ISSN 1674-1056
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Citation: Chin. Phys. B . 2019, 28(9): 094216 . **doi:** 10.1088/1674-1056/28/9/094216
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Polarization dependence of gain and amplified spontaneous Brillouin scattering noise analysis for fiber Brillouin amplifier*

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(Received 26 April 2019; revised manuscript received 28 May 2019; published online 23 August 2019)

The polarization dependences of gain and amplified spontaneous Brillouin scattering (ABS) noise for fiber Brillouin amplifier (FBA) are analyzed through theories, simulations, and experiments. Modified vector propagation equations for calculating the gain of the probe signal and the ABS noise are derived and analyzed in the Stokes spaces. In simulations and experiments, we prove that the gain of the probe signal and the ABS noise are strongly dependent on the relative state of polarization (SOP) of the pump and probe signals. The closer the relative SOP of the pump and probe signals is, the more obvious ABS noise suppression effect will be brought by increasing the power of the input probe signal.

Keywords: fiber Brillouin amplifier, state of polarization, stimulated Brillouin scattering, spontaneous Brillouin scattering

PACS: 42.65.Es, 13.88.+e **DOI:** 10.1088/1674-1056/ab38ab

1. Introduction

Stimulated Brillouin scattering (SBS) has attracted much attention as a favorable mechanism for its highly selective gain, simplicity of implementation, and low-threshold pump power in standard single-mode fiber. SBS has exhibited great potential in the fields of fiber Brillouin amplifier (FBA),[1–4] distributed sensing of temperature and strain,[5] optical filter,[6] fiber lasers,[7,8] and even optical processing of high frequency microwave signals.[9]

It is known that the strength of the SBS is often quantified in terms of an exponential gain coefficient γ_0, but the interaction at a given point along the fiber is strongly and inherently polarization-dependent.[10] The SBS reaches the most efficient interaction when the electric fields of the pump and signal are aligned, and vanishes for orthogonally polarized fields.[11] So the gain of the FBA is deeply dependent on the relative SOP of pump and probe signal.

Just as the amplified spontaneous emission (ASE)[12] noise exists in the erbium-doped fiber amplifier (EDFA).[13] One important feature of the FBA is its level of amplified spontaneous Brillouin scattering (ABS) noise,[14] which could prevent the use of the FBA in many fields. The ABS noise of the FBA has previously been theoretically studied regarding that the gain coefficients of ABS noise and probe signal were equal.[15,16] In 2019, Sheng *et al.*[17] have proposed a method to filter out the amplified probe signal from the ABS noise via mode conversion and spatial filtering, and they also think the ABS noise will be amplified with nearly the same gain as the probe signal. However, the probe signal has its own SOP, which may be different from that of the pump. And the original spontaneous Brillouin scattering signal originates from the pump, so the spontaneous Brillouin scattering signal which has the same SOP as the pump will be amplified rapidly. The pioneering work of He *et al.*[18] reported that, when the probe signal was gradually strengthened, the interaction between the probe signal and pump would inhibit the ABS noise. But they failed to analyze this phenomenon theoretically.

In this paper, modified vector propagation equations in Stokes spaces are derived and exploited to study the simultaneous amplification process of probe signal and ABS noise in the FBA. Considering the SOPs, the amplification efficiencies of probe signal and ABS noise cannot always be considered to be the same, which are analyzed by the modified equations. The gain polarization dependence of probe signal and ABS noise for FBA are also inspected by simulations, for different relative SOPs of pump and probe signal. As predicted by the analysis, the competition relationship between the probe signal and ABS noise, which caused by the unequal amplification coefficient, has been verified in experiments. In addition, the effect of ABS noise suppression by increasing the power of probe signal is also analyzed in simulations and experiments when the relative SOPs of probe light and pump are in different situations.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61531003, 61690195, 61701040, and 61427813), the Fund of State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications (BUPT), China, and the Youth Research and Innovation Program of BUPT, China.

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2. Analytical description polarization dependence of gain and ABS noise for FBA

In FBA, the weak probe signal and typically strong pump launch into the fiber at $z = L$, $z = 0$, respectively, and propagate in opposite directions. They interfere with each other, through electrostriction, and form a moving modulated grating in the fiber.[19,20] At the same time, the random fluctuation phonons in the optical fiber also scatter the pump light to produce spontaneous Brillouin scattering signal. The spontaneous Brillouin scattering signal also interacts with the pump light to form a noise grating. As shown in Fig. 1, the modulated grating and noise grating will mediate power transfer from the pump to the probe signal and spontaneous Brillouin scattering signal respectively. So while the probe signal is amplified along the fiber, the spontaneous Brillouin scattering signal is also amplified simultaneously, which becomes the main noise of FBA.

