

# Dual-pump push-pull polarization control using stimulated Brillouin scattering

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**Abstract:** Stimulated Brillouin scattering (SBS) amplification of probe signals is highly polarization dependent. Maximum and minimum gain values are associated with a pair of orthogonal states of polarization (SOP), which are related to the pump SOP. Since the maximum gain is much higher than the minimum, the SOP of the output probe is pulled towards that of the maximum amplification. Polarization pulling is restricted, however, by pump depletion. In this work, a new method is proposed, analyzed and demonstrated for enhanced SBS polarization pulling, using two orthogonal pumps. Here, one pump amplifies one polarization component of the probe wave, and at the same time the other pump attenuates the corresponding orthogonal component, resulting in a push-pull effect. In the undepleted regime and for equal total power, the same degree of pulling is achieved as in the single pump case, but at a significantly less signal gain. Thus, the dual pump technique can provide high pulling efficiency for stronger input signals, deferring the onset of depletion.

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## 1. Introduction

Polarization control is of utmost importance in many sensing architectures, especially those using interferometry. In applications where the use of polarization maintaining fibers is not an option, one must resort to polarization diversity solutions or to active control of the state of polarization (SOP), using feedback systems. Recently, optical nonlinear interactions have been utilized to impose the SOP of one waveform on that of another [1]. Examples of such nonlinearly-mediated *polarization pulling* include the use of stimulated Brillouin scattering (SBS) [2–5], four-wave mixing [6,7] and stimulated Raman scattering (SRS) [8], where the former is the effect used in this work. Potentially, nonlinear polarization pulling could allow for the all-optical synthesis of an arbitrary SOP.

Vector analysis of SBS reveals that at the undepleted pump regime, the probe wave amplification is analogous to that of an effective linear medium of polarization dependent gain (PDG) [2]. Excluding singularities, the SOP of an arbitrarily polarized Stokes probe wave subject to SBS amplification is drawn towards a particular state, whereas the SOP of an attenuated anti-Stokes wave is repelled from the same state. In standard, weakly birefringent fibers, that 'focal' SOP of the probe wave is represented by a Jones vector which is the complex conjugate of that of the input pump (in a coordinate system shared by both counter-propagating waves, see [2]). The effectiveness of polarization pulling is determined by the ratio of the maximum and minimum gain values of the PDG medium. Since the maximum gain is limited by pump depletion, SBS polarization pulling of probe waves of non-negligible power levels would be restricted.

In this work, we propose, analyze and demonstrate a technique for enhanced SBS polarization pulling, based on two orthogonally polarized pumps that are separated in frequency by twice the Brillouin shift. Dual pump configurations have been previously used for extending the usable bandwidth of SBS-induced slow light setups [9]. The SOP of a probe wave, whose frequency is centered between those of the two pumps, is drawn towards the conjugate of the higher-frequency pump. The pulling is strengthened by the lower frequency pump, which repels the probe SOP from the orthogonal state. While the differential gain provided is the same as that induced by a single pump of equal total power, the dual-pump configuration generates a more modest maximal gain, and is therefore less susceptible to depletion. The superior performance is demonstrated experimentally.

## 2. Analysis and simulations

Let us denote the Jones column vector of an SBS probe wave as  $\vec{E}_{sig}(z)$ , where  $z$  is the position coordinate along a fiber of length  $L$ . The probe wave enters the fiber at  $z = 0$ , and it is assumed to be monochromatic with frequency  $\omega$ . Consider first the amplification of the probe by a single pump wave, launched at  $z = L$ , and of frequency  $\omega + \Omega_B$ , where  $\Omega_B$  is the Brillouin frequency shift of the fiber. We denote the pump power and unit Jones vector by  $2P$  and  $\hat{e}_p^{(1)}(z)$ , respectively. The superscript <sup>(1)</sup> is used to distinguish between the Jones vector of this first pump wave and that of a second pump wave, which is introduced later. Neglecting linear losses over a relatively short  $L$ , as well as polarization mode dispersion effects within the narrow spectral range of  $\Omega_B \sim \pm 2\pi \cdot 10$  GHz, the propagation equation of  $\vec{E}_{sig}(z)$  in the *undepleted pump regime* is given by [2]:

$$\frac{d\vec{E}_{sig}(z)}{dz} = \left[ \frac{d\mathbf{T}(z)}{dz} \mathbf{T}^\dagger(z) + \frac{\gamma_0 \cdot 2P}{2} \hat{e}_p^{(1)}(z) \hat{e}_p^{(1)\dagger}(z) \right] \vec{E}_{sig}(z). \quad (1)$$

