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High-gain and low-distortion Brillouin amplification based on pump multi-frequency intensity modulation*

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Using a pump with a multi-line spectrum to broaden the Brillouin gain bandwidth is an effective way to achieve low-distortion amplification with high gain. Here, we theoretically and experimentally investigate the generation of a broadband Brillouin gain spectrum based on multi-frequency intensity modulation in an optical fiber. The arbitrary bandwidth of the Brillouin gain spectrum of stimulated Brillouin scattering (SBS) can be obtained as expected. In our experiment, a broadband Brillouin gain spectrum with a bