The development of a PMD Emulator

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Abstract — **In this paper we propose a novel deterministically first order PMD emulator using nonlinear chirped FBGs written into highly birefringence fibers.**

I. INTRODUCTION

Polarization mode dispersion (PMD) is an important impairment in optical transmission systems operating at 40Gb/s and above. PMD compensators development becomes then a priority to make possible the achievement of good performances at these high bit rates.

The statistical nature of the PMD effect makes difficult to assess the PMD compensators. If we use an installed communication system to this assessment we will need to wait very long times to evaluate the emulator over a significant range of differential group delay (DGD) values.

An accurate assess of PMD compensators is only possible with a PMD emulator system, that presents the same PMD properties of the link and that could quickly cycle through different DGD values. A PMD emulator makes possible a fast and versatile access to all possible DGD values, especially DGD values with low probability. Nevertheless the PMD statistics produced by an emulator should be related, in a known way, with the real fiber statistics.

The PMD phenomenon in optical fibers occurs because fibers contain some amount of anisotropy owing to an accidental loss of circular symmetry. Both the non circular waveguide geometry and the non symmetrical stress field in the glass are the two main contributions to this loss of symmetry and to the consequently birefringence rise. The birefringence changes randomly along the fiber length but it is always possible to define a special orthogonal pair of polarizations at the fiber input called the Principal States of Polarization (PSPs). Light launched into a PSP does not changes its polarization at the fiber output when wavelength is tiny varied. These PSP modes have different group delays, τ_g, which are the maximum and minimum mean time delays in the time domain view. The difference between the two delays is called the differential group delay (DGD) and characterizes the first-order PMD effects.

Using the Principal States Model [1], PSPs and DGD may both being described by the PMD vector, $\vec{\Omega}$. The PMD vector is just a vector in the Stokes space pointing in the direction of the fast PSP, $\vec{\mathrm{p}}$, with length equal to the differential group delay, $\Delta\tau$,

$$\vec{\Omega} = \Delta\tau\,\vec{\mathrm{p}} \qquad (1)$$

(here $\vec{\Omega}$ is defined in a left-circular Stokes space, where the s_3 Stokes parameter is unity and positive for left-handed circular polarization).

For long length fibers the mean square root of DGD has a square root of length dependence, $\Delta\tau_{rms} = D_p\sqrt{z}$, where D_p quantify the PMD effect. The probability density function (pdf) of DGD is a Maxwellian [2][3]:

$$p(\Delta\tau) = \frac{8}{\pi^2\langle\Delta\tau\rangle}\left(\frac{2\Delta\tau}{\langle\Delta\tau\rangle}\right)^2 e^{-\left(\frac{2\Delta\tau}{\langle\Delta\tau\rangle}\right)^2\frac{1}{\pi}} \qquad (2)$$

where $\langle\Delta\tau\rangle$ is the mean DGD. The mean DGD is related with $\Delta\tau_{rms}$ by the expression $\langle\Delta\tau\rangle = \sqrt{\frac{8}{3\pi}}\Delta\tau_{rms}$. A pdf of DGD well described by a Maxwellian function is the first key performance that a PMD emulator should meet.

Second order PMD characterizes the PMD vector changes with wavelength, and is described by the derivative,

$$\vec{\Omega}_\omega = \Delta\tau_\omega\vec{\mathrm{p}} + \Delta\tau\vec{\mathrm{p}}_\omega \qquad (3)$$

where the subscript ω indicates differentiation. The first component is parallel to $\vec{\Omega}$, and his magnitude $\Delta\tau_\omega$ describes de change of DGD with wavelength. The second component is orthogonal to $\vec{\Omega}$ and describes the PSP depolarization. The statistical theory of second order [4] had provided the pdf for the magnitude of second order PMD $\left|\vec{\Omega}_\omega\right|$,

$$p(\left|\vec{\Omega}_\omega\right|) = \frac{8}{\pi^2\tau^2}\frac{4\left|\vec{\Omega}_\omega\right|}{\tau^2}\tanh\left(\frac{4\left|\vec{\Omega}_\omega\right|}{\tau^2}\right)\mathrm{sech}\left(\frac{4\left|\vec{\Omega}_\omega\right|}{\tau^2}\right) \qquad (4)$$

The τ parameter is related with the mean value of the magnitude of second order PMD by the expression $\left\langle\left|\vec{\Omega}_\omega\right|\right\rangle = \frac{2G}{\pi}\tau^2$, where Catalan's constant, G, is given approximately by 0.915965.

