Polarization Properties of Stimulated Brillouin Scattering and their Implications on Slow and Fast Light

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Invited Paper

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Abstract: Vector formalism for stimulated Brillouin scattering amplification in birefringent fibers is used to model the fiber as an equivalent, pseudo-linear, polarization-dependent gain medium. Implications on slow and fast light setups are discussed.

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1. Introduction

Stimulated Brillouin scattering (SBS) is a non-linear optical propagation effect, in which a high power pump wave and a typically weaker, counter-propagating signal wave are coupled by a longitudinal acoustic wave [1]. Given that proper phase matching requirements are met, the signal power may be exponentially amplified (Stokes wave), or attenuated (anti-Stokes wave). The amplification, or attenuation, of the signal is accompanied by frequency-varying phase delays, in accord with the Kramers-Kronig relations [1]. Within a limited bandwidth, these phase variations are a nearly-linear function of frequency, representing an additive positive or negative group delay for the Stokes and anti-Stokes waves, respectively. These group delays, easily controlled by the pump power, have made SBS a favorable underlying mechanism in many studies of slow and fast light [2-3]. Many efforts have been dedicated over the last four years to broadening the usable bandwidth of SBS slow light, and to reducing the distortion of the delayed signals [4-8]. Both high rate digital data [7-9], and broadband radar signals [10], were successfully delayed.

Since SBS originates from optical interference, the SBS interaction, at a given point, is most efficient when the electric fields of the pump and signal are aligned, i.e., their vectors trace parallel ellipses and in the same sense of rotation. Conversely, if the two ellipses are again similar, but traced in opposite senses of rotation, with their long axes being orthogonal to each other, then the SBS interaction averages to zero over an optical period. Consequently, the overall signal gain depends on fiber birefringence, as well as on the input states of polarization (SOPs) of both waves. In this work, we provide vector formalism for SBS interaction in birefringent fibers, in both Jones and Stokes spaces [11]. The analysis shows that in the undepleted pump regime, the fiber may be regarded as an equivalent, pseudo linear, polarization dependent gain medium, characterized by a pair of orthogonal input SOPs which give rise to the maximum and minimum output signal power. Using these two axes as a convenient basis, we predict that the output SOP corresponding to an arbitrarily polarized input signal is drawn towards a specific state, which is determined by the input pump SOP. This prediction is supported by both simulations and experiments [11]. A similar effect was recently studied in stimulated Raman amplification [12].

The polarization properties of SBS have significant implications on slow and fast light realizations. As the signal gain depends on its input polarization, so does the delay, and polarization control and tracking is often required. This difficulty was recently alleviated by the introduction of a Faraday rotating mirror (FRM) in a double-pass configuration [13]. In addition, an arbitrarily polarized signal could lead to non-linear dependence of the SBS induced delay on the pump power [14]. Finally, the projection of a signal pulse to the maximum and minimum gain axes may also lead to SBS-induced polarization mode dispersion (PMD) and considerable distortion, as the two components experience different group delays.

2. Vector formalism for SBS in birefringent fibers

Let us denote the Jones column vectors of monochromatic signal and pump waves as $\vec{E}_{sig}(z)$, $\vec{E}_{pump}(z)$, with z the position along a fiber of length L. We assume that the difference between the two optical frequencies equals the Brillouin shift ν_B, for maximum interaction [1]. We restrict the analysis to the undepleted pump regime and neglect linear fiber losses. Birefringence is represented by the Jones matrix $\mathbf{T}(z)$. The frequency dependence of $\mathbf{T}(z)$ is neglected, since ν_B is only ~10 GHz and L is only a few km. Subject to the assumptions above, the equations of propagation for the signal and pump waves are given by [1, 15-16]:

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

$$\vec{E}_{pump}(0)=\mathbf{T}^{T}(z)\vec{E}_{pump}(z)\rightarrow\vec{E}_{pump}(z)=\mathbf{T}^{*}(z)\vec{E}_{pump}(0),$$

with γ_0 denoting the SBS gain coefficient in $[\mathrm{W\cdot m}]^{-1}$. Note that the differential equation for the signal wave is linear. The linear matrix $\mathbf{H}(z)$ depends on the fiber birefringence and the input SOPs of both waves, and is generally non-unitary. Nonetheless, using the singular value decomposition technique, $\mathbf{H}(z)$ can be represented as:

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

where $\mathbf{U}$, $\mathbf{V}$ are unitary matrices and $G_{\max}$, $G_{\min}$ are the maximum and minimum SBS signal amplitude gains, respectively. Equation (2) states that a birefringent, SBS amplifying fiber is equivalent to a linear, polarization dependent gain medium. The orthogonal signal input SOPs leading to $G_{\max}$, $G_{\min}$ are $\vec{E}^{in\_\max}_{sig}=\mathbf{V}\cdot[1 \quad 0]^T$ and $\vec{E}^{in\_\min}_{sig}=\mathbf{V}\cdot[0 \quad 1]^T$, respectively, and the corresponding output SOPs are $\vec{E}^{out\_\max}_{sig}=\mathbf{U}\cdot[1 \quad 0]^T$, $\vec{E}^{out\_\min}_{sig}=\mathbf{U}\cdot[0 \quad 1]^T$. An arbitrarily polarized input signal may be expressed as $\vec{E}^{in}_{sig}=\alpha_0\vec{E}^{in\_\max}_{sig}+\beta_0\vec{E}^{in\_\min}_{sig}$, leading to the following Jones vector and power for the output signal:

$$\vec{E}^{out}_{sig}=\alpha_0 G_{\max}\vec{E}^{out\_\max}_{sig}+\beta_0 G_{\min}\vec{E}^{out\_\min}_{sig}\ ;\ P^{out}_{sig}=|\alpha_0|^2|G_{\max}|^2+|\beta_0|^2|G_{\min}|^2 \tag{3}$$

Transforming Eq. (1) to Stokes space, we obtain the following equation for the signal power, and its solution:

$$\mathrm{d}P_{sig}(z)/\mathrm{d}z=\tfrac{1}{2}\gamma_0 P_{pump}\left[1+\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right]P_{sig}(z)\ ;\ P^{out}_{sig}=P_{sig}(0)\exp\left\{\tfrac{1}{2}\gamma_0 P_{pump}L\left[1+\left\langle\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right\rangle_L\right]\right\} \tag{4}$$

In Eq. (4) $P_{sig}(z)$ denotes the signal power, P_{pump} is the fixed pump 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 $\langle\ \rangle_L$ denotes averaging over $z\in[0 \quad L]$. If the fiber birefringence is sufficiently large and the fiber long enough, the pump and signal SOPs along the fiber become evenly distributed on the Poincare sphere. In that limit, it has been shown that the maximum and minimum values of $\left\langle\hat{s}_{pump}(z)\cdot\hat{s}_{sig}(z)\right\rangle_L$ are $\pm\frac{1}{3}$ [17], with $\vec{E}^{out\_\max}_{sig}$ aligned with the complex conjugate of $\vec{E}_{pump}(L)$ [11]. We therefore find:

$$G_{\max}=\exp\left(\tfrac{2}{3}\gamma_0 P_{pump}L/2\right),\ G_{\min}=\exp\left(\tfrac{1}{3}\gamma_0 P_{pump}L/2\right). \tag{5}$$

This result, derived using a non-formal argument, was stated in the pioneering work of van Deventer and Boot [18]. Equation (5) states that for a sufficiently long fiber and/or a sufficiently strong pump, $G_{\max}>>G_{\min}$. Equations (3) therefore suggests that unless α_0 is negligible, $\vec{E}^{out}_{sig}$ would be closely aligned with $\vec{E}^{out\_\max}_{sig}$. In addition, the equations suggest that the logarithmic SBS gain for an arbitrarily polarized input signal is not necessarily a linear function of pump power.