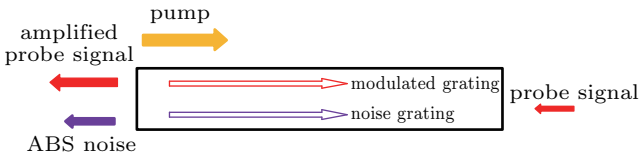


Fig. 1. The amplification process including probe signal and ABS noise.

For initial work, the SBS process is analyzed by using vector propagation equations by Zadok *et al.*[21] However, in the derivation process of the equations, they neglected the amplification of the spontaneous Brillouin scattering noise by the pump. So when the probe signal, ABS noise, and pump are all considered in FBA, the local evolutions of $\boldsymbol{E}_{\rm sig}(z)$, $\boldsymbol{E}_{\rm abs}(z)$, and $\boldsymbol{E}_{\rm pump}(z)$ are driven by the SBS effect and the fiber attenuation can be expressed as

$$\begin{cases} \dfrac{{\rm d}\boldsymbol{E}_{\rm sig}(z)}{{\rm d}z} = -\left[\dfrac{\gamma_0}{2}\boldsymbol{E}_{\rm pump}(z)\boldsymbol{E}^{\dagger}_{\rm pump}(z) - \dfrac{\alpha}{2}\right]\boldsymbol{E}_{\rm sig}(z), \\ \dfrac{{\rm d}\boldsymbol{E}_{\rm abs}(z)}{{\rm d}z} = -\left[\dfrac{\gamma_0}{2}\boldsymbol{E}_{\rm pump}(z)\boldsymbol{E}^{\dagger}_{\rm pump}(z) - \dfrac{\alpha}{2}\right]\boldsymbol{E}_{\rm abs}(z), \\ \dfrac{{\rm d}\boldsymbol{E}_{\rm pump}(z)}{{\rm d}z} = -\left[\dfrac{\gamma_0}{2}\boldsymbol{E}_{\rm sig}(z)\boldsymbol{E}^{\dagger}_{\rm sig}(z) \right. \\ \qquad\qquad \left. + \dfrac{\gamma_0}{2}\boldsymbol{E}_{\rm abs}(z)\boldsymbol{E}^{\dagger}_{\rm abs}(z) + \dfrac{\alpha}{2}\right]\boldsymbol{E}_{\rm pump}(z), \end{cases} \tag{1}$$

where γ_0 is the gain coefficient, and α is the fiber attenuation coefficient.

To obtain the power evolutions of the probe signal, ABS noise, and pump in terms of the Stokes parameters, we use the common definitions expressed below

$$\begin{cases} I \equiv \boldsymbol{E}^{\dagger}\boldsymbol{E}, \\ \dfrac{I}{2}(\boldsymbol{I} + \boldsymbol{s}\cdot\boldsymbol{\sigma}) \equiv \boldsymbol{E}E^{\dagger}, \\ I\boldsymbol{s} = \boldsymbol{E}^{\dagger}\boldsymbol{\sigma}E, \end{cases} \tag{2}$$

$$\boldsymbol{\sigma_1} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad \boldsymbol{\sigma_2} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \boldsymbol{\sigma_3} = \begin{bmatrix} 0 & -{\rm j} \\ {\rm j} & 0 \end{bmatrix}.$$

I and $\boldsymbol{s}$ denote the power and normalized Stokes vector which correspond to $\boldsymbol{E}$, respectively. $\boldsymbol{\sigma}$ is a vector of the Pauli spin matrices. $\boldsymbol{I}$ denotes the 2×2 unit matrix, superscript sign † represents the conjugate transpose of the matrix.

