OMP4.pdf

Fiber Beat Length Estimates via Polarization Measurements of Stimulated Brillouin Scattering Amplified Signals

Avi Zadok†, Elad Zilka, Avishay Eyal, Luc Thévenaz*, and Moshe Tur

School of Electrical Engineering, Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel
** Ecole Polytechnique Fédérale de Lausanne, Institute of Electrical Engineering, STI-GR-SCI Station 11, CH-1015 Lausanne, Switzerland*
† Presently with the Department of Applied Physics, MC 128-95, California Institute of Technology, Pasadena, CA 91125, USA
avizadok@caltech.edu, luc.thevenaz@epfl.ch, avishay@eng.tau.ac.il, tur@eng.tau.ac.il

Abstract: Simple, continuous wave based beat length measurement technique is proposed, using statistics of the states of polarization of stimulated Brillouin scattering amplified signals. Polarization statistics are studied analytically, numerically and experimentally.

OCIS codes: (290.5900) Scattering, stimulated Brillouin; (120.5410) Polarimetry; (060.2300) Fiber measurements.

1. Introduction

Polarization mode dispersion (PMD) is a significant propagation impairment which could limit the range and capacity of high rate fiber-optic communication links [1]. One of the key parameters which determine the extent of PMD in a given fiber is the beat length, which quantifies the magnitude of the local birefringence [2]. Most techniques for measurement of the beat length rely on polarization dependent optical time domain reflectometry (P-OTDR), in which back-scattered signals pass through a polarization analyzer and their temporal evolution and statistics are studied [2, 3]. Using these techniques, both the average and the local beat length can be extracted. Other proposed methods include polarization dependent optical frequency domain reflectometry [4], and twisting of fiber sections inside a non-linear fiber loop mirror [5]. Fiber birefringence can also be quantified through its interplay with stimulated Brillouin scattering (SBS). Since one of the driving mechanisms of SBS is optical interference between the pump and signal waves [6], it is inherently and strongly dependent on polarization. Based on this dependence, local birefringence measurements were demonstrated with a Brillouin OTDR setup [7].

In a recent previous work [8], we examined the output state of polarization (SOP) of SBS amplified signals in birefringent fibers. More specifically, we observed that the output SOPs corresponding to randomly polarized input signals tend to converge at a particular SOP as the pump power is increased [8]. Here, we show analytically that the residual scatter of the output SOP decreases with increasing pump power, fiber physical length and beat length. Using numerical simulations of the SBS vector propagation equation in a birefringent medium, we find that the scatter of the output SOP provides a quantitative measure of the average fiber beat length. Unlike the P-OTDR or Brillouin OTDR methods, the technique requires continuous waves only and no pulses or synchronization are necessary. The scatter of the signal SOP following SBS amplification was measured experimentally, and a good agreement with simulations was found. The analysis and results also provide further insight into the interplay of birefringence and SBS in standard fibers.

2. Theory

Let us denote the Jones column vectors of the signal and pump waves as $\vec{E}_{sig}(z)$, $\vec{E}_{pump}(z)$, z representing position along the fiber. We assume for simplicity that both waves are monochromatic, and that the optical frequency of the signal is downshifted from that of the pump by the Brillouin shift ν_B for maximum interaction [6]. We further assume that the pump wave is sufficiently strong so that it is negligibly affected by SBS (undepleted pump regime), and neglect linear fiber losses. The fiber birefringence is represented by the Jones matrix $\mathbf{T}(z)$. The wavelength dependence of $\mathbf{T}(z)$ is neglected since ν_B is of the order of only 10 GHz and the fiber length is only a few km. Hence we assume that the same $\mathbf{T}(z)$ governs the propagation of both pump and signal waves. Subject to the assumptions above, the differential equation of propagation for the signal wave is linear and is given by [6, 9, 10]:

$$\frac{d\vec{E}_{sig}(z)}{dz} = \left[\frac{d\mathbf{T}(z)}{dz}\mathbf{T}^{\dagger}(z) + \frac{\gamma_0}{2}\vec{E}_{pump}(z)\vec{E}^{\dagger}_{pump}(z)\right]\vec{E}_{sig}(z) \quad \Rightarrow \quad \vec{E}_{sig}(z) = \mathbf{H}(z)\vec{E}_{sig}(0) \qquad (1)$$

with γ_0 denoting the SBS gain coefficient in $[\mathrm{W}\cdot\mathrm{m}]^{-1}$. The matrix $\mathbf{H}(z)$ depends on the SBS gain, the fiber birefringence, the input SOPs of the pump and signal waves and the position z, and it is in general non-unitary. Nonetheless, using the singular value decomposition technique, it can be shown that

$$\mathbf{H}(z) = \mathbf{U}(z)\cdot\begin{bmatrix} G_{\max}(z) & 0 \\ 0 & G_{\min}(z) \end{bmatrix}\cdot\mathbf{V}^{\dagger}(z), \tag{2}$$

were $\mathbf{U}$, $\mathbf{V}$ are unitary matrices and $G_{\max}$, $G_{\min}$ are the maximum and minimum SBS signal amplitude gains, respectively. Equation (2) states that the birefringent, SBS amplifying fiber may be regarded as an equivalent, polarization dependent gain medium, whose primary input SOPs for maximum and minimum gain are orthogonal. When $G_{\max} >> G_{\min}$, one can statistically expect that the output SOPs corresponding to randomly polarized input signals would be closely aligned with that of $\mathbf{U}\cdot[1 \quad 0]^T$. This convergence of the output SOP becomes more pronounced as the ratio $G_{\max}/G_{\min}$ is increased.

Transforming Eq. (2) to Stokes space, we obtain the following equation for the signal power, and its solution:

$$\frac{dP_{sig}(z)}{dz} = \frac{\gamma_0 P_{pump}}{2}\left[1+\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right]P_{sig}(z) \;;\; P_{sig}(L) = P_{sig}(0)\exp\left\{\frac{\gamma_0 P_{pump}}{2}L\left[1+\left\langle\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right\rangle_L\right]\right\} \tag{3}$$

In Eq. (3) L is the fiber length, P_{pump} is the fixed pump power, $P_{sig}(z)$ is the signal power, $\hat{s}_{pump}(z)$ and $\hat{s}_{sig}(z)$ are the unit three-element Stokes column vectors of the pump and signal waves and the brackets $\langle\ \rangle_L$ denote averaging over z along $[0 \quad L]$. The SBS signal gain is determined by the average projection between the pump and signal Stokes vectors. When the fiber is completely free of birefringence, the maximal projection is obtained if the pump and signal are launched with aligned SOPs, leading to $\max\left\{\left\langle\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right\rangle_L\right\}=1$ and $G_{\max}=\exp(\gamma_0 P_{pump}L/2)$. The minimal average projection is such a fiber is obtained for orthogonal input SOPs: $\min\left\{\left\langle\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right\rangle_L\right\}=-1$, $G_{\min}=1$. The ratio $G_{\max}/G_{\min}$ in a birefringence free fiber is the largest possible.

The presence of birefringence will inevitably lower the maximum value, and raise the minimum value, of the average projection. If the fiber birefringence is sufficiently large and the fiber long enough, the pump and signal SOPs along the fiber are evenly distributed on the Poincare sphere. For that condition, is has been shown that the maximum and minimum value of $\left\langle\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right\rangle_L$ are $\pm\frac{1}{3}$ [3, 11]. In that scenario $G_{\max}=\exp\left(\frac{2}{3}\gamma_0 P_{pump}L/2\right)$, $G_{\min}=\exp\left(\frac{1}{3}\gamma_0 P_{pump}L/2\right)$. Consequently, higher pump power levels (or a longer fiber) would be required to obtain effective convergence of the amplified signal SOP, compared with that of the birefringence free fiber. The relation between the SOP convergence and the fiber beat length are quantified next through numerical simulations of Eq. (1).

