Polarization Evolution of Stimulated Brillouin Scattering Amplified Signals in Standard Fibers

Avi Zadok[1, 2], Elad Zilka[1], Avishay Eyal[1], Luc Thévenaz[3], and Moshe Tur[1]
[1]*School of Electrical Engineering, Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel*
[2]*Currently with the Department of Applied Physics, MC 128-95, California Institute of Technology, Pasadena, CA 91125, USA*
[3]*Ecole Polytechnique Fédérale de Lausanne, Institute of Electrical Engineering, STI-GR-SCI Station 11, 1015 Lausanne, Switzerland*
avizadok@caltech.edu; avishay@eng.tau.ac.il; luc.thevenaz@epfl.ch; tur@eng.tau.ac.il;

Abstract: The polarization evolution of stimulated Brillouin scattering amplified signals in the presence of fiber birefringence is examined in analysis, simulation and experiment. The signal polarization is drawn towards the conjugate of the pump polarization.

OCIS Codes: (290.5900) Scattering, Stimulated Brillouin; (120.5410) Polarimetry.

1. Introduction

Optical interference between the pump and signal waves is the main driving mechanism of stimulated Brillouin scattering (SBS) [1]. The local SBS interaction, at a given point along an optical fiber, is maximal when the state of polarization (SOP) of the pump is aligned with that of the signal, and it vanishes if the two SOPs are orthogonal. In standard single mode fibers, the overall SBS signal amplification (or attenuation) depends on the birefringence properties of the fiber, as well as on the input SOPs of both the pump and the seed signal waves. As SBS is studied intensively for applications such as fiber lasers [2], distributed sensing [3] and slow light [4], a thorough examination of its polarization properties is of large relevance. In this work we extend upon the study of van Deventer and Boot [5] and examine the SBS amplification of an arbitrarily polarized input signal, as well as the role of SBS in the evolution of the signal SOP. The analysis includes both Stokes and anti-Stokes waves. In particular, we find that the output SOP of an SBS amplified Stokes wave in a standard, single mode fiber is drawn towards the complex conjugate of the input pump SOP. On the other hand, the output SOP of the residual, attenuated anti-Stokes signal is repelled from the conjugate of the pump [6]. These findings are supported by simulations and experiments.

2. Analysis

Let us denote the local power of the pump and signal waves at point z along the fiber as $S^0_{pump}(z)$ and $S^0_{sig}(z)$, respectively, and the corresponding unit Stokes vectors as $\hat{s}_{pump} = \begin{bmatrix} s^{(1)}_{pump} & s^{(2)}_{pump} & s^{(3)}_{pump} \end{bmatrix}$, $\hat{s}_{sig} = \begin{bmatrix} s^{(1)}_{sig} & s^{(2)}_{sig} & s^{(3)}_{sig} \end{bmatrix}$. Both SOPs are defined in a single reference frame, so that $\hat{s} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$, for example, signifies a right-handed circular polarization for the signal wave and a left-handed circular polarization for the pump wave. The signal and pump are launched at $z = 0$ and $z = L$ respectively, with L the fiber length. The propagation of S^0_{sig} and $\hat{s}_{sig}$, subject to both fiber birefringence and SBS, may be expressed using the following two coupled equations [6]:

$$\mathrm{d}S^0_{sig}(z)/\mathrm{d}z = \tfrac{1}{2}\gamma_0 S^0_{pump}(z)\left(1 + \hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right)S^0_{sig}(z)\,, \tag{1}$$

$$\mathrm{d}\,\hat{s}_{sig}(z)/\mathrm{d}z = \vec{\beta}(z)\times\hat{s}_{sig}(z) + \tfrac{1}{2}\gamma_0 S^0_{pump}(z)\left[\hat{s}_{pump}(z) - \left(\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right)\hat{s}_{sig}(z)\right]. \tag{2}$$

