Polarization-Mode-Dispersion Emulator Using Variable Differential-Group-Delay (DGD) Elements and Its Use for Experimental Importance Sampling

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***Abstract*—We demonstrate a practical polarization-mode-dispersion (PMD) emulator using programmable differential-group-delay (DGD) elements. The output PMD statistics of the emulator can be chosen by varying the average of the Maxwellian DGD distribution applied to each element. The emulator exhibits good stability and repeatability in a laboratory environment. In addition, we demonstrate how this emulator may be used to experimentally employ the powerful technique of importance sampling to quickly generate extremely low probability events. This technique is used to measure the Q-factor degradation due to both average and rare PMD values in a 10-Gb/s transmission system.**

***Index Terms*—Differential-group-delay (DGD), emulator, importance sampling, optical communications, polarization-mode dispersion (PMD).**

I. 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]–[3]. 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.

Previously demonstrated PMD emulators are typically constructed using several randomly coupled polarization maintaining (PM) fibers [4], [5] or birefringent crystals mounted on rotation stages [6]. Two major drawbacks of current emulators are: 1) the lack of stability or repeatability and 2) 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 ($\text{penalty} > 1$ dB) due to PMD occur with a probability of 10^{-6} or less (<1 min/yr) [2]. 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 [7]. 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 [8]–[11]. 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 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 publication shows another PMD emulation approach that

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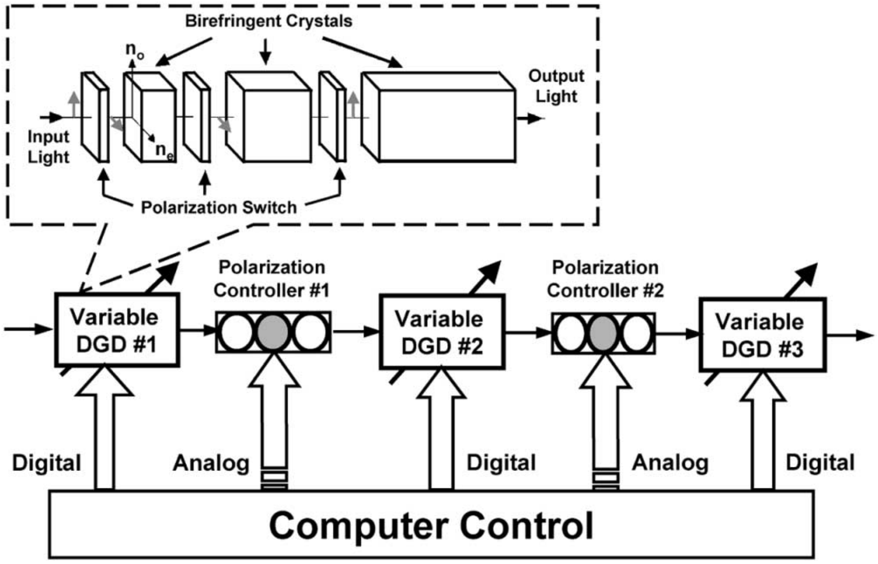
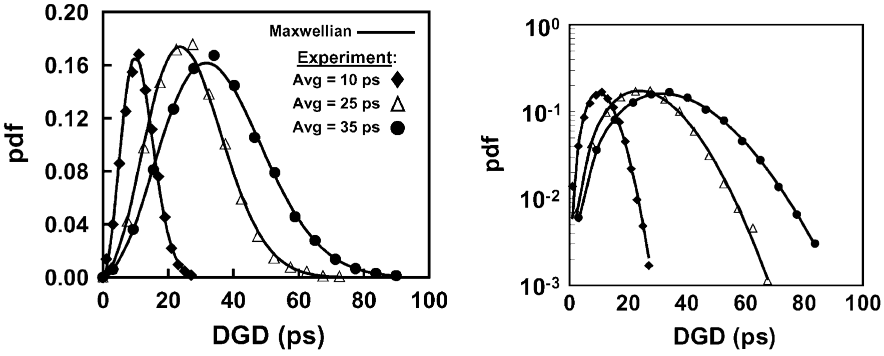