Considering the probe signal, we obtain

$$\frac{{\rm d}\boldsymbol{E}_{\rm sig}}{{\rm d}z} = -\left[\frac{\gamma_0 I_{\rm pump}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{\sigma}) - \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm sig}. \tag{3}$$

Equation (3) can be used to obtain the power evolution of the probe signal

$$\begin{aligned} \frac{{\rm d}I_{\rm sig}}{{\rm d}z} &= \frac{{\rm d}\left(\boldsymbol{E}^{\dagger}_{\rm sig}\boldsymbol{E}_{\rm sig}\right)}{{\rm d}z} \\ &= \boldsymbol{E}^{\dagger}_{\rm sig}\left[-\frac{\gamma_0 I_{\rm pump}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{\sigma}) + \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm sig} \\ &\quad + \boldsymbol{E}^{\dagger}_{\rm sig}\left[-\frac{\gamma_0 I_{\rm pump}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{\sigma}) + \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm sig} \\ &= -\frac{\gamma_0}{2}(1 + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{s}_{\rm sig})I_{\rm pump}I_{\rm sig} + \alpha I_{\rm sig}. \end{aligned} \tag{4}$$

Following the similar steps, the corresponding equations for ABS noise and the pump can also be derived as

$$\begin{aligned} \frac{{\rm d}I_{\rm abs}}{{\rm d}z} &= \frac{{\rm d}\left(\boldsymbol{E}^{\dagger}_{\rm abs}\boldsymbol{E}_{\rm abs}\right)}{{\rm d}z} \\ &= \boldsymbol{E}^{\dagger}_{\rm abs}\left[-\frac{\gamma_0 I_{\rm pump}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{\sigma}) + \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm abs} \\ &\quad + \boldsymbol{E}^{\dagger}_{\rm abs}\left[-\frac{\gamma_0 I_{\rm pump}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{\sigma}) + \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm abs} \\ &= -\frac{\gamma_0}{2}(1 + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{s}_{\rm abs})I_{\rm pump}I_{\rm abs} + \alpha I_{\rm abs}, \end{aligned} \tag{5}$$

$$\begin{aligned} \frac{{\rm d}I_{\rm pump}}{{\rm d}z} &= \frac{{\rm d}\left(\boldsymbol{E}^{\dagger}_{\rm pump}\boldsymbol{E}_{\rm pump}\right)}{{\rm d}z} \\ &= \boldsymbol{E}^{\dagger}_{\rm pump}\left[-\frac{\gamma_0 I_{\rm abs}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm abs}\cdot\boldsymbol{\sigma}) \right. \\ &\quad \left. - \frac{\gamma_0 I_{\rm sig}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm sig}\cdot\boldsymbol{\sigma}) - \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm pump} \\ &\quad + \boldsymbol{E}^{\dagger}_{\rm pump}\left[-\frac{\gamma_0 I_{\rm abs}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm abs}\cdot\boldsymbol{\sigma}) \right. \\ &\quad \left. - \frac{\gamma_0 I_{\rm sig}}{4}(\boldsymbol{I} + \boldsymbol{s}_{\rm sig}\cdot\boldsymbol{\sigma}) - \frac{\alpha}{2}\right]\boldsymbol{E}_{\rm pump} \\ &= -\frac{\gamma_0}{2}(1 + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{s}_{\rm abs})I_{\rm pump}I_{\rm abs} \\ &\quad - \frac{\gamma_0}{2}(1 + \boldsymbol{s}_{\rm pump}\cdot\boldsymbol{s}_{\rm sig})I_{\rm pump}I_{\rm sig} - \alpha I_{\rm pump}. \end{aligned} \tag{6}$$

Equations (4)–(6) represent the power distribution of probe signal, ABS noise, and pump along the single-mode fiber. We can see that the ABS noise and probe signal will be amplified by the pump along the fiber simultaneously. $\boldsymbol{s}_{\rm sig} = \left[s_{1,\rm sig}\ s_{2,\rm sig}\ s_{3,\rm sig}\right]^{\rm T}$, $\boldsymbol{s}_{\rm abs} = \left[s_{1,\rm abs}\ s_{2,\rm abs}\ s_{3,\rm abs}\right]^{\rm T}$, and $\boldsymbol{s}_{\rm pump} = \left[s_{1,\rm pump}\ s_{2,\rm pump}\ s_{3,\rm pump}\right]^{\rm T}$ are 3×1 normalized Stokes vectors, describing the SOPs of the probe signal, ABS noise, and pump, respectively. Through the analysis, the last terms in

Eqs. (4)–(6) represent the light transmission loss in optical fiber.