In equations (1) and (2), $\vec{\beta}(z)$ denotes the Stokes vector pointing towards the slow axis of the local birefringence [7], and γ_0 is the SBS exponential power gain coefficient, in $[\mathrm{W\cdot m}]^{-1}$. In the undepleted pump regime, $S^0_{pump}(z)$ is constant and equation (1) can be simply solved to obtain:

$$S^0_{sig}(L) = S^0_{sig}(0)\exp\left[S^0_{pump}L\cdot\tfrac{1}{2}\gamma_0\left(1 + \left\langle \hat{s}_{pump}\cdot\hat{s}_{sig}\right\rangle_L\right)\right] \equiv S^0_{sig}(0)\exp\left[\gamma_{eff}S^0_{pump}L\right];\ \gamma_{eff} = \tfrac{1}{2}\gamma_0(1+\eta);\ \eta \equiv \left\langle \hat{s}_{pump}\cdot\hat{s}_{sig}\right\rangle_L . \tag{3}$$

η, the average mixing efficiency, denotes the longitudinal average of the scalar product between the unit Stokes vectors of the pump and signal waves. Equation. (2) specifies two driving forces that control the evolution of the SOP along the fiber. The first, $\vec{\beta}\times\hat{s}_{sig}$, describes the birefringence-induced evolution of the signal SOP [7]. The second term, $\tfrac{1}{2}\gamma_0 S^0_{pump}\left[\hat{s}_{pump} - \left(\hat{s}_{pump}\cdot\hat{s}_{sig}\right)\hat{s}_{sig}\right]$, represents the effect of SBS amplification on the signal SOP. This term represents a vector on the Poincare sphere, orthogonal to $\hat{s}_{sig}$, and tangentially (on the sphere surface) pointing towards $\hat{s}_{pump}$. Thus, this term signifies a local force pulling $\hat{s}_{sig}$ towards $\hat{s}_{pump}$. The magnitude of this pulling force scales with the pump power, and depends on the local projection of $\hat{s}_{pump}(z)$ on $\hat{s}_{sig}(z)$.

In standard, single mode fibers, the magnitude of the first term in equation (2) is considerably larger than that of the second term. For a weak pump power, the evolution of both the pump and signal SOPs is governed by birefringence alone. When the fiber is sufficiently long, this approximation leads to $\eta = \frac{1}{3}\left(s^{(1)}_{pump}s^{(1)}_{sig} + s^{(2)}_{pump}s^{(2)}_{sig} - s^{(3)}_{pump}s^{(3)}_{sig}\right)$, with both vectors taken at the signal input $(z=0)$ [6,8]. $\text{Max}(\eta)=\frac{1}{3}$ is obtained for an input signal SOP of $\hat{s}^{\max}_{sig} = \left[s^{(1)}_{pump} \quad s^{(2)}_{pump} \quad -s^{(3)}_{pump}\right] \equiv \hat{s}^{*}_{pump}$, corresponding to $\max(\gamma_{eff}) = \frac{2}{3}\gamma_0$. The Jones vectors corresponding to $\hat{s}^{\max}_{sig}$ and $\hat{s}_{pump}$ form a complex conjugate pair, a relation that holds for any z. $\text{Min}(\eta) = -\frac{1}{3}$ and $\min(\gamma_{eff}) = \frac{1}{3}\gamma_0$ are obtained for $\hat{s}^{\min}_{sig} = -\hat{s}^{\max}_{sig}$. An arbitrarily polarized input signal can be decomposed using the orthogonal basis of $\left\{\hat{s}^{\max}_{sig}, \hat{s}^{\min}_{sig}\right\}$ [6]. Since $\exp\left[\max(\gamma_{eff})S^0_{pump}L\right] >> \exp\left[\min(\gamma_{eff})S^0_{pump}L\right]$, the output SOP of an amplified Stokes signal, having an arbitrary input polarization, would be drawn towards that of $\hat{s}^{\max}_{sig}$ [6]. For SBS attenuation of an anti-Stokes signal $\gamma_0 < 0$, and the SOP of the residual output would be repelled from $\hat{s}^{\max}_{sig}$ [6]. The above considerations are strictly valid only when $\frac{1}{2}\gamma_0 S^0_{pump} << \left\langle\left|\vec{\beta}\right|\right\rangle$. Their validity for large SBS amplification or attenuation in standard fibers was examined in both simulations and experiments.