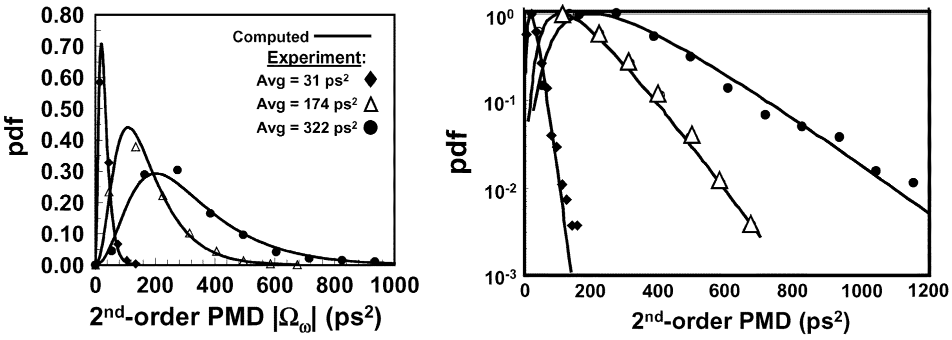
Fig. 1. PMD emulator with three programmable DGD elements separated by two electrically driven polarization controllers.



(a)

(b)

Fig. 2. Three output DGD distributions with different statistical averages, each showing a good fit to the Maxwellian pdf expected from a real fiber: (a) linear scale and (b) logarithmic scale.



(a)

(b)

Fig. 3. The corresponding second-order PMD distributions to Fig. 2: (a) linear scale and (b) logarithmic scale. The solid curves are drawn from computer simulation results of this emulator, showing that the mean second-order PMD is about 30% lower than that expected from a real fiber with the same average DGD since only three sections are used.

may be a good candidate for such applications, though it has not yet been demonstrated for importance sampling [12].

In this paper, 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 35 ps and corresponding second-order statistics. The stability and repeatability of the emulator DGD and output state of polarization (SOP) are characterized. 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 four times.

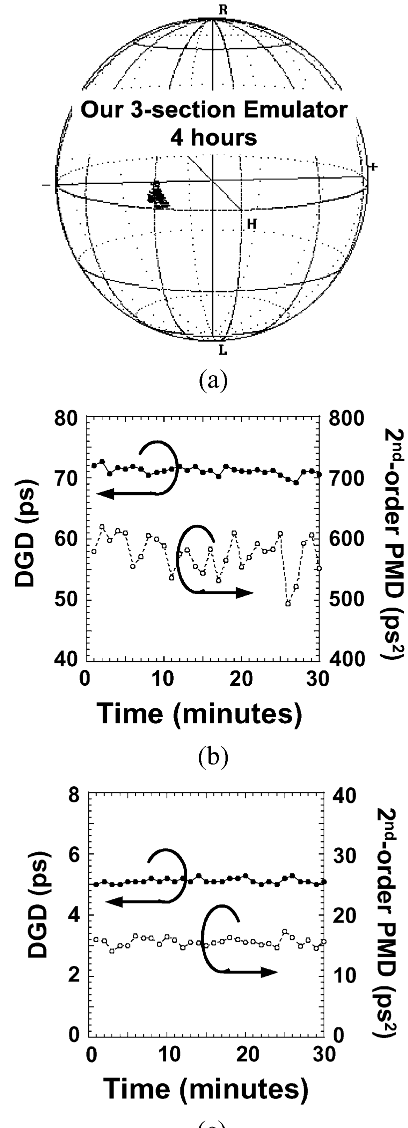
Using this emulator, we present a new method to readily enable experimental importance sampling to produce low-probability events without the need to determine and control the direction of the PMD vector between sections. With this emulator, we show that importance sampling can be accomplished by simply 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 $\langle \mathrm{DGD} \rangle = 15$ ps) and correspondingly rare second-order PMD events after taking only 1000 samples. We also employ "multiple importance-sampling" techniques to combine the results from three different distributions to achieve better coverage of the entire sample space. The resulting distribution tail extends to 10^{-30}.

In addition, experimental measurements have been performed in the past to characterize the system Q degradation due to PMD [13]. However, an impractically large number of random samples must be taken to explore the rare events in the distribution tail using these previous methods. Therefore, we also use multiple importance-sampling to measure the Q degradation due to the PMD generated by our emulator. The measured Q-penalty probability distribution extends to $<10^{-17}$ with only 1800 experimental samples.