As the original spontaneous Brillouin scatter signal is obtained by scattering of pump light, the spontaneous Brillouin scattering signal which has the same SOP as the pump will be amplified rapidly. Then the gain coefficient of ABS noise should be a constant quantity $(\gamma_0/2)\left(1+\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{abs}}\right)=\gamma_0$, which is not affected by SOP. But the SOPs of probe signal and pump may be different. So, the gain efficiency of probe signal still depends deeply on the relative SOP of pump and probe signal. Based on the above discussion, the coupled equations should be changed as

$$\begin{cases} \dfrac{\mathrm{d}I_{\text{abs}}}{\mathrm{d}z}=-\gamma_0 I_{\text{pump}}I_{\text{abs}}+\alpha I_{\text{abs}}, \\ \dfrac{\mathrm{d}I_{\text{sig}}}{\mathrm{d}z}=-\dfrac{\gamma_0}{2}\left(1+\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}\right)I_{\text{pump}}I_{\text{sig}}+\alpha I_{\text{sig}}, \\ \dfrac{\mathrm{d}I_{\text{pump}}}{\mathrm{d}z}=-\gamma_0 I_{\text{pump}}I_{\text{abs}}-\dfrac{\gamma_0}{2}\left(1+\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}\right)I_{\text{pump}}I_{\text{sig}} \\ \qquad\qquad -\alpha I_{\text{pump}}. \end{cases} \tag{7}$$

Equation (7) can explain the competition process between probe signal and ABS noise for pump energy in FBA, theoretically. We have not obtained the analytical solutions for the new coupled equations, but still we can use numerical methods to get the amplified power of probe signal and the ABS noise.

3. Simulations for polarization dependence of gain and ABS noise for FBA

Numerical methods are used to solve Eq. (7) to get the power distributions of pump, probe signal, and ABS noise along the fiber. Three different kinds of relative SOPs of pump and probe signal are simulated to show the competitive relationship between the probe signal and ABS noise for pump power. Here, the fiber length is set as 5.3 km. The fiber attenuation coefficient α and SBS gain coefficient γ_0 are set as 0.2 dB/km and 0.07775 $[\mathrm{W}\cdot\mathrm{m}]^{-1}$ respectively. Pump and probe signal input powers are 14.8 dBm and -20 dBm, and the original spontaneous Brillouin scattering signal power is set as -34.6 dBm. The pump propagates in the $+z$ direction, whereas the probe signal and ABS noise travel in the $-z$ direction.

In Fig. 2(a), we plot the maximum amplified probe signal power of 10.3 dBm and minimum ABS noise power of -4.3 dBm when the input probe signal SOP is aligned with that of the pump, *i.e.*, $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=1$. In Fig. 2(b), the amplified probe signal power is decreased to 5.17 dBm and the ABS noise power is increased to 3.73 dBm in the case of $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=1/3$. In Fig. 2(c), when the scalar product of the pump and probe signal vectors satisfies the relationship of $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=-1/3$, the ABS noise power of 5.9 dBm is larger than the amplified probe signal power of -7.00 dBm.

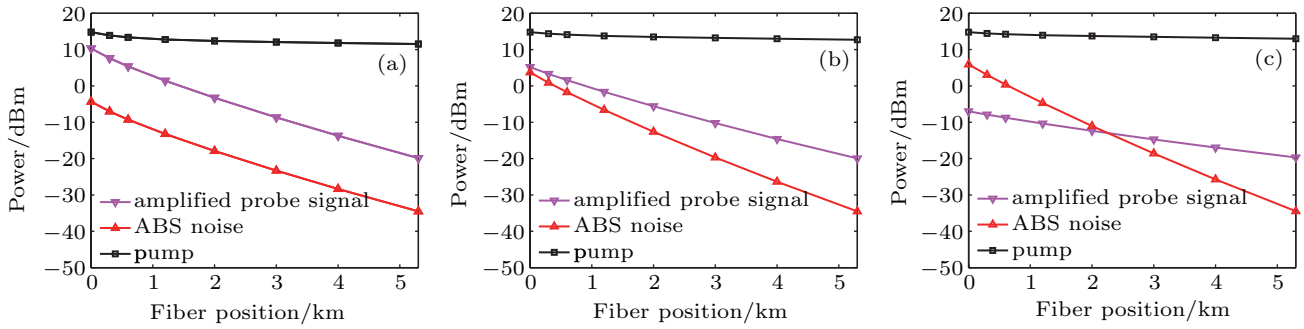


Fig. 2. Numerical results of pump, amplified probe signal, and ABS noise power distribution along the fiber position: (a) $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=1$, (b) $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=1/3$, (c) $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=-1/3$.

