Emulator of First- and Second-Order Polarization-Mode Dispersion

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Abstract—Contrary to approaches which try to mimic a standard fiber as closely as possible, the emulator presented here gives constant (but user adjustable) values for differential group delay (DGD) and ratio of first- to second-order polarization-mode dispersion (PMD). Once it is set, the ratio is conserved while the DGD can be easily varied within a range of 0–300 ps. This allows to investigate the low-probability events of large DGD and second-order PMD important for system outage.

Index Terms—Communication system testing, polarization-mode dispersion.

I. INTRODUCTION

UPGRADING the existing telecom systems to high bit rates ($\geq$10 Gb/s) leads to several problems. Already some time ago, the impact of first- and second-order polarization-mode disperison (PMD) in such systems has been analyzed [1], [2]. It was found that second-order PMD, i.e., the frequency dependence of the principle states vector (PSP) $\vec{\Omega}$, can lead to important fluctuations around the mean penalties induced by first-order PMD. For the case of large values of the chromatic dispersion, second-order PMD becomes in fact a major source of performance degradation [1]. Moreover, with the advent of PMD compensators, which typically compensate for first-order effects only (leaving higher orders unaffected or even increasing them), impairments due to accumulated second-order PMD are to be expected [3].

Consequently, second-order PMD is an important issue for a proper assessment of system performance and PMD emulators should therefore not only include the first, but also the second order. The emulators of today have the strategy to mimic as closely as possible long standard fibers with polarization-mode coupling [4]–[6]. They typically consist of pieces of highly birefringent polarization maintaining (PM) fibers joint either by splicing or by rotatable connectors. In the first type, the desired Maxwellian pdf for the DGD is obtained by taking an ensemble over a large wavelength interval. However, the wavelength dependence of the PSP $\vec{\Omega}$ is usually not accounted for in a correct way [4]. Using a fixed wavelength and changing the coupling among the PM fibers (e.g., by changing the temperature or by mechanically varying the birefringence axes directions of the individual trunks) to obtain a Maxwellian distributed DGD, there are indications that second-order PMD could be quite well approximated [5]. However, a large number of trunks (>15, [4],

[5]) and a large number of different realizations are to be used. This adds to the emulator complexity and measurement time. Moreover, there are indications that the rare events of large DGD values (tail of the Maxwell distribution) in these PMD emulators can be orders of magnitudes smaller than the desired theoretical values [7]—however, it is these large DGD events which are important for the system outage probability!

We, therefore, opt for a different approach, where the user can set a constant value for the DGD and the ratio of DGD to instantaneous second-order PMD[1] , independent of the wavelength. Consequently, contrary to the other emulators, no statistics is reproduced (we therefore have a "DGD emulator" rather than a PMD one). The values for DGD and instantaneous second-order PMD are known precisely without having to measure them and can be experimentally linked to the corresponding system penalty. In addition, our emulator also allows to simulate situations—like a first-order compensated system with low DGD and large second-order PMD—not achievable in emulators that mimic long standard fibers.

II. PRINCIPLE OF OPERATION

The emulator is based on two trunks of PM fiber, with a coupling angle φ between their birefringence axes. The overall PSP $\vec{\Omega}$ then becomes [8]

$$\vec{\Omega}(\omega) = \frac{1}{2}\beta_2\vec{e}_2 + \frac{1}{2}\beta_1(\vec{e}_1 \cdot \vec{e}_2)\vec{e}_2$$
$$+ \frac{1}{2}\beta_1\cos(\beta_2\omega)(\vec{e}_1 - (\vec{e}_1 \cdot \vec{e}_2)\vec{e}_2) + \frac{1}{2}\beta_1\sin(\beta_2\omega)\vec{e}_1\times\vec{e}_2 \quad (1)$$

where $\vec{\Omega}_{1,2} = \beta_{1,2}\vec{e}_{1,2}$ are the PSP of the first and second trunk with DGDs of β_1 and β_2, respectively. Assuming that β_i and $\vec{e}_i$ are independent of wavelength (a very good approximation for PM fibers), one can straightforwardly calculate the overall DGD and instantaneous second-order PMD

$$\left|\vec{\Omega}(\omega)\right|^2 = \text{DGD}^2 = \beta_1^2 + \beta_2^2 + 2\beta_1\beta_2\cos(\varphi)$$
$$\left|\frac{\partial}{\partial\omega}\vec{\Omega}(\omega)\right| = \left|\vec{\Omega}_\omega\right| = \beta_1\beta_2\sin(\varphi). \quad (2)$$