In Eq. (1),  $\mathbf{T}(z)$  is the Jones matrix which describes the linear propagation of the probe along the fiber up to point  $z$ , and  $\gamma_0$  is the SBS gain coefficient in units of  $[\text{W} \cdot \text{m}]^{-1}$ . Note that Eq. (1) is linear in the probe wave. Previous analysis of Eq. (1) has shown that the maximum and minimum values of the probe power gain,  $G^{\max}$  and  $G^{\min}$ , are associated with a pair of orthogonal SOPs of the probe input [2]. We denote the unit Jones vectors of these two states as  $\hat{e}_{sig}^{in \max}$  and  $\hat{e}_{sig}^{in \min}$ , respectively.  $G^{\max}$  and  $G^{\min}$  also correspond to a pair of orthogonal SOPs of the probe *output*, the Jones vector of which are denoted by  $\hat{e}_{sig}^{out \max}$  and  $\hat{e}_{sig}^{out \min}$ . For an arbitrarily polarized input probe:  $\vec{E}_{sig}(0) = a\hat{e}_{sig}^{in \max} + b\hat{e}_{sig}^{in \min}$ , the amplified output Jones vector can be expressed as:

$$\vec{E}_{sig}(L) = a\sqrt{G^{\max}} \hat{e}_{sig}^{out \max} + b\sqrt{G^{\min}} \hat{e}_{sig}^{out \min}. \quad (2)$$

Since typically  $G^{\max} \gg G^{\min}$ , the SOP of  $\vec{E}_{sig}(L)$  is closely aligned with  $\hat{e}_{sig}^{out \max}$ , unless  $a$  is vanishingly small. Equation (2), therefore, describes *polarization pulling* of the output probe wave towards a particular state, which is determined by the pump polarization [2]. The effectiveness of the pulling increases with the ratio  $G^{\max}/G^{\min}$ . For standard fibers that are weakly and randomly birefringent, these two gain values are [2, 10]:

$$G_S^{\min} = \exp(\frac{1}{3}\gamma_0 L \cdot 2P), G_S^{\max} = \exp(\frac{2}{3}\gamma_0 L \cdot 2P) = (G_S^{\min})^2 \quad (3)$$

(the subscript  $S$  stands for single pump), while the output SOPs for maximum and minimum gains are related to the pump SOP by [2]:

$$\hat{e}_{sig}^{out \max} = \hat{e}_p^{(1)*}(L), \hat{e}_{sig}^{out \min} = \hat{e}_p^{(1)\perp}(L). \quad (4)$$

Here  $*$  and  $\perp$  denote complex conjugation and orthogonality, respectively.

Figure 1 shows the Stokes vectors corresponding to  $\vec{E}_{sig}(L)$  following SBS amplification, calculated for 200 randomly chosen input signal SOPs using numeric integration of Eq. (1). Polarization pulling of the amplified probe wave is evident.



Fig. 1. Input arbitrary probe SOPs (left). Simulated output probe SOPs for a single amplifying pump (right), in the undepleted pump regime. Simulation parameters:  $L = 2$  km,  $P = 25$  mW,  $\gamma_0 = 0.18$   $[\text{W} \cdot \text{m}]^{-1}$ . The red and blue circles represent SOPs on the visible and hidden faces of the Poincaré sphere, respectively.

Consider next the proposition of this paper, namely: a dual-pump scenario. Here, an amplifying pump of frequency  $\omega + \Omega_B$  and input unit Jones vector  $\hat{e}_p^{(1)}(L)$ , and an attenuating pump of frequency  $\omega - \Omega_B$  and an orthogonal launch polarization:

$\hat{e}_p^{(2)}(L) \perp \hat{e}_p^{(1)}(L)$ . The two pumps are of equal power  $P$ . The probe propagation equation is now [2]:

$$\frac{d\bar{E}_{sig}(z)}{dz} = \left[ \frac{d\mathbf{T}(z)}{dz} \mathbf{T}^\dagger(z) + \frac{\gamma_0 \cdot P}{2} \hat{e}_p^{(1)}(z) \hat{e}_p^{(1)\dagger}(z) - \frac{\gamma_0 \cdot P}{2} \hat{e}_p^{(2)}(z) \hat{e}_p^{(2)\dagger}(z) \right] \bar{E}_{sig}(z). \quad (5)$$