When the SOPs of pump and probe signal are parallel, *i.e.*, $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=1$, the gain efficiency of the probe signal $(\gamma_0/2)\left(1+\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}\right)$, as shown in Eq. (7), is the same as that of the ABS noise γ_0. In this case, the power growth rates of the probe signal and ABS noise are identical because of the same gain efficiencies. And since the power of original spontaneous Brillouin scattering signal is lower than that of the input probe signal, the maximum probe signal gain and the minimum ABS noise can be obtained as shown in Fig. 2(a). Along with the relative SOP of pump and probe signal changing from parallel to orthogonal, the scalar product of the pump and probe signal Stokes vectors $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}$ will decrease gradually. The smaller of the gain efficiency of the probe signal is, the less pump power will be consumed by it. Therefore, more pump power will be used to amplify the ABS noise. This is the reason why the growth rate of the probe signal along the optical fiber position becomes slower while the rate of ABS noise changes faster from Fig. 2(a) to Fig. 2(c). When the gain efficiency of the probe signal reduces to a certain limit, the output power of ABS noise by the amplifier will exceed that of the amplified probe signal.

Figure 3 shows numerical results of ABS noise power for different relative SOPs of pump and probe signal, while the input probe signal power is increased form -30 dBm to -10 dBm. When the SOP of input probe signal is aligned with that of the pump, *i.e.*, $\boldsymbol{s}_{\text{pump}}\cdot\boldsymbol{s}_{\text{sig}}=1$, the ABS noise

power is changed from 2.27 dBm to −12.44 dBm, which is decreased by 14.71 dB. Then the scalar product of the pump and probe signal Stokes vectors satisfies the relationships of $s_{\text{pump}} \cdot s_{\text{sig}} = 1/3$ and $s_{\text{pump}} \cdot s_{\text{sig}} = -1/3$. The ABS noise power in the two cases is suppressed by 9.37 dB and 0.96 dB, by increasing the same power of input probe signal, respectively.

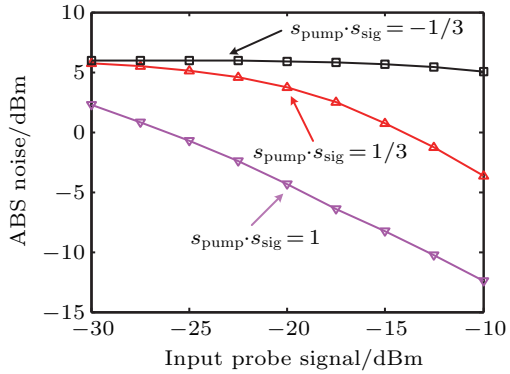


Fig. 3. Numerical results of ABS noise power as a function of input probe signal power.

When the gain efficiency of the probe signal, is fixed, *i.e.* $(\gamma_0/2)\left(1+s_{\text{pump}}\cdot s_{\text{sig}}\right)$, the intensity of the modulated grating generated by the interaction between the pump and the probe signal will be enhanced with the increases of the input probe signal power. Thus the modulated grating will scatter more pump energy to the probe signal. Correspondingly, the pump energy used to amplify the ABS noise will be reduced. This is why the ABS noise power can be suppressed by increasing the input power of probe signal. For larger value of $s_{\text{pump}} \cdot s_{\text{sig}}$, even if the increment of input probe signal power is the same, more pump power will be transferred to the probe signal, so the ABS noise will naturally be suppressed faster.

4. Experiments setup and results

The experimental setup for characterizing the gain polarization dependence of probe signal and ABS noise in FBA is shown in Fig. 4. On the left side, an Agilent 81640A tunable laser is used as the pump. The pump wavelength is adjusted to 1550.739 nm and the power is amplified to 14.8 dBm by EDFA. Then the pump is directed into the fiber which is used as the gain medium via circulator. The length of the fiber is 5.3 km, and its measured Brillouin frequency shift is about 10.875 GHz. On the right side, the probe signal power is adjusted to −20 dBm at 1550.826 nm by a variable optical attenuator (VOA). Two polarization controllers (PC) are used to adjust the input SOPs of pump and probe signal, and the amplified probe signal and ABS noise are separated from each other by a polarization beam splitter (PBS).

In the gain of probe signal and ABS noise measurements, when the pump light is turned off, the un-amplified probe signal outputs completely from the port 1 of the PBS by selecting a particular angle of PC2. We believe that the amplified probe signal should have the same SOP as the input probe signal. So when the pump is added, the amplified signal with the same SOP as the input probe signal could be screened out by the PBS. The SOP of input pump is adjusted from aligning with the SOP of the probe signal to orthogonal state by PC1, then the power variation of amplified probe signal and ABS noise could be recorded.