The emulator should also produce accurate higher-order PMD statistics and the second order PMD results should be well fitted with (4).

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For large changes in ω the PSPs have a rotation and the Principal States Model becomes inapplicable. The calculation of the autocorrelation function (ACF) of the PMD vector, $g_{\vec{\Omega}}(\omega_1,\omega_2)=\left\langle \vec{\Omega}(\omega_1)\cdot\vec{\Omega}(\omega_2)\right\rangle$ (the angled brackets denote ensemble averaging), gives the exact knowledge of the bandwidth over witch first order PMD is applicable. The expression for ACF present on literature [5][6] is

$$\left\langle \vec{\Omega}(\omega_1)\cdot\vec{\Omega}(\omega_2)\right\rangle = \frac{3}{\Delta\omega^2}\left[1-\exp\left(\pi\frac{\Delta\omega^2}{8}\left\langle\Delta\tau\right\rangle^2\right)\right] \quad (5)$$

where $\Delta\omega=\omega_1-\omega_2$ and $\left\langle\Delta\tau\right\rangle$ is the average length of the PMD vector. The ACF presents a theoretical quadratic decay with $\Delta\omega$, which is another important performance that PMD emulator should meet. Ideally the residual correlation must have values less than 10% for all frequencies outside of a 0.2 nm bandwidth.

By other side, to act as a practical measurement tool, a PMD emulator should also exhibit features like stability, repeatability, predictability and simplicity. Stability, because the measurement times using an emulator should last some minutes to hours. The repeatability and predictability are important features since it should be possible to choose any desired PMD state of the emulator. The birefringence elements that constitute the emulators are, in general, dependent to environmental fluctuations, which can easily affect the stability and repeatability of the emulator. Like some other device the emulator implementation should be simple and power efficient and the change between different PMD emulator states should also be simple and quick.

II. EMULATOR TYPES

A real fiber is usually modeled by the concatenation of randomly coupled linear birefringence sections. In the same way, a device to emulate fiber PMD may be constructed by the concatenation of several birefringence elements [1]. These birefringence elements may be sections of polarization maintaining fiber (PMF), birefringence crystals, or other device that provides a differential group delay between the two orthogonal polarization axes.

When the birefringence elements are PMF, the length of each section can be chosen equal or unequal but using randomly unequal lengths will yield the most accurate PMD statistics. In this case, each section length is generated with a Gaussian distribution probability, around a mean value L_{mean},

$$L_{mean}=\frac{DGD/section}{\lambda/cL_b} \quad (6)$$

where L_b is the beat length, λ is the wavelength and c the light speed. The value of DGD/section is calculated using the following expression,

$$DGD/section=\frac{\sqrt{\frac{3\pi}{8}}<DGD>}{\sqrt{N}} \quad (7)$$

where <DGD> is the desired mean DGD of emulator and N is the number of sections. The splicing angles θ_i between each PMF section may be all equals, with θ_i=45º, or all different and randomly generated following a uniform distribution, with $0\le\theta_i\le 2\pi$. The advantage of all θ_i=45º configuration is a rapid frequency decorrelation of the resultant PMD vector with the number of sections increase.

The main PMD Emulators can be classified in to one of the five main emulator types:

1) Emulators with fixed orientation sections.

The PMD emulators with fixed orientations, may be constructed by the concatenation of several number of PMF sections [7] [8] spliced at fixed angles.

These emulator types have been used only in polarization analyzer tests and comparison of different PMD measurement devices and techniques. A rigorous statistic analysis of his results was only made theoretically. A computational simulation [7] of an emulator with 15 equal length PMF sections, spliced randomly, has generated a DGD distribution well described by a Maxwellian distribution over an ensemble of frequencies. However, these emulator types have strong limitations since only with wide varying wavelength is possible to obtain different PMD emulator states.