As one can see, both these quantities are constant with wavelength. The derivative of the modulus of $\vec{\Omega}$, which accounts for about 1/9th of the total amount of second-order PMD in a long

[1]In the remainder of the letter, we use the following definitions and terms:

first-order PMD: $\sqrt{\left\langle\left|\vec{\Omega}(\omega,t)\right|^2\right\rangle_t}$, DGD: $\left|\vec{\Omega}(\omega,t)\right|$ (varies with time)

second-order PMD: $\sqrt{\left\langle\left|(\partial/\partial\omega)\vec{\Omega}(\omega,t)\right|^2\right\rangle_t}$, instantaneous second-order PMD: $\left|(\partial/\partial\omega)\vec{\Omega}(\omega,t)\right|$ (varies with time).
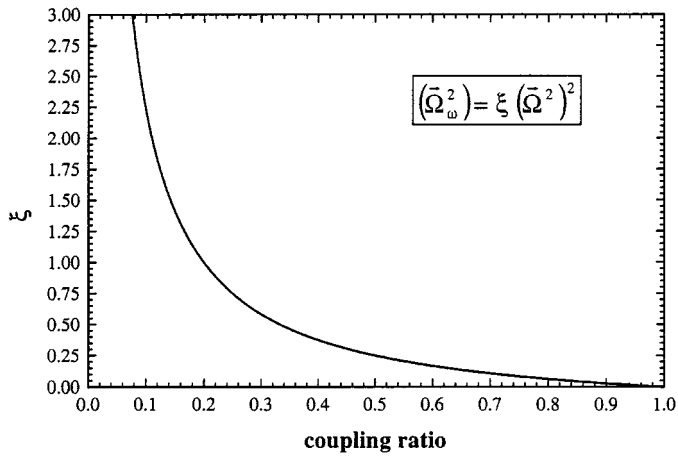
Fig. 1. Ratio of first- to second-order PMD, as a function of the coupling ratio between two PM fibers with arbitrary, but equal DGD [as calculated from (2)].
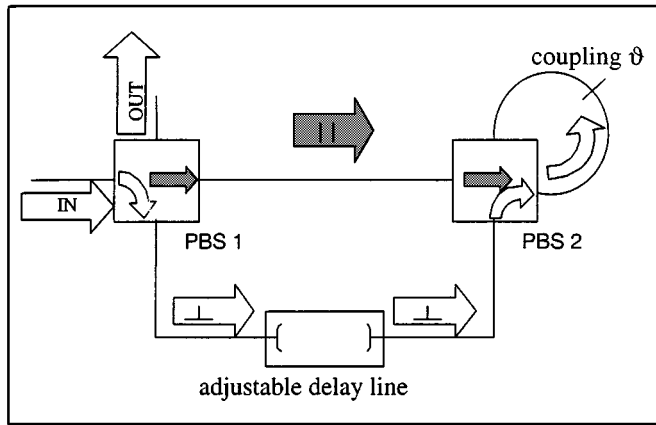

Fig. 2. Experimental setup of the emulator for first- and second-order PMD. The arrows indicate the light path during the forward pass of the emulator, corresponding to the first PM fiber. All fibers in the setup are polarization maintaining. PBS: Polarizing beamsplitter.

Fig. 3. Interferometric PMD measurements of the emulator for a fixed delay line setting of 15 ps and couplings of $\vartheta = 0°$ (top), $90°$ (middle) and $41°$ ($\xi = 1/3$). The power has been normalized so that the central peak is one and the curves were offset vertically for clarity.

standard fiber [2], is therefore zero and the second-order PMD vector $\vec{\Omega}_\omega$ becomes orthogonal to the PSP $\vec{\Omega}$.

Due to the dependence of DGD and instantaneous second-order PMD on the coupling angle φ (2), one can set a desired ratio ξ of the instantaneous second-order PMD to the DGD as is illustrated in Fig. 1 for two PM fibers having the same DGD. Note that rather than the coupling angle φ, the coupling ratio $\cos(\varphi)^2$ has been used as it is this value which can easily be measured for the emulator adjustment. Note that the ratio $\varphi \xi = (\tan(\varphi)/2)^2$ is conserved for any values of DGD, as long as they are the same for both fibers. The situation of $\beta_1 = \beta_2 = \beta$ is, therefore, advantageous and consequently employed in our emulator.