This article is structured as follows: The emulator concept and construction are described in Section II. The stability and repeatability characteristics are discussed in Section III. The experimental importance sampling techniques are detailed in Section IV followed by the measurement results in Section V. The system level characterization of the PMD-induced Q degradation is then shown in Section VI.

II. PMD EMULATION WITH TUNABLE STATISTICS

As shown in Fig. 1, the emulator is constructed from three variable DGD elements separated by two fiber-squeezer-based polarization controllers. Several variable DGD generation approaches have been proposed [14], [15] and here we employ a very practical approach that was described recently in [16]. 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 [16]. 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 [17]. 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 $\Delta\tau$ [18], [19]. This yields an average DGD of $3^{1/2}(\Delta\tau)$ for the total emulator and an average second-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 [19]. To demonstrate tunability of the PMD statistics, three different distributions are generated, as shown in Figs. 2 and 3 for $\langle \mathrm{DGD} \rangle = 10, 25,$ and 35 ps. As expected, the DGD values closely match the expected Maxwellian distribution. The corresponding second-order PMD distributions have averages of 31, 174, and 322 ps^2, which are $\sim$30% lower than expected for a real fiber, and also lower than the expected values in the recent simulations [19]. All of the PMD measurements shown throughout this paper were performed using the Jones matrix method on a commercial PMD analyzer [20].



(a)

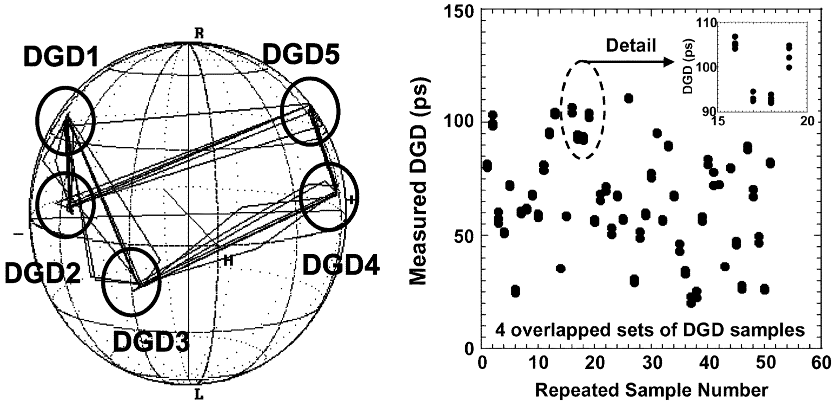
(b)

(c)

Fig. 4. (a) Output SOP stability of the emulator over 4 h. (b) and (c) measurements of the DGD and second-order PMD over 30 min for two different average DGD values: (b) $\langle \mathrm{DGD} \rangle = 71$ ps and (c) $\langle \mathrm{DGD} \rangle = 5$ ps.

III. 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. 4(a) shows that the output



(a) (b)

Fig. 5. (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).

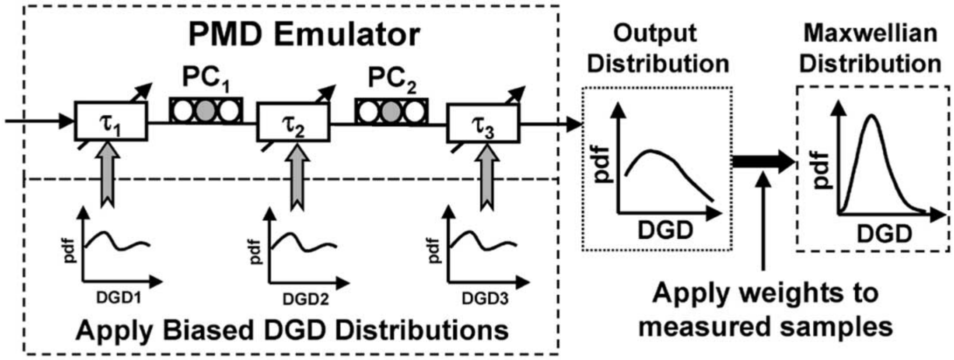


Fig. 6. Conceptual diagram of PMD emulation using importance sampling, which is accomplished by applying a biased DGD distribution to each section (chosen to emphasize the region of interest) and then appropriately weighting the results to obtain the desired pdf.