Figure 1 shows experimental validation of the above predictions [11]. Panel 1(a) shows the measured SBS signal gain, in logarithmic scale, with the input SOP adjusted for $\vec{E}^{in\_\max}_{sig}$ and $\vec{E}^{in\_\min}_{sig}$. The ratio between the slopes of the two curves is very close to 2. The figure also shows the SBS gain for a third input SOP, $\vec{E}^{in\_near\_\min}_{sig}$, which is slightly detuned from $\vec{E}^{in\_\min}_{sig}$. The observed logarithmic gain for $\vec{E}^{in\_near\_\min}_{sig}$ agrees very well with equation (3), and is not linearly proportional to P_{pump}. The convergence of the output SOP is illustrated in Fig. 1(b). The output SOPs $\vec{E}^{out\_\max}_{sig}$ and $\vec{E}^{out\_\min}_{sig}$ are pump power invariant, and orthogonal to each other. The output SOP observed for $\vec{E}^{in\_near\_\min}_{sig}$ is gradually drawn from $\vec{E}^{out\_\min}_{sig}$ towards $\vec{E}^{out\_\max}_{sig}$ as P_{pump} is increased.

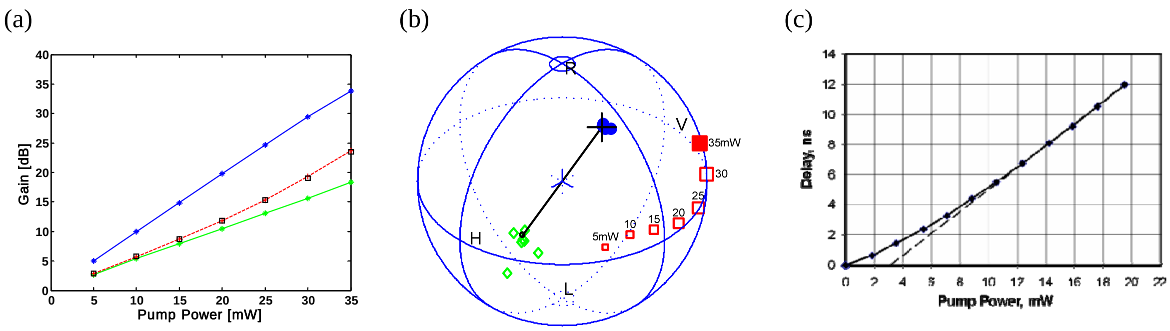

Fig. 1: (a) Measured SBS gain as a function of pump power for a 2250 m long fiber [11]. The input signal SOP was optimized for maximum output (upper, blue), adjusted for minimum output (lower, green), and fixed at a specific state $\vec{E}_{sig}^{in\_near\_min}$.(middle, red); (b) Corresponding output SOPs [11]. Symbols colors match those of (a). Open symbols signify SOPs at the back of the Poincare sphere. Power levels next to the red squares indicate the pump power. (c) Measurement of SBS slow light delay as a function of pump power level [14], showing deviations from a linear relation.

3. Implications on SBS slow and fast light

In slow and fast light applications, the monochromatic signal is replaced by a pulse envelope, which may be decomposed in the basis of $\vec{E}_{sig}^{in\_\max}$ and $\vec{E}_{sig}^{in\_\min}$. Each projection would experience a different SBS gain, and hence, as described by the Krmaers-Kronig relation, a different delay as well. Consequently, the observed delay becomes polarization dependent, in accord with the everyday experience of researchers in the field. Following the gain, the delay can also become a non-linear function of P_{pump} , as seen in Fig. 1(c) [14]. $\vec{E}_{sig}^{in\_\max}$ and $\vec{E}_{sig}^{in\_\min}$ may also be regarded as principal axes of an SBS-induced PMD. As the difference between the delays associated with $\vec{E}_{sig}^{in\_\max}$ and $\vec{E}_{sig}^{in\_\min}$ can be close to the pulse duration, the distortion associated with such SBS-induced PMD may become severe. This polarization dependence makes SBS slow and fast light setups susceptible to environmental instabilities.

An elegant solution to the polarization sensitivity of SBS slow light was recently proposed by Walker *et al.* [13], who launched linearly polarized, orthogonal pump and signal waves from the same end of the fiber, with an FRM at the opposite end. In this configuration, the signal wave is guaranteed to interact with a counter-propagating pump wave of a complex conjugate Jones vector, regardless of changes to $\mathbf{T}(z)$ along the fiber. This method is in agreement with the above analysis, which shows that conjugate pump and probe polarizations would provide the maximum SBS gain and delay in a sufficiently long, standard fiber. This result holds for high pump powers [11].

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