III. EXPERIMENTAL SETUP AND RESULTS

The experimental setup for the emulator is shown in Fig. 2. It is nothing else than the analog to two PM fibers with adjustable DGD and a coupling φ between them.

The parallel and perpendicular orthogonal polarization mode of the input PM fiber are split at the first PBS, allowing to induce a retardation (0–300 ps) on the orthogonal mode using a free space delay line. The two modes are recombined at the second PBS, again with the axes of the following PM fiber aligned. The
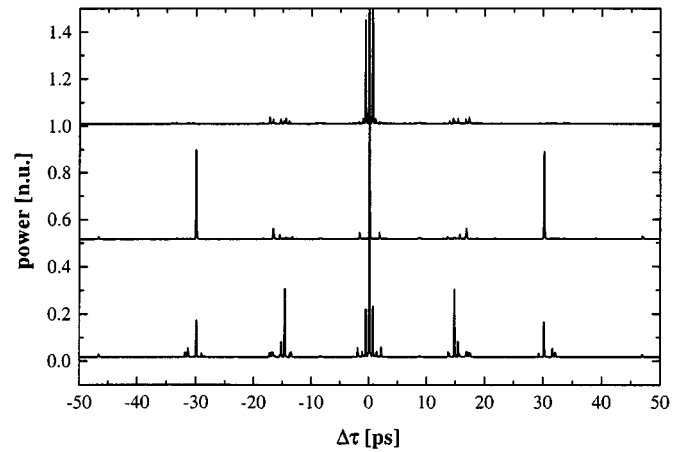
light trajectory up to the coupling ϑ, therefore, represents the first PM fiber, with DGD $\Delta\tau_1$. The polarization-mode extinction ratio at the second PBS was measured to be $\sim$22 dB. The loss up to the coupling point was $\sim$3 dB for the lower arm and 1 dB for the upper arm. The difference can be explained by the insertion loss of the delay line ($\sim$1 dB) and a bad splice in the lower arm. The loss of the upper arm was thereafter increased to the value of the lower one. The second fiber (after the coupling point) consists of the backward pass through the same polarization interferometer. Note that for the two "quasi-PM" fibers to be aligned ϑ has to be set to $90°$. Therefore, in order to have the same situation as for two real PM fibers with a coupling φ, one has to use $\vartheta = 90° - \varphi$. The coupling ratio can be easily determined by adjusting the input light to the $\parallel$ mode (see Fig. 2) and measuring the decrease in power when blocking the delay line. Physically, the coupling was realized by inserting a polarization controller with ultralow PMD (Lefèvre controller), but could be achieved more conveniently using a rotatable connector.