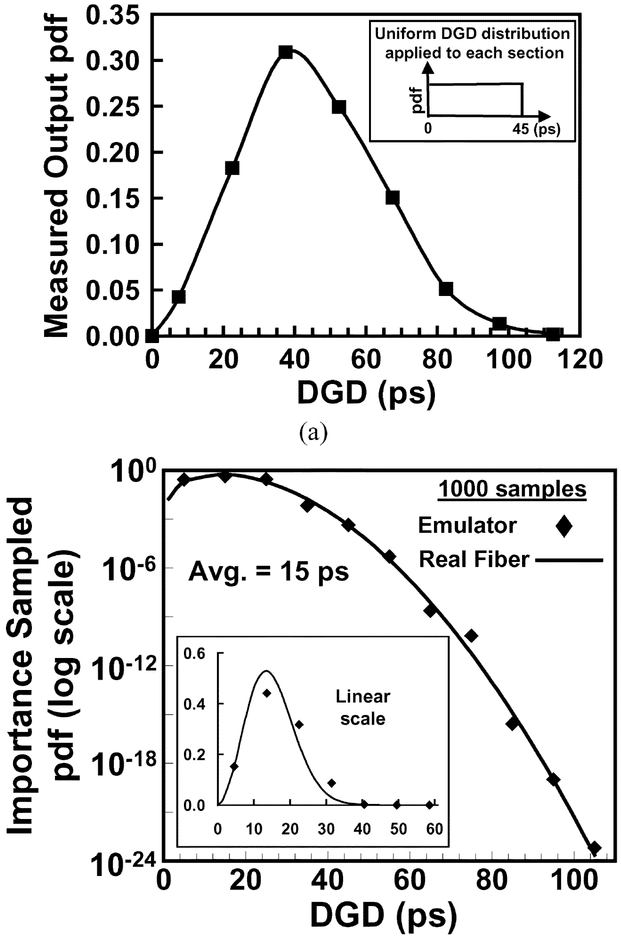
SOP of our three-section emulator remains nearly constant over a 4-h period. For each individual section, we observed that the SOP varied negligibly over tens of hours. In order to characterize the stability of our emulator, we measured the variation of the emulator's DGD and second-order PMD over 30 min for both high and low DGD values. As shown in Figs. 4(b) and (c), the DGD remained remarkably stable for both cases, and the second-order PMD varied within a reasonable range (e.g., for the sample with 72-ps DGD, the DGD varied <5% and the second-order PMD varied ∼15% over 30 min). It should be noted that some of this variation is due to the inherent measurement error of the PMD analyzer system (the same measurement for a single piece of PM fiber with 50 ps DGD also showed ∼5% variation over 30 min).

To characterize the SOP repeatability, the emulator was repeatedly cycled six times through five different DGD states at 1-min intervals. Fig. 5(a) shows that the output SOP repeatedly returns to the same point on the Poincaré sphere for each DGD state (The traces shown in the figure may not illustrate the real phase or PMD vector variations during polarization switching due to the relatively slow response of the polarization analyzer). 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. 5(b). At each sample point, the DGD variation is typically <5%, indicating the ability to generate a lookup table of control parameters and corresponding DGD output values.