3. Simulations

Figure 1 shows the scatter of the amplified signal SOP for a 2.25 km long fiber, whose average beat length L_B was 40 m, at several pump power levels. As expected, the output SOPs corresponding to randomly polarized input signals converge towards a preferred polarization with increasing pump power.

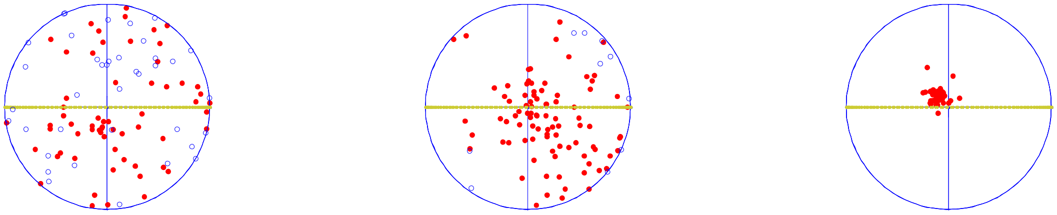

Fig. 1. Output signal SOPs on the Poincare sphere, corresponding to 100 random input signal SOPs, $\gamma_0 = 0.2[\mathrm{W}\cdot\mathrm{m}]^{-1}$. The pump power levels were 5 mW (left), 25 mW (center) and 50 mW (right).

The scatter of the output SOP may be quantified using the following metric:

$$\alpha(P_{pump}, L) \equiv \left\langle\cos^{-1}\left[\hat{s}_{sig}(L)\cdot\left\langle\hat{s}_{sig}(L)\right\rangle\right]\right\rangle \tag{4}$$

with the brackets here denoting the ensemble average. Figure 2 (left and center) shows simulated curves of α, calculated for different L, L_B. For given L and P_{pump}, the scatter of the output signal SOP increases with fiber birefringence (shorter L_B). The scatter saturates at an asymptotic value, however, when the birefringence is strong enough to reach the conditions for $G_{\max} = \exp\left(\frac{2}{3}\gamma_0 P_{pump} L/2\right)$ at the particular length. Shorter beat lengths may still be resolved using shorter fiber spans. Reconstruction of the α curves for different sample lengths of the same fiber, therefore, could provide information regarding its average beat length.

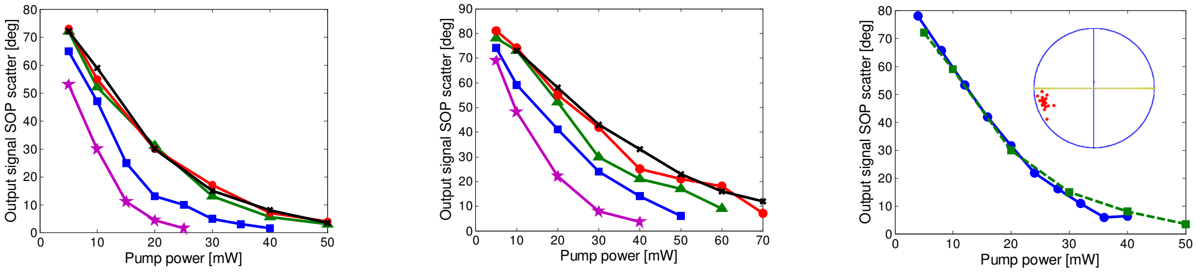

Fig. 2. Left and center: Simulated angular scatter α of the signal output SOP *vs.* pump power for different fiber realizations. The beat lengths were 45 m (x, black), 90 m (circles, red), 180 m (triangles, green), 350 m (squares, blue) and 750 m (stars, magenta). Fiber lengths were 2.25 km (left), and 1.125 km (center). Right: Measured α for a 2.25 km long fiber (blue), alongside simulated α for the same length and beat lengths ≤ 180 m. Inset: measured output signal SOPs, corresponding to 20 evenly distributed input SOPs. The pump power was 45 mW.