Note that the effects of the amplifying and attenuating pumps do not cancel out, due to their different SOPs. Under the non-depletion assumption and in the absence of polarization dependent loss (PDL),  $\hat{e}_p^{(2)}(z) \perp \hat{e}_p^{(1)}(z)$  for all  $0 \leq z \leq L$ . Since these two Jones vectors form an orthonormal pair, it follows that:  $\hat{e}_p^{(1)}(z) \hat{e}_p^{(1)\dagger}(z) + \hat{e}_p^{(2)}(z) \hat{e}_p^{(2)\dagger}(z) = \mathbf{I}$  (the identity  $2 \times 2$  matrix), and Eq. (5) can be rearranged:

$$\frac{d\bar{E}_{sig}(z)}{dz} = \left[ \frac{d\mathbf{T}(z)}{dz} \mathbf{T}^\dagger(z) + \frac{\gamma_0 \cdot 2P}{2} \hat{e}_p^{(1)}(z) \hat{e}_p^{(1)\dagger}(z) \right] \bar{E}_{sig}(z) - \frac{\gamma_0 \cdot P}{2} \bar{E}_{sig}(z). \quad (6)$$

Equation (6) differs from Eq. (1) by a simple scalar loss term only, so that the scalarly modified signal field,  $\bar{E}_{sig}(z) \exp(-\gamma_0 P z / 2)$ , *exactly* obeys Eq. (1). We can therefore conclude that the effect of a pair of orthogonal gain and loss pumps, each of power  $P$ , on the propagation of an arbitrary, non-depleting input  $\bar{E}_{sig}(0)$ , is the same as that of a single amplifying pump of power  $2P$ , except for a scalar attenuation factor  $\exp(-\gamma_0 P z / 2)$ . Therefore, the maximum and minimum power gain values for the dual pump configuration are just those of the single pump case, Eq. (3), multiplied by the factor:  $[\exp(-\gamma_0 L \cdot P / 2)]^2 = \exp(-\gamma_0 L \cdot P)$ , i.e.,

$$G_D^{\min} = \exp(-\gamma_0 L \cdot 2P / 6), G_D^{\max} = \exp(+\gamma_0 L \cdot 2P / 6) = 1 / G_D^{\min} \quad (7)$$

( $D$  stands for dual pumps). Clearly,  $G_D^{\max} / G_D^{\min} = G_S^{\max} / G_S^{\min}$ . Since the output probe SOPs obtained with the two configurations are the same, the extent of polarization pulling should be equal as well.

The gains of the dual pump case, Eq. (7), could also be derived using the following observations based on the analysis and discussion of [2]. Let us express an input signal in the basis of  $\hat{e}_s^{in \max} = \hat{e}_p^{(1)*}(0)$ ,  $\hat{e}_s^{in \min} = \hat{e}_p^{(1)\perp}(0)$ :  $\bar{E}_{sig}(0) = a \hat{e}_s^{in \max} + b \hat{e}_s^{in \min}$ . Pump  $\hat{e}_p^{(1)}$  of power  $P$  amplifies  $\hat{e}_s^{in \max}$  by  $\exp(\frac{2}{3} \gamma_0 L \cdot P)$  and  $\hat{e}_s^{in \min}$  by  $\exp(\frac{1}{3} \gamma_0 L \cdot P)$ . The orthogonally polarized attenuating pump  $\hat{e}_p^{(2)} = \hat{e}_p^{(1)\perp}$ , also of power  $P$ , imposes a maximal attenuation of  $\exp(-\frac{2}{3} \gamma_0 L \cdot P)$  on the signal component parallel to  $\hat{e}_p^{(2)*}(0) = \hat{e}_p^{(1)\perp*}(0) = \hat{e}_s^{in \min}$  [2]. The other component, parallel to  $\hat{e}_p^{(2)\perp*}(0) = \hat{e}_p^{(1)*}(0) = \hat{e}_s^{in \max}$ , is only attenuated by  $\exp(-\frac{1}{3} \gamma_0 L \cdot P)$ . It follows that the maximally amplified component  $\hat{e}_s^{in \max}$  is also the least attenuated, and that the minimally amplified component  $\hat{e}_s^{in \min}$  is also the most attenuated. In conclusion, the net gain experienced by  $\hat{e}_s^{in \max}$  is  $\exp((\frac{2}{3} - \frac{1}{3}) \gamma_0 L \cdot P) = \exp(\frac{1}{3} \gamma_0 L \cdot P)$ , while that of  $\hat{e}_s^{in \min}$  is  $\exp((\frac{1}{3} - \frac{2}{3}) \gamma_0 L \cdot P) = \exp(-\frac{1}{3} \gamma_0 L \cdot P)$ , as in Eq. (7).