In the first realization of the emulator [9], an important difference in the DGD of the forward ($\Delta\tau_1$) and backward ($\Delta\tau_2$) pass (analog to the first and second PM fiber) was found. As discussed in Section II, the ratio of DGD to instantaneous second-order PMD was, therefore, no longer preserved as a function of the delay line setting. The reason for the discrepancy between $\Delta\tau_1$ and $\Delta\tau_2$ can in fact be easily understood by analyzing the emulator for a setting of $\vartheta = 0°$ (i.e., $\varphi = 90°$). The output for that case should be $|\Delta\tau_1 - \Delta\tau_2| = 0$, but is actually given by the DGD of the empoyed PM fiber (per length) times the total length through the emulator. This is because all the PM fibers in the emulator are aligned: a $\parallel$ input light (see Fig. 2) will remain so throughout its path to the ouput and the same holds for $\perp$ input light. $|\Delta\tau_1 - \Delta\tau_2|$ is independent of the delay line setting (which was also verified experimentally). It was nulled by adding a PM fiber with reversed axes and the correct DGD to the emulator output fiber. Fig. 3 shows interferometric PMD measurements of the emulator for a delay line setting of $\Delta\tau = 15\,\mathrm{ps}$ and different couplings ϑ of $0°$ (top), $90°$ (middle) and $41°$ (corresponding to the statistical case of $\xi = 1/3$ for long fibers, bottom). For $\vartheta = 0°$, the corresponding peak gives $|\Delta\tau_1 - \Delta\tau_2|$.
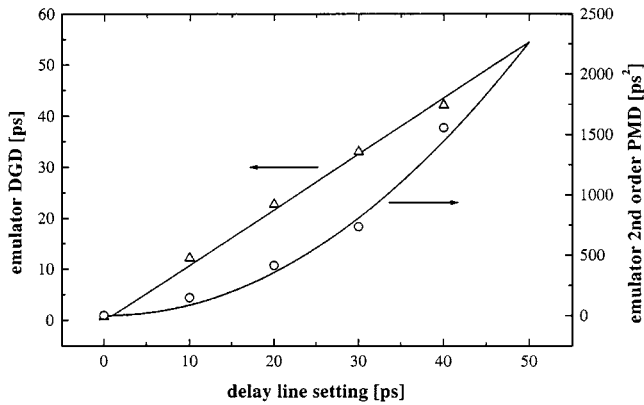
Fig. 4. DGD and instantaneous second-order PMD of the emulator as a function of the delay line setting. The coupling ratio was fixed at $\cos^2 \varphi = 0.3$ (roughly corresponding to $\xi = 2 \cdot 1/3$). Solid lines: Theoretical values. Symbols: Measured values.
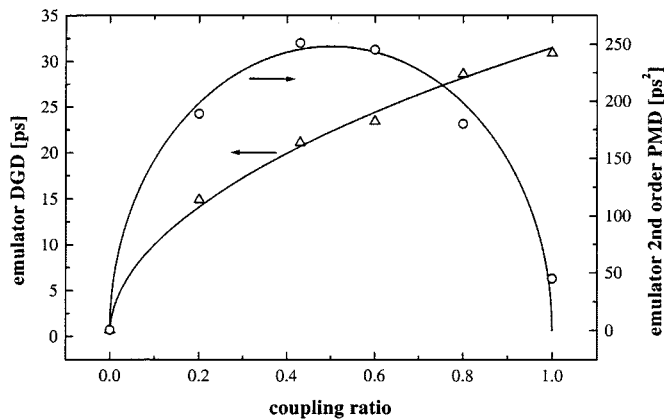

Fig. 5. DGD and instantaneous second-order PMD of the emulator as a function of the coupling ratio. The delay line setting was fixed at 15.75 ps. Solid lines: Theoretical values. Symbols: Measured values.

The measurement shows that a small difference of $\sim$0.6 ps persists because of a slight mismatch in DGD between the original emulator and the PM fiber added to the output. However, this difference is now too small to significantly change the ratio ξ as a function of the delay line setting. Fig. 3 further demonstrates that for a coupling of $\vartheta = 90°$, only a peak at $\Delta\tau_1 + \Delta\tau_2 \approx 2\Delta\tau$ is obtained, whereas for nonaligned fiber axes, peaks at both $\Delta\tau$ and $2\Delta\tau$ appear.

Fig. 4 shows theoretical (2) and measured DGD and instantaneous second-order PMD for a coupling ratio of 0.3 (corresponding to $\xi = 0.59$), as a function of the delay line setting $\Delta\tau$. The original standard Jones Matrix Eigenanalysis (JME) method as presented by Heffner et al. [10] was used to extract the PSP as a function of wavelength. For that purpose, the emulator was put into a temperature-controlled box to keep the output polarization stable with time. Using wavelength steps adapted to the DGD and instantaneous second-order PMD [10], a good agreement of the measurements (dots) and the model (lines) was obtained.

Thereafter, we set $\Delta\tau$ to 15.75 ps (giving a DGD of $\sim$20 ps for $\xi = 1/3$, which is about the tolerated limit in a 10-Gb/s link)

and varied the coupling ratio, i.e., ξ (Fig. 1 shows their relationship). Fig. 5 shows these results and once more, a remarkable agreement with the theory is found.

IV. CONCLUSION

A PMD emulator with adjustable DGD and ratio between DGD and instantaneous second-order PMD was presented. Although this emulator does not give any statistical output as real fibers do, it allows even the better to evaluate the impact of low-probability events of large (instantaneous) first- and second-order PMD on the system under test.

The principle of operation is based on two PM fibers, where the coupling between the two fibers sets the ratio of DGD to instantaneous second-order PMD. By changing a variable delay line, the emulator DGD can be easily varied from 0 to 300 ps (while the ratio of DGD to instantaneous second-order PMD is conserved). As the absolute wavelength does not enter the game, the emulator operates in a very broad wavelength region. The emulator performance was tested with JME measurements and the experimental values for DGD and instantaneous second-order PMD were found to agree well with the desired values set by the operator.

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