In-band DGD monitoring based on polarization controlled Stimulated Brillouin Scattering

Pascual Sevillano, Jesús Subías, Asier Villafranca and Javier Pelayo

***Abstract*—In this paper we present a new all-optical method for the measurement of the wavelength-resolved state-of-polarization vector across the bandwidth of multiple in-service channels. Taking advantage of the narrow spectral selectivity of stimulated Brillouin scattering and its dependence with the relative polarization alignment between the pump and the stimulus, polarization selective spectral measurements are performed on the signal under test. Obtaining the spectra for three pairs of orthogonal polarization states of the pump, the three Stokes parameters are retrieved for each spectral component. Differential Group Delay is then calculated from the spectral evolution of the polarization state.**

***Index Terms*—Nonlinear optical devices, Stokes parameters, Optical fiber polarization, Optical communication equipment, Optical fiber communication.**

I. Introduction

THE deployment of 100G channels over existing DWDM infrastructure is requiring a massive requalification of existing fibers due to the higher sensitivity to polarization mode dispersion (PMD) [1]. Performing these measurements without interrupting the service is essential for telecom operators, thus limiting the use traditional PMD measurement hardware and methods. State-of-the-art monitoring techniques for PMD in non-coherent conventional modulation schemes can be divided in post-filtering RF analysis [2], eye pattern analysis [3] and State of Polarization (SOP) evolution monitoring [4]. The latter is the only one that can be performed in the optical domain without the need for demodulation, and is based on the identification of the polarization plane with the highest delay between orthogonal polarizations for a given signal under test (SUT), measuring the differential group delay (DGD) from the interferometer-like effect of this delay over the spectrum. However, all published methods based on resolved polarization analysis of the signal spectrum require either previous alignment of the system or manipulation of the signal polarization state [5-7], thus limiting the measurement to individual channels.

In this letter, we propose a method for live monitoring of the DGD values for any given number of channels simultaneously and without the need of system or signal alignment, thus enabling a much faster measurement of a full DWDM system. Thanks to the speed of the measurement, this method could also be applied to monitor instantaneous DGD

For this purpose, we rely on the use of Stimulated Brillouin Scattering (SBS) high spectral and polarization selectivity to obtain high-resolution polarization selective spectra of the SUT for 6 different polarizations of the pump. From these spectra, we obtain the three Stokes parameters of the whole signal along its bandwidth and thus calculate the wavelength-resolved SOP. From the evolution of the in-band SOP, we can easily extract DGD and thus PMD for each channel individually and simultaneously without prior knowledge of the modulation format or fast electronics detection. Determination of spectral evolution of PMD vector along a channel spectrum allows accurate all-order PMD measurement.

II. Theoretical Background

Stimulated Brillouin Scattering is known to couple two counter-propagating waves, SUT and pump, through an acoustic wave due to an electrostriction effect. This phenomenon has been previously used as a high-gain swept-tunable optical amplifier for spectrometry thanks to its narrow width (~10Mhz) and large dynamic range [8]. The polarization dependence of the Brillouin gain arises from the absence of the phenomenon when the pump and signal under test (SUT) fields are orthogonal. When the scattering takes place in a spool of fiber, both fields experience the same evolution of their SOP along the fiber with respect to their original states. This yields to a differential gain of the filter which depends on the relative polarization of pump and SUT that is given by:

$$\gamma_b = \frac{\gamma_0}{2}\left(1+\left\langle \hat{s}_p \cdot \hat{s}_{SUT} \right\rangle_L\right) \tag{1}$$

Where the two vectors stand for the Stokes space representation of the SOP for the pump and the SUT. The length-averaged dot product of both vectors along the fiber has been proved to vary from minus one third, when they are orthogonal in one end, to one third, when they are parallel [9]. So the SBS can be treated as a polarization selective element

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that presents two different gains for the states parallel and perpendicular to the pump when it is injected in the spool of fiber $\left[\hat{s}_p\left(z=L\right),\hat{s}_p^{\perp}\left(z=L\right)\right]$. This behavior has been recently studied and proposed as a high-rejection bandpass gain filter [10]. These different gain values for the two orthogonal polarization states yields to a different final output value of the amplified spectral component when it exits the fiber depending on its income polarization. For high enough power of the pump this gain difference can be considered as an effective rejection ratio between these orthogonal states that depends on the range of powers, reaching values above 30dB polarization selective gain between orthogonal states [9]. Thanks to this polarization sensitivity, six high resolution spectra can be obtained, which correspond to the projection of the SUT to three pairs of orthogonal states of the pump matching the three axes of the Stokes space. The ratios between corresponding spectra return the evolution of the Stokes parameters with wavelength.

