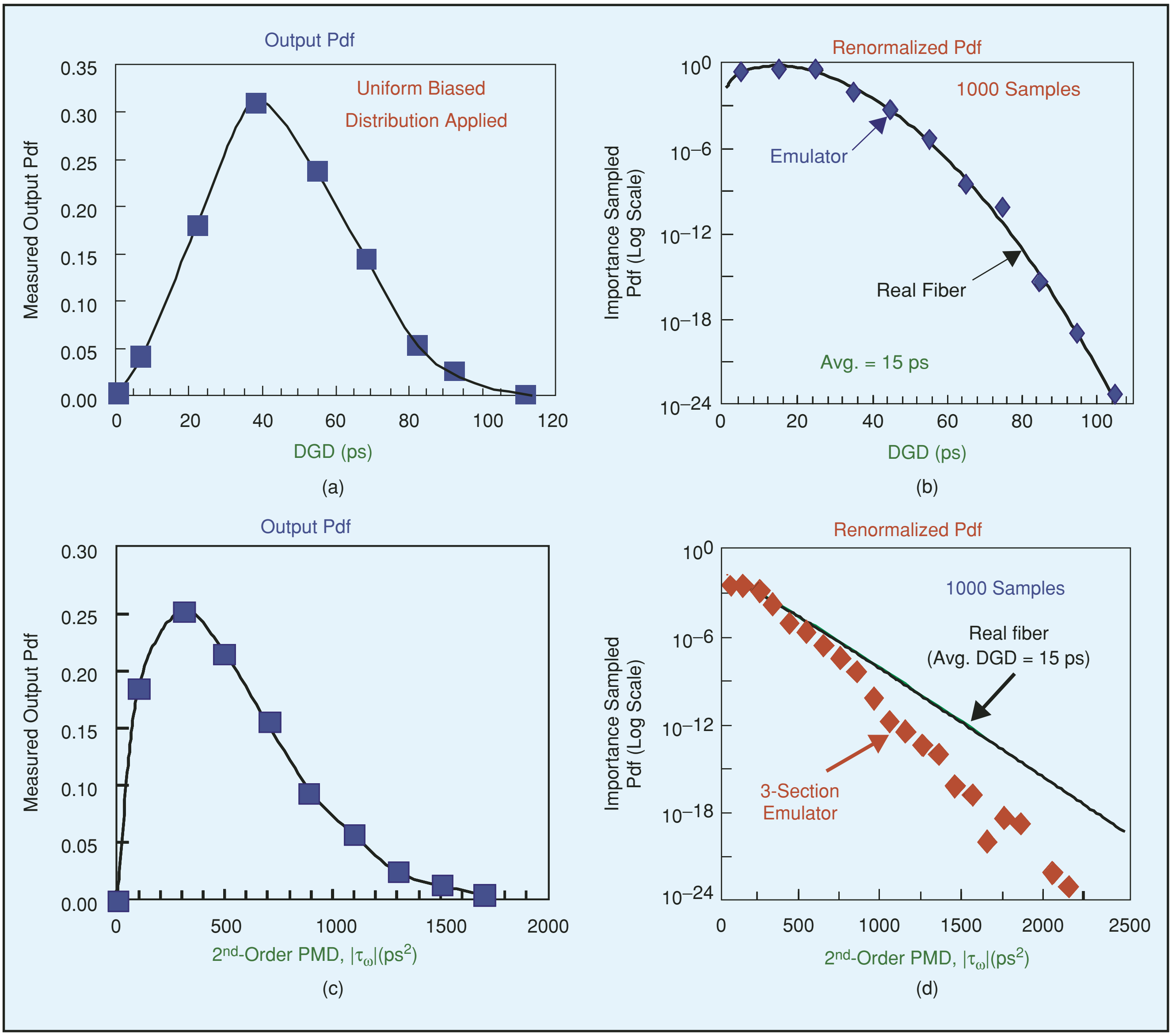


Figure 5 Experimental results of importance sampling (a) generated DGD distribution (b) normalized DGD distribution (c) generated SOPMD distribution and (d) normalized SOPMD distribution

it is notable that large 2nd-order PMD values are obtained with this method.

In addition to the PMD emulation results using importance sampling, we further apply this technique into real system evaluation, i.e. the Q-factor distribution due to statistical PMD effects [14]. The measured Q-penalty probability distribution extends to $<10^{-17}$ with only 1800 experimental samples.

Conclusion

In summary, we demonstrated an electronically controllable and programmable DGD based PMD emulator that can generated tunable statistics. For the first time, the stable and repeatable DGD programmability of the emulator enables the experimental realization of importance sampling, a powerful technique that allows system designers to investigate extremely low probability events that may cause system outages for only minutes per year with relatively few random samples. Due to its reconfigurable nature, this emulator can be used as a powerful platform and will find various applications in the manipulation of PMD effects, including distributed PMD compensation and advanced PMD emulation (importance sampling, multicanonical, slow dynamics, etc.).

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