2) Emulators with uniform scattering of polarization.

This emulators type consist in placing polarization scramblers between the PMF sections to uniformly scatter the polarization state over the Poincaré sphere. The uniform scatter of the polarization is easy to model in a computer but hard to realize in practice where polarizations controllers are used. Simulation results of three different emulators, each one with different number (three, five and ten) of randomly PMF sections length, was be compared by [7]. Results showed that only with ten or more PMF sections the pdf of DGD is well fitted with a Mawellian distribution. The pdf of the three and five PMF sections emulators have bad results mainly to large DGD values. It should be noted that are the higher DGD values, appearing in the tail of the Maxwellian distribution, which can generate more several signal degradations. This type of emulators, with equal length sections, was used in [9] and similar results were obtained.

3) Emulators with rotatabe sections

In emulators with rotatable sections, the birefringence sections are randomly rotate relative to each other. Damask [10] constructed an emulator consisting in twelve equal-length yttrium ortho-vanadate (YVO_4) birefringence crystals mounted to twelve independent and motorized rotation stages placed in cascade. Aspheric lenses couple light to and from the input and output fibers. The collimated beam between the input and the output pass through over all crystals. First and higher orders PMD have been generated. However, all moving parts can affect emulator features like stability or durability.

Two PMD emulators, with 3 and 15 PMF sections connected with rotatable connectors, had been constructed also [11]. This technique makes it possible easily to generate different fibers realizations, at any specific wavelength, by randomly rotating the connectors. Rotatable connectors allow the polarization axes of any two adjacent fibers to be rotated with respect to each other. The length of PMF sections were chosen randomly. The results show that only with 15 PMF sections the emulator has DGD values in good agreement with the Maxwellian distribution. The 15 PMF sections emulator exhibits also good results in the autocorrelation function of the PMD vector. An average level of 10% correlation remains between well-spaced wavelengths.

4) Emulators with tunable birefringence

Although the reasonably results exhibit by last two emulator types, they still present some issues like cumbrously, relatively high losses or an insufficient automatic control. An emulator with tunable birefringence sections, exploiting the temperature sensitivity of PMF, was present by [12]. Thirty sections of FiberCore HiBi polarization maintaining optical fibers was fusion spliced together at 45º angles. Near the center of each PMF sections a microheater consisting in two short and thin layers of metal (15 nm titanium layer for good adhesion to the glass and a 120 nm layer gold for good electrical conductivity) was deposited. Applying voltages, the microheaters thermally tune the birefringence of each DGD section. A simple software program was used to apply a set of 30 random voltages to the microheaters and made possible cycle through different PMD states.

This emulator was exhibit reasonably results: first order PMD was well fitted with a Maxwellian distribution and measured second order PMD only differs from expected theoretical distribution in the low probability tail; The autocorrelation function was higher residual correlation value, 20%, comparatively with the 15 PMF sections connected with rotatable connectors emulator described above, that have only 10% of residual correlation. A possible away to solve these two issues is increasing the number of PMF sections.

The main advantages of this compact emulator over others emulators are low loss, electrically controllable, no moving parts, negligible polarization dependent loss (PDL) and no internal reflections.

5) Emulators with tunable statistics

An emulator with tunable statistics presented by [13] makes use of three programmable DGD elements separated by two fiber-squeezer-based polarization controllers. The DGD elements consist of several birefringence crystals whose lengths increase in a binary series separated by electrically driven polarization switches and can be programmed to generate any desired DGD value [14]. Varying the DGD of each element according to a Maxwellian distribution with average $\langle \Delta\tau \rangle$ and uniformly scattering the polarization between sections a Maxwellian distribution with average $3^{1/2}\langle \Delta\tau \rangle$ is yield at the emulator output.