III. Experimental Setup

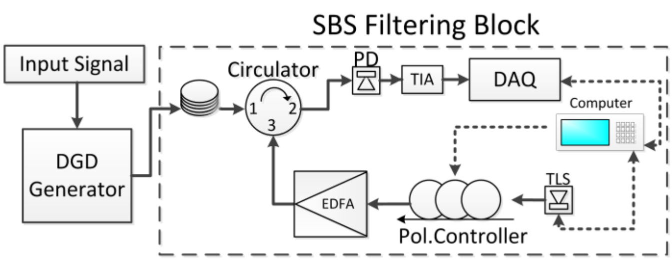

Fig. 1. Schematic of the necessary set-up for the retrieving of the frequency resolved state of polarization divided in three blocks.

The pump for SBS is generated by an external-cavity TLS that emits linearly polarized light and is continuously swept over the wavelength region of interest. The pump polarization is controlled with a piezoelectric polarization state generator, capable of generating the six polarization states required for a full Stokes vector characterization (0, 45, 90 and -45 degrees of linear polarization (LP), right-hand circular (RHC) and left-hand circular (LHC) polarization) with a switching time lower than 1ms, which allows seamless switching of states. Pump power is controlled by an EDFA working in constant power mode. An optical circulator is used to inject the pump into the fiber spool and retrieve the backscattered light produced by SBS, detected by the Photodetector (PD) and acquired by a data acquisition card (DAQ) right after the Transimpedance Amplifier (TIA). The SUT is injected directly on the opposite termination of the fiber spool. DGD of the SUT is induced by a passive PMD generator. Specific parameters of fiber length and pump power to reproduce the Brillouin spectrum analysis technique can be found in previous work [8].

As the TLS is swept along the spectral region of the SUT for six SOP generated with the polarization controller, the high-resolution optical spectra of the SUT are revealed and the Stokes parameters calculated.

IV. Results and Discussion

The measured power spectra for a 0 deg LP pump is shown in fig. 2 for an OOK-NRZ 40-GHz signal modulated with a pseudo-random bit sequence of 2^{31}-1 bit pattern length both with and without PMD. The spectrum of the PMD-free SUT corresponds to what has been widely reported for this kind of PRBS modulation, i.e. a sinc shape with the carrier and clock-frequency components. On the other hand in the spectrum where DGD has been induced on the SUT, the spectrum exhibits distortion in the shape of the spectrum with one prominent minimum value in its spectral width. Note that due to its narrowness, noise levels registered in the power spectra would be 30dB lower than grated-based spectrum analyzers.

This spectral shape is the consequence of the evolution of the SOP through the spectral components of the signal produced by DGD. Due to the sensitivity of the SBS effect to the polarization state, the amplification of each spectral component depends on its relative polarization to the pump TLS; yielding to a minimun for those componets with a relative orthogonal polarization state and a maximun for those parallel. Then, it can be easily deduced that this shape is the product of the sinc function, corresponding to the case without PMD, with the periodic variation of the polarization due to the PMD induced in the generator. Now by switching the polarization state of the pump to its perpendicular state (90 deg LP), the complementary spectrum is obtained, and then the maximum points turn to be minimum and likewise for the prior minimum, hence the combination of both recovers the original shape of the sinc function for the non-distorted signal.

Using a complete controller, the polarization state of the pump TLS can be rotated to the other four principal polarization states. Thus by rotating the pump to +45 LP and

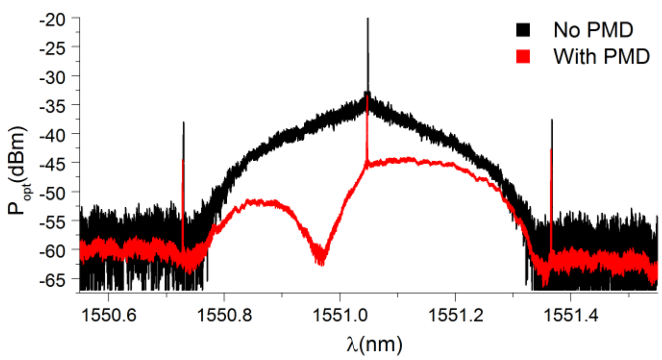

Fig. 2. Measured single-polarization spectra for a 40G OOK-NRZ SUT with no DGD (black) and 8.55ps DGD (red).