4. Experiment

As a preliminary validation of the simulations predictions, the asymptotic curve of α for long fibers was obtained experimentally. The output of a single laser source was split in two, and used to generate both pump and signal waves. The pump portion was amplified by a high power Erbium doped fiber amplifier. In the signal path, the source was downshifted in frequency by ν_B using suppressed carrier modulation and subsequent filtering by a narrowband fiber Bragg grating [12]. A programmable polarization controller was used to generate different signal input SOPs. The pump and signal waves were launched into the opposite ends of a 2.25 km long fiber, and the output signal was examined by a commercial polarization analyzer. The inset in Fig. 2 (right) shows the scatter of the output signal SOPs, corresponding to 20 different input SOPs that were evenly distributed on the Poincare sphere, for a pump power of 45 mW. Convergence of the output SOP is evident. Figure 2 (right) shows a very good agreement between the measured α and the asymptotic simulated prediction ($L_B \leq 180$ m).

In summary, a new method for estimating the beat length in optical fibers was proposed and demonstrated both numerically and experimentally. The method, which is based on polarimetric measurements of SBS amplification, is simple and does not require pulsed sources or synchronized acquisition.

References

[1] M. Brodsky, M. Boroditsky, A. Galtarossa, M. Matsumoto, and M. Tur, “Guest editorial: special issue on polarization effects in fiber-optic networks,” J. of Lightwave Technol. **24**, 3872-3874, (2006).

[2] A. Galtarossa, L. Palmieri, M. Schiano, and T. Tambosso, “Measurements of beat length and perturbation length in long single mode fibers,” Opt. Lett. **25**, 384-386, (2000).

[3] F. Corsi, A. Galtarossa, and L. Palmieri, “Analytical treatment of polarization mode dispersion in single mode fibers by means of the backscattered signal,” J. Opt. Soc. Am. A **16**, 574-583, (1999).

[4] M. Wegmuller, M. Legre, and N. Gisin, “Distributed beatlength measurement in single-mode fibers with optical frequency domain relfectometry,” J. of Lightwave Technol. **20**, 828-835, (2002).

[5] E. A. Kuzin, J. M. Estudillo Ayala, B. Ibarra Escamilla, and J. W. Haus, “Measurements of beat length in short low birefringence fibers,” Opt. Lett. **26**, 1134-1136, (2001).

[6] R. W. Boyd, Chapter 9 in *Nonlinear optics*, pp. 409-427. San Diego, CA: Academic Press, (2003).

[7] L. Thevenaz, S. Foaleng Mafang, and M. Nikles, “Fast measurement of local PMD with high spatial resolution using stimulated Brillouin scattering,” paper 10.1.2 in *ECOC 2007*, Berlin, Germany, (2007).

[8] L. Thevenaz, A. Zadok, A. Eyal, and M. Tur, “All-optical polarization control through Brillouin amplification,” paper OML7 in OFC/NFOEC 2008, San Diego, Ca, (2008).

[9] J. P. Gordon and H. Kogelnik, "PMD fundamentals: polarization mode dispersion in optical fibers", P. Natl. Acad. Sci. USA **97**, 4541-4550, (2000).

[10] R. H. Stolen, “Polarization effects in fiber Raman and Brillouin lasers,” *IEEE J. of Quantum Electron*. **15**, 1157-1160, (1979).

[11] M. O. vanDeventer, and A. J. Boot, "Polarization properties of stimulated Brillouin scattering in single mode fibers," J. Lightwave Technol. **12**, 585-590, (1994).

[12] A. Loayssa, D. Benito, and M. J. Grade, “High resolution measurement of stimulated Brillouin scattering spectra in single-mode fibers,” IEE Proc. Optoelectron. **148**, 143-148, (2001).