IV. 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 Fig. 6. 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.

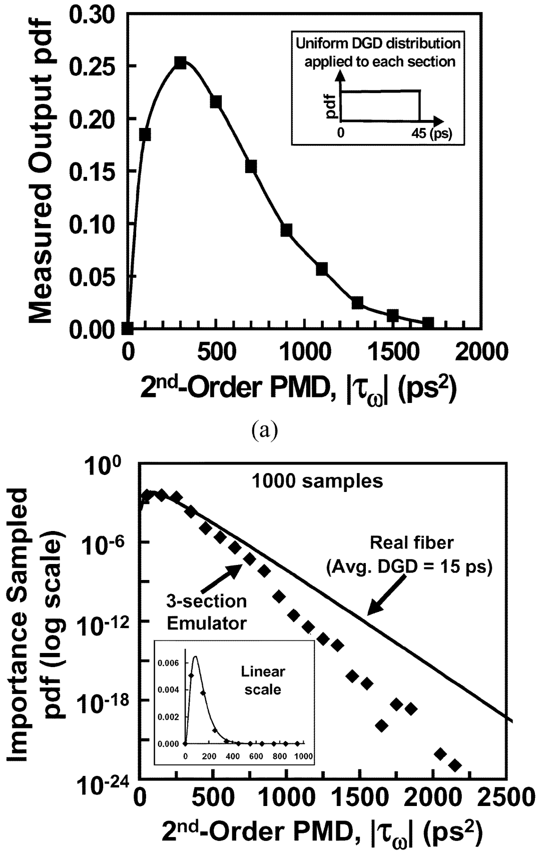


(a)

(b)

Fig. 7. Importance sampling results for 1000 uniformly distributed DGDs applied to each section (0–45 ps). (a) Measured output pdf (note several values at large DGDs are generated) and (b) pdf after renormalizing the data to obtain a Maxwellian distribution with $\langle \mathrm{DGD} \rangle = 15$ ps. Points down to 10^{-24} are generated with only 1000 samples. The inset shows the linear scale.

The DGD applied to each element and the corresponding output DGD and second-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 $\mathrm{p(x_i)}$ be the probability of obtaining DGD $\mathrm{x_i}$ using the desired Maxwellian pdf (with an average DGD of $\Delta\tau = \langle \mathrm{DGD} \rangle / (3^{1/2})$) and $\mathrm{p^*(x_i)}$ be the probability using the uniform pdf. For each sample, i, three likelihood ratios, $\mathrm{p(x_i)/p^*(x_i)}$, are computed using the three applied DGD values for the $\mathrm{x_i}$s. 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.



(a)

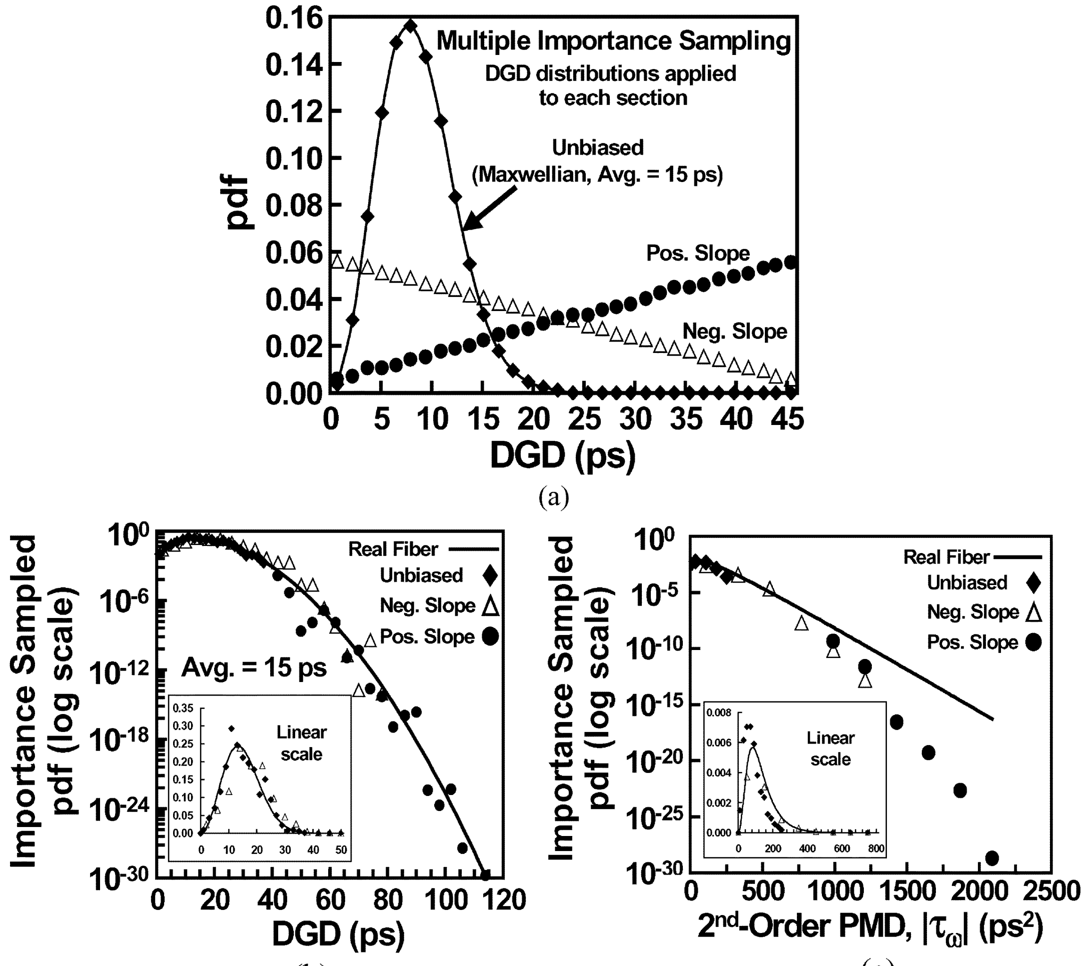
(b)