3. Numerical simulations and experimental results

Figures 1(a) and 1(b) show the simulated output signal SOP $\hat{s}_{sig}(L)$, for a 2.25 km long fiber realization, whose beat length was 20 m, and for a pump power level of 50 mW. The maximum SBS power gain for the chosen parameters is above 50 dB. $\hat{s}_{sig}(L)$ was calculated for 100 random $\hat{s}_{sig}(0)$, and the results show convergence of $\hat{s}_{sig}(L)$ for both Stokes and anti-Stokes signals. The two convergence points are in close proximity to $\hat{s}^{*}_{pump}$ and to its antipodal vector, for Stokes and anti-Stokes signals respectively. Figures 1(c) and 1(d) show the measured $\hat{s}_{sig}(L)$ for Stokes and anti-Stokes signals, corresponding to 20 different input SOPs which were evenly distributed on the Poincare sphere. Convergence of the output SOPs is also evident in the experiment. The results open the way for a simple and stable all-optical synthesis of an arbitrary signal SOP.

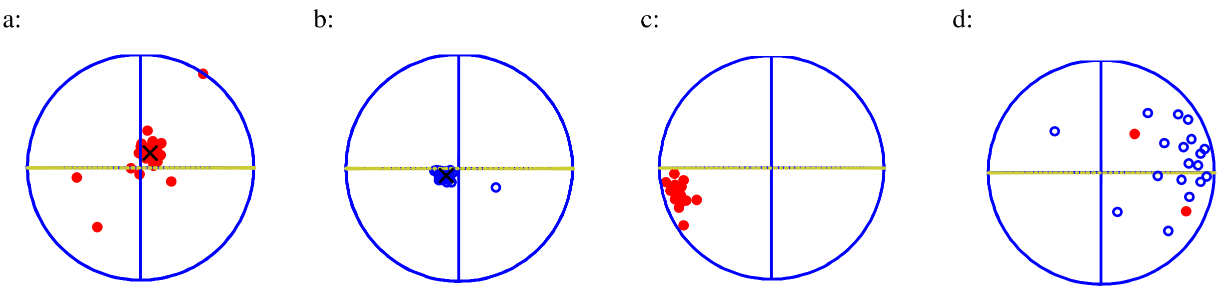

Fig. 1: (a-b): Simulated signal SOPs at the output of a 2.25 km long fiber realization, having a beat length of 20 m, corresponding to 100 random input signal SOPs. The pump power was 50 mW, and the input pump Stokes vector $\hat{s}_{pump}$ was chosen as $[0 \quad 1 \quad 0]^T$. (a): Stokes signal. (b): Anti-Stokes signal. 'X' signs in (a-b) indicate the ensemble average of the output signal SOP. (c-d): Measured signal SOPs at the output of a 2.25 km long fiber, for 20 evenly distributed input SOPs. (c): Stokes signal, pump power 45 mW. (d): Anti-Stokes signal, pump power 20 mW. Attenuation measurements were restricted to low pump power by spontaneous Brillouin scattering noise. The horizontal and vertical axes in all figures correspond to the Stokes $s^{(1)}$ and $s^{(3)}$ axes, respectively. Red closed (blue open) circles indicate SOPs for which $s^{(2)} > 0$ ($s^{(2)} < 0$).

5. References

1. R. W. Boyd, Nonlinear optics, (San Diego, CA: Academic Press, 2003) chapter 9, 409-427.
2. J. C. Yong, L. Thévenaz, and B. Y. Kim, J. Lightwave Technol. **12**, 546-554, (2003).
3. T. Horiguchi, T. Kurashima, and M. Tateda, IEEE Photon. Technol. Lett. **2**, 352-354, (1990).
4. M. González-Herráez, K.-Y. Song, and L. Thévenaz, Appl. Phys. Lett. **87**, 081113, (2005).
5. M. O. van Deventer, and A. J. Boot, J. Lightwave Technol. **12**, 585-590, (1994).
6. A. Zadok, E. Zilka, A. Eyal, L. Thévenaz, and M. Tur, "Vector analysis of stimulated Brillouin scattering amplification in standard single-mode fibers," submitted for publication in Opt. Express **16**, (2008).
7. J. P. Gordon and H. Kogelnik, P. Natl. Acad. Sci. USA **97**, 4541-4550, (2000).
8. F. Corsi, A. Galtarossa, and L. Palmieri, J. Opt. Soc. Am. A **16**, 574-583, (1999).