This predicted equivalence between the single and dual pump configurations is however restricted to the undepleted pump regime. Pump depletion hinders the probe polarization pulling since it reduces the ratio  $G^{\max} / G^{\min}$  by limiting  $G^{\max}$  without affecting  $G^{\min}$ . The onset of depletion occurs when the input probe power  $P_{sig}$ , multiplied by the small-signal value of the maximum gain  $G^{\max}$ , approaches the pump power level [11]. Since the dual

pump configuration is characterized by a more modest  $G^{\max}$  for the same  $G^{\max}/G^{\min}$ , it is expected to withstand higher signal input powers for a given pump power, or equivalently higher pump powers  $P$  for a given signal input power, before reaching depletion. We therefore expect more effective polarization pulling using the dual pump configuration.

### 3. Experimental setup and results

Polarization pulling with one and two pumps was examined experimentally. The measurement setup is shown in Fig. 2 [12]. Light from a distributed feedback laser diode (DFB-LD) with frequency  $\omega$  is amplified by an Erbium-doped fiber amplifier (EDFA) and split in two paths. Light in the upper arm is modulated by a Mach-Zehnder electro-optic modulator (EOM), which is driven by a sine wave of frequency  $\Omega_B$  and biased to suppress the carrier wave. The dual-sideband modulated waveform is split into two branches yet again. In each branch, one of the  $\omega \pm \Omega_B$  sidebands is selected using an appropriate narrowband fiber Bragg grating (FBG) filter. EDFAs are used in both filtering branches to compensate for modulation and FBG losses. The sideband power is controlled with a variable optical attenuator (Att), and its input polarization (IP) is adjusted to one of two orthogonal states. The two sidebands are then combined by a polarization beam combiner (PBC), forming dual orthogonal pump waves with respect to the soon to be defined probe wave at frequency  $\omega$ : an amplifying one ( $\omega + \Omega_B$ ) and an attenuating one ( $\omega - \Omega_B$ ). The dual pumps are launched into a 2250 m long fiber under test (FUT) via a circulator. The DFB-LD light in the lower arm is launched into the FUT from the opposite direction, as an SBS probe wave. A variable optical attenuator and a programmable digital polarization controller adjust the power and SOP of the input probe wave, respectively. The amplified probe wave at the FUT output is filtered by a narrowband FBG whose reflection band is centered at  $\omega$ , for eliminating back-scatter at the dual pump frequencies.

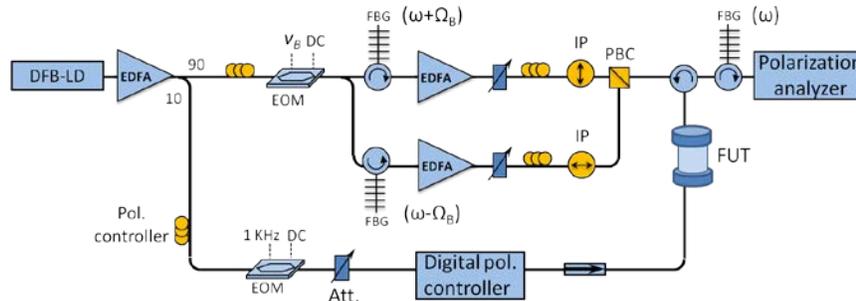


Fig. 2. Experimental setup for SBS polarization pulling with two orthogonal pumps.

Measurements of the output probe power and SOP are normally disturbed by additive noise due to the amplified spontaneous emission that accompanies the Brillouin scattering amplification process (SBS-ASE) [13]. In order to distinguish between signal and noise, the input probe wave is modulated by a 1 kHz tone (see lower arm in Fig. 1). The output probe power is measured by an optical detector followed by a lock-in amplifier, tuned to 1 kHz. The lock-in amplifier effectively filters out SBS-ASE. Polarization measurements are performed by a fast polarization analyzer, which samples all four Stokes parameters at 10,000 samples per second. Fourier analysis of the measurements is used to distinguish between the SOPs of the output probe wave and noise contribution from the SBS-ASE. This broad-bandwidth analyzer, therefore, allows for 'lock-in' measurements of the SOPs of the amplified and/or attenuated SBS probe waves. The launch power levels of the probe and both pumps, as well as the modulation depth of both EOMs, were continuously monitored throughout the measurements.