Fig. 8. Second-order PMD pdf for the importance sampling experiment described in Fig. 7. (a) Measured output pdf and (b) pdf after renormalizing the data. The three-section emulator produces a second-order pdf with the correct shape, but a slightly lower average than that of a real fiber because of the small number of sections. The inset shows the linear scale.

V. EXPERIMENTAL IMPORTANCE SAMPLING RESULTS

The resulting DGD and second-order PMD probability distributions when 1000 uniformly distributed DGDs are applied to the three sections are shown in Figs. 7 and 8. Figs. 7(a) and 8(a) show the distributions of the unprocessed, measured values. Clearly, numerous large DGD and second-order PMD values result, relative to the unbiased case. In Figs. 7(b) and 8(b), the measured samples have been renormalized as described above, where $\mathrm{p(x_i)}$ 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 $\langle \mathrm{DGD} \rangle = 3^{1/2}(8.7) =$ 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 second-order PMD pdf [Fig. 8(b)] has the correct shape, but falls short of the theoretical pdf for a real fiber because only three sections are used. However, it is notable that large second-order PMD values are obtained with this method.

To efficiently obtain PMD events covering the entire range from low to high values, we used the technique of “multiple importance sampling” [9] to combine the results of several experiments using different DGD pdfs applied to each section. As shown in Fig. 9(a), an unbiased, Maxwellian pdf was used to obtain several values in the low DGD region, a negatively sloped linear pdf was used to obtain low to medium DGDs and a pos-



(a)

(b) (c)

Fig. 9. Multiple importance sampling results. (a) The three DGD distributions applied to each section (840 samples/distribution). (b) Resulting DGD distribution showing that each pdf generates samples in different regions to cover the entire Maxwellian. (c) Resulting second-order PMD pdf. The insets show the pdfs on a linear scale, where it is evident that better coverage of lower values is achieved in comparison to the case shown in Figs. 7 and 8.

itively sloped pdf was used to obtain high DGDs. 840 samples were taken for each distribution. The experimental results are weighted as described in [9] to obtain the distributions shown in Figs. 9(b) and (c). The multiple IS technique provides better coverage of the entire sample space. The resulting distribution tail extends to 10^{-30}.

VI. MEASUREMENT OF Q DEGRADATION

In addition to characterizing the PMD statistics of the emulator, it was inserted into a 10-Gb/s transmission system and the multiple IS technique was used to characterize the impact of the PMD on the statistics of the system Q for both average and extremely rare PMD events. The Q values are measured at the optically pre-amplified receiver for 10-Gb/s NRZ data using a $2^{23} - 1$ PRBS. The Q measurement is performed using the method presented in [21].

Similar to the method used in the previous section, importance sampling for Q measurements is accomplished by applying a biased DGD distribution to each emulator section (chosen to emphasize the region of interest) and then appropriately weighting the Q penalty results to obtain the proper pdf. Instead of applying Maxwellian-distributed DGDs to each section (the conventional, unbiased case), a uniform distribution is applied to each section to cause the emulator to generate more samples at high DGD values, which often correspond to low Q values. The applied DGDs and measured Q values are recorded for each sample point and the measured Q probabilities are then appropriately corrected for the effects of biasing the DGD distributions.