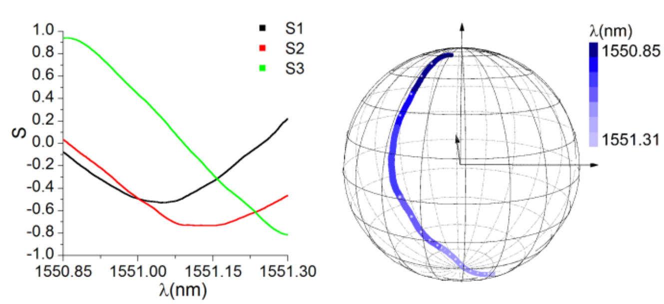

Fig. 3. (a) Recovered Stokes parameters resolved spectrally. (b) Representation of the SOP vector along the signal bandwidth in the Poincare sphere.

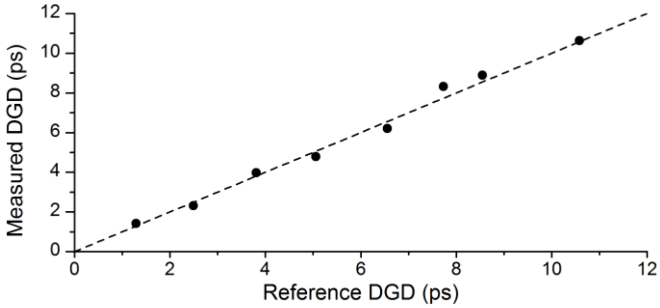

Fig. 4. Measured values of DGD for the different reference DGD values.

then to -45 LP, the normalized ratio of these two spectra corresponds then to the second Stokes parameter resolved spectrally. Finally, by setting the pump to LHC and RHC the third Stokes parameter can be retrieved [11]. In the fig. 3, the three Stokes parameters for the signal are depicted across the signal bandwidth, togheter with the Ponicaré sphere representation of the spectrally-resolved SOP.

These parameters determine completely the evolution of the polarization vector in the Stokes space. Unlike the measurement methods using one single axis, this analysis provides information of the full SOP evolution, allowing higher-order PMD effects to be easily observed. To obtain effective DGD values, the trajectory of the SOP in the sphere is integrated. Power spectra for the six states are optimally perfomed sweeping the pump TLS frequency at the speed of 10nm/s and the rotation bewteen the states is perfomed while the data is processed. With these measurements the complete characterization of the signal polarization state can be resolved across its bandwidth, [S1(ω),S2(ω),S3(ω)], in times below 0.5 sec for a 100GHz span with an spectral resolution of 0.08pm. The measured values of the DGD for the different values set in the DGD generator are depicted in Fig.4. Measurement range is limited by the accuracy in the acquisition of the power spectra, optimizing TLS sweep in this experiment the limit was set to 0.8ps.

One of the main advantages of the method is its capability to measure the DGD of several channels simultaneously without prior knowledge. In fig.5 we can see the evolution of SOP of two NRZ-OOK signals at 40GHz and 10GHz

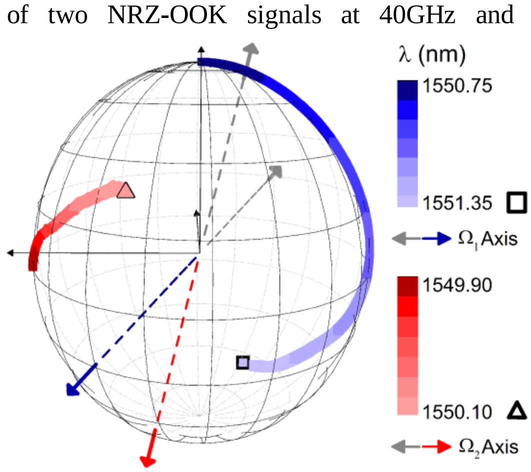

Fig. 5. Retrieved SOP resolved spectrally for both channels. Ω_1 ,Ω_2 represent the different DGD axis for both channels.

modulation rates spaced by less than 50GHz. The two signals experience the same DGD but as the rates are different, the effects are much more evident for the high rate one. It is also calculated the axis of rotation for both signals. More realistic scenarios require statistical treatment of the measured DGD values in order to fully characterize PMD due to the random birefringence present in the deployed lines. It can be seen that with this high-resolution spectral polarimetry, high order PMD effects can be analyzed and monitored from the depicted arc and its axis, or their evolution.

V. Conclusions

We have presented a new method for the measurement of spectrally-resolved SOP of optical signals taking advantage of the spectral and polarization selectivity of SBS. This complete characterization allows live monitoring of polarization dispersion related impairment such as PMD, and gives a complete visualization of the polarization Stokes vector shift along the spectral components for multiple channels, without losing in-band resolution. Unlike state-of-the-art methods that require alignment for each channel, the proposed system can measure in-channel polarization drifts along the whole C+L band which yields to a full characterization of all-order PMD values for each channel without need of channel filtering, demultiplexing or alignment.

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