Figure 3 shows the experimental logarithmic gains as a function of the *total* pump power, for a single amplifying pump ( $G_S^{\max}$  and  $G_S^{\min}$ ) and for the dual orthogonal pump configuration ( $G_D^{\max}$  and  $G_D^{\min}$ ). The probe input power  $P_{sig}$  was  $-15$  dBm. The maximum and minimum gains were found using the following procedure [2]: The programmable polarization controller in the signal path was set to four non-degenerate SOPs, and the output signal power was recorded for each. Based on these four measurements, the top row of the 4X4 Mueller matrix describing the pumped fiber under test was extracted [14], and signal SOPs for minimum and maximum output power could be calculated.

The small-signal gain values were extrapolated from a linear fit of the measurements of Fig. 3a at low pump power, i.e., far from depletion. They were found to be (in decreasing order and in dB/mW): 1.5, 0.78 (for the single pump) and 0.4 and  $-0.4$  (for the dual pumps). These values quite accurately match the detailed predictions of Eqs. (3) and (7).

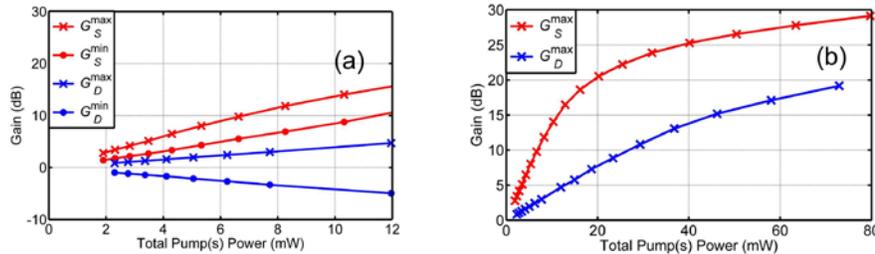


Fig. 3. Measured Brillouin gain as a function of total pump(s) power when the input probe SOP is optimized to provide either maximum gain (X) or minimum gain (●). The initial linear dependence of the gain on pump power is shown in (a) for low pump powers. The red curves (two upper ones in (a) and the upper one in (b)) are for the single pump case, while the blue lower curves are for the dual pump configuration, which is characterized by a higher depletion threshold (b). The input signal power level was  $30\mu\text{W}$ .

To study depletion, we define its threshold as the pump power for which the measured  $G^{\max}$  is 3 dB lower than its expected small signal value. As expected, the threshold of depletion with a single amplifying pump ( $\sim 15$  mW) is lower than that of the dual pump configuration ( $\sim 45$  mW). The onset of pump depletion can be calculated with numeric integration of the coupled equations for pump and signal power levels [1]. For the choice of  $P_{sig}$  in the experiment, the depletion threshold for the single amplifying pump is on the order 15-18 mW, in agreement with the measurements. Due to depletion, the ratio  $G^{\max}/G^{\min}$  for the single pump monotonically decreases with the total pump power beyond its linear regime, whereas the corresponding ratio for the dual pump configuration continues to increase until reaching its own depletion threshold at a higher total power.

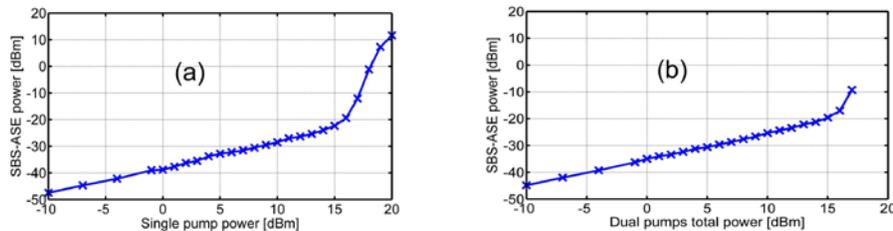


Fig. 4. Measured power of amplified spontaneous emission of stimulated Brillouin scattering as a function of total pump power, for a single amplifying pump (left) and two orthogonal pumps (right).