To achieve good coverage of both low and high probability events, we also employed multiple IS here, in which the results from two IS experiments were combined as shown in Fig. 10(a), for an unbiased Maxwellian (~750 samples) applied to each section and a biased uniform distribution (~1000 samples). The unbiased distribution provides good coverage of high probability (average) events, whereas the biased case yields a large number of low-probability values since a large number of high-DGD samples are generated. The resulting Q probability distribution is shown in Fig. 10(b) for a system with 15-ps average DGD (linear scale is shown on inset). The Q degraded to ~12 dB at a probability of $\sim 10^{-17}$, and a complete loss of the signal was observed in several samples (not plotted here). This is an extremely low-probability event that occurs when the PMD is ≥ 1 bit time. It should also be noted that these Q measurement include the effects of both the first-order and higher order PMD, although the mean of the second-order

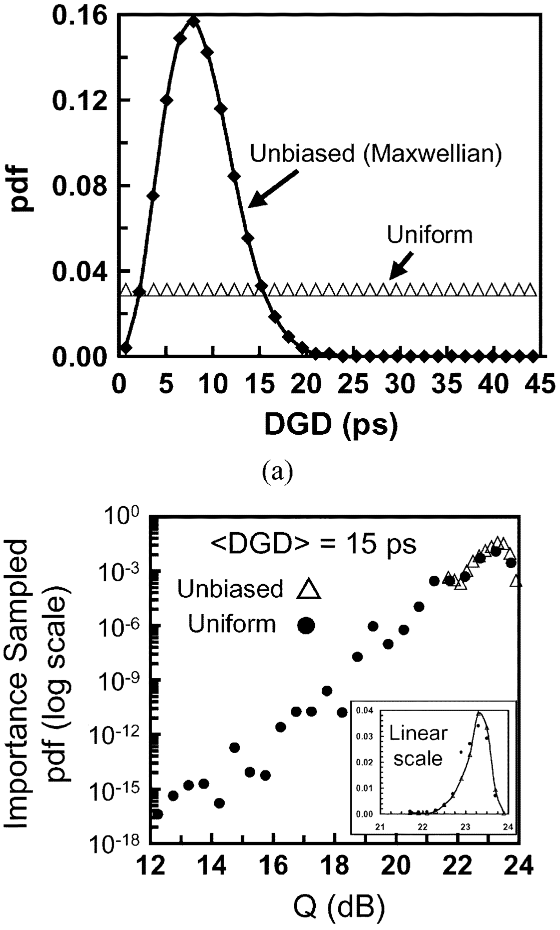


Fig. 10. (a) The DGD distributions applied to each section for the measurements of Q degradation: unbiased (Maxwellian, with average DGD $\sim$ 8.7 ps per section) and biased (uniform). (b) Measured Q probabilities using multiple IS for a system with average $\text{DGD} = 15$ ps ($\sim 10^{-17}$ prob. that Q drops to $\sim$12 dB).

PMD distribution of this emulator is ~30% lower than that of a real fiber with the same mean DGD because only three tunable DGD elements are used.

VII. CONCLUSION

In summary, an electronically controllable PMD emulator that is constructed from three programmable DGD elements has been experimentally characterized and used to study the effects of PMD on a fiber transmission system. The generated PMD statistics of the emulator can be readily tuned by simply applying different DGD distributions to each section. 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. The PMD emulator's statistics, performance in terms of stability and repeatability, and use for a system characterization in terms of PMD-induced Q degradation were evaluated. One of the limitations of this emulator is that it would require more DGD elements in order to accurately emulate the statistics of second-order PMD. However, we would also note that, as more sections are added, the efficiency of this importance sampling method (biasing the DGD distribution of each section toward higher values while uniformly scattering the polarization between sections) is likely to decrease because we expect that it will become less probable for the PMD vectors of the DGD elements to be aligned as the number of sections increases due to the uniform polarization coupling. This is in contrast to the method commonly used in computer simulations where the PMD vectors of the sections are preferentially aligned, while their DGDs remain fixed. While the technique presented here is experimentally simpler to employ and works well for first-order PMD, it is not yet clear what the tradeoff is between the importance sampling efficiency and the number of tunable DGD sections used in the emulator.

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X. S. Yao (M'97), biography and photograph not available at the time of publication.

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