The experimental results show an accurate tunability of the PMD statistics. The first order PMD values are well fitted by a Maxwellian, however, the mean of second-order PMD is about 30% lower than the expected for a real fiber. Simulation results reveal that only with fifteen or more DGD elements it is possible to obtain an ACF with residual correlation values lower than 10% [15]. Thus, one limitation of this emulator is that it would require more DGD elements in order to accurately emulate the statistics of second order PMD and to exhibit reasonable residual correlation values. Nevertheless, features like stability and repeatability are well achieved. Another advantage of this emulator is the possibility of being used to experimentally employ the powerful technique of importance sample to quickly generate extremely low probability events.

III. OUR PMD EMULATOR

Our goal is develop a programmable group delay module using two nonlinear chirped fiber Bragg gratings (FBGs) written into a highly-birefringence (HiBi) fiber. The large refraction index difference present in HiBi fiber makes with the Bragg refraction from the chirped grating for a given signal wavelength occurs at different locations for different polarizations. We can say that the two signal polarizations “see” two different gratings due to the birefringence. The position difference of the reflection produces a differential time delay between the two polarizations, corresponding to first order PMD [16].

The proposed architecture for our module is shown in Fig.1.

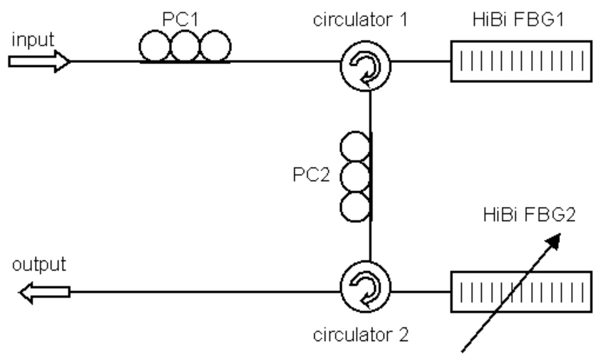

Fig.1 Shematic diagram of the group delay module using two nonlinear chirped FBGs written into a HiBi fiber.

The key elements are the two polarization controllers (PC1 and PC2) and the two nonlinear chirped FBGs (HiBi FBG1 and HiBi FBG2) written into a HiBi fiber. The input signal enters in the PC1 in order to assure an equal power in the fast and slow axes of HiBi FBG1. The PC2 ensure a correct coupling between the fast birefringence axis of HiBi FBG1 and the slow birefringence axis of HiBi FBG2. In this configuration the two DGDs, respectively generated at each grating, will be subtract.

The DGD corresponding to HiBi FBG1 has a constant value $\Delta\tau_1$ ps and the corresponding to HiBi FBG2, has a tunable value $\Delta\tau_2(\text{V})$ ps. This can continuously be varied mounting the HiBi FBG2 on a voltage-controlled piezoelectric element. The mechanical stretching should induce a variation in the DGD between the two orthogonal polarizations. If no voltage is applied to HiBi FBG2 $\Delta\tau_2$ has the same value that HiBi FBG1 ($\Delta\tau_2(\text{V=0}) = \Delta\tau_1$) and in case of maximum voltage applied (related with the maximum stretch grating support) has the value $\Delta\tau_2(\text{V=v}^m) = \Delta\tau_2{}^m$. The total DGD generated by this module, $\Delta\tau_t$, could then takes values between 0 and ($\Delta\tau_2{}^m$ - $\Delta\tau_1$) ps.

The precise and repeatable DGD generation capability of our DGD module will be related with the rigorous parameters calibration of the curve $\Delta\tau_2(\text{V})$, that describes the DGD variation with applied voltage. To any applied voltage in HiBi FBG2 it should correspond a deterministically $\Delta\tau_2(\text{V})$ value and a respective $\Delta\tau_t$ at the module output. Eventual environmental perturbations, like temperature variation, will induce time delay variations in both gratings. This means that the difference between them remains unchanged. Developing the software tools necessary to control the DGD module it should be possible use it to generate statistical DGD samples with a Maxwellian distribution and a selectable average.

By the concatenation of several modules like this, separate by polarization scatter, it should be possible emulate second order PMD [13].

VI. CONCLUSIONS

We have presented in this paper an overview of the different PMD emulator types and the main performance required by them. A novel architecture to first and second order PMD emulation using nonlinear chirped FBGs written into highly birefringence fibers was also presented. Future work will be focused in the laboratory implementation of this PMD emulator.

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