Figure 4 shows the measured power of SBS-ASE for the two pumping configurations. While the SBS-ASE threshold is on the order of 40 mW for both configurations, the SBS-

ASE power level for the two-pump case appears to be slightly higher. Further research is needed to clarify this observation.

Polarization pulling was quantified by launching 20 different probe SOPs, which span the Poincare sphere (see Fig. 5a). The corresponding output SOPs for a total pump power of 12.5 mW are shown in panels 5b and 5c for single and dual pumps, respectively. A similar extent of polarization pulling is evident in both figures, as expected in the undepleted pump regime. Figures 5d and 5e show the output probe SOP for a total pump power of 25 mW. Here, depletion of the single amplifying pump reduces the gain, and consequentially, restricts the probe polarization pulling, whereas the 20 output SOPs in the dual pump configuration form a cluster that is tightly packed. The experimental results, therefore, support the analysis of section 2. Effective polarization pulling with a measured degree of polarization exceeding 0.98, as well as the added value of the dual pump scheme, are thus demonstrated at a total pump power level that is below the threshold of SBS-ASE.

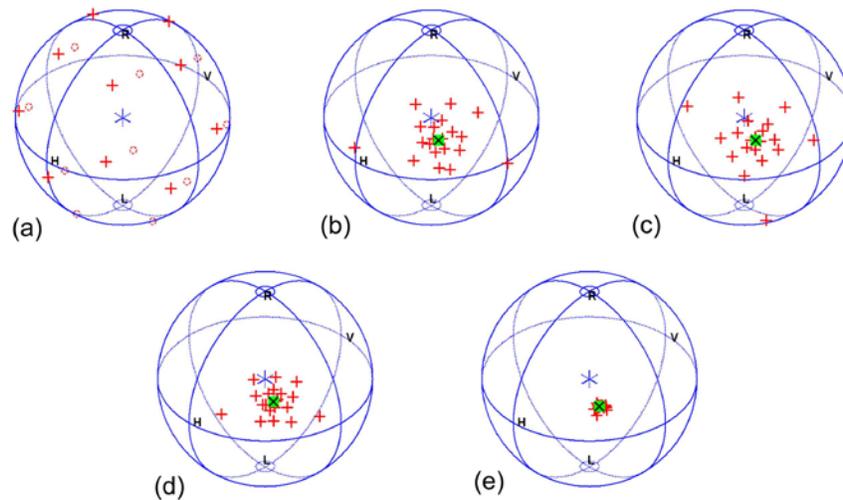


Fig. 5. Poincare sphere pictures of polarization pulling. (a) The 20 input probe SOPs: the + signs and broken circles represent SOPs on the visible and hidden faces of the Poincare sphere, respectively. Corresponding measured output SOPs for single pump and dual pumps of the same total power are shown in (b)-(e). (b)-(c): Moderate pulling is observed for 12.5 mW, which is below the depletion threshold for the single pump case; (d)-(e) For a total pump power of 25 mW, the single pump is depleted while the dual pumps are not, resulting in much tighter pulling in the latter case. Input signal power was  $30\mu\text{W}$ . 'x' denotes the SOP of the complex conjugate of the amplifying pump Jones vector ( $\hat{e}_{sig}^{out\ max}$  of Eq. (4)). It is also the SOP of SBS-ASE for high pump power [2].

#### 4. Conclusions

A novel architecture for SBS-based all-optical polarization pulling has been proposed and demonstrated, in both simulations and experiments. The technique relies on two orthogonally polarized SBS pump waves: one pump amplifies the signal wave, whereas the other attenuates it. In the undepleted pump regime, the extent of polarization pulling provided by the dual pumps is equivalent to that of a single pump of the same total power. However, the dual pump method is shown to be more depletion resistant. Consequently, the dual pump configuration could pull the SOP of stronger probe waves more effectively, and provide stronger pulling with the application of higher pump power levels. Future work is necessary to examine the ratio of signal power to SBS-ASE noise power of data-carrying signals following polarization pulling.

Even though SBS-based polarization pulling was only recently proposed, it has already found application in advanced modulation formats [15]. The prospect of a more robust

polarization pulling using dual pumps is applicable to fiber-optic interferometric sensors and coherent communications. Finally, the performance of optical and microwave-photonics SBS filters can be enhanced via careful control of polarization [16-17].

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