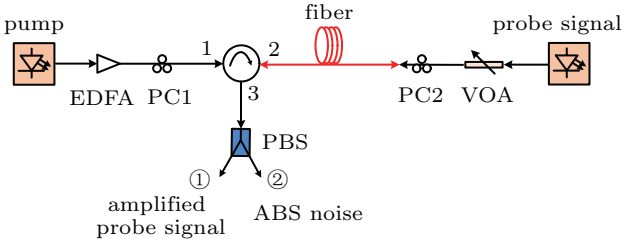


Fig. 4. Experimental setup for characterizing the polarization dependence of gain and ABS noise for FBA.

Figure 5 shows the experimental results of competition between probe signal and ABS noise as a function of relative SOPs of the pump and probe signal. The downward-triangle dashed line shows the power of the amplified probe signal, the upward-triangle dashed line represents the power of the ABS noise and the sum of them is displayed as the upper square dashed line. In these curves, the gain of the probe signal is strongly and inherently dependent on the relative SOP of the pump and probe signal, reaching the highest gain when the electric fields of the pump and signal are aligned, and reducing with the adjustment of the SOPs to the orthogonal state. However, the power of ABS noise increases with the decreases of the gain of the probe signal, as obtained in the simulations. Due to the influence of fiber birefringence,[22,23] even when the relative SOP of the input pump and probe signal is adjusted to orthogonal state, the probe signal will still be magnified slightly in the experiment.

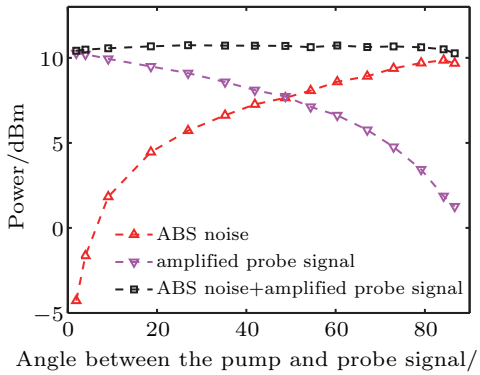


Fig. 5. Experimental results for polarization dependence of gain of probe signal and ABS noise.

Figure 6 shows the effect of input probe signal power on the ABS noise in two particular relative SOPs of pump and probe signal. For the lack of polarization analyzer, the two exact value of the scalar product of the pump and probe signal Stokes vectors, $s_{\text{pump}} \cdot s_{\text{sig}}$, are unknown. But we are sure the

scalar product of the curve 1 is smaller than the value of the curve 2, which can be seen from the ABS noise power. As the results show, the ABS noise appears to be inversely proportional to the input probe signal power over the entire measurement range, indicating the ABS noise can be suppressed by increasing the power of input probe signal. And when the scalar product of the pump and probe signal Stokes vectors is larger, the SOP of the probe signal is closer to that of the pump, better ABS noise suppression effect can be achieved by increasing the same probe signal power, as obtained in the simulations.

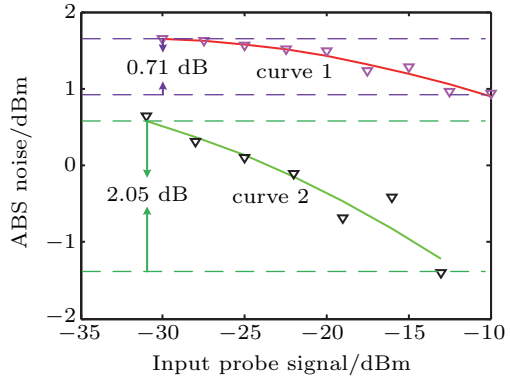


Fig. 6. Experimental results of ABS noise power as a function of input probe signal power.

Due to the following restrictions, the experimental data cannot be completely equal to the analytical solutions of the modified equations. We use a PBS to separate the amplified probe signal and the ABS noise by distinguishing the SOPs. But the experiment shows that the device cannot completely distinguish the ABS noise from the amplified probe signal, and there is crosstalk between them. And the fiber random birefringence effect also interferes with the SOP of the light.

5. Conclusion

In this work, the analysis shows when considering the SOP, the gain coefficient of ABS noise should be a constant quantity when the gain efficiency of probe signal varies with the relative SOP of pump and probe signal. In the experiment, when we only adjust the relative SOP of pump and probe signal, variable gains of probe signal and ABS noise are obtained. We also find that increasing the input probe signal power can suppress ABS noise. And larger scalar product of pump and probe signal Stokes vectors will bring more obvious ABS noise suppression effect. All the experiment results are consistent with the analytical solutions of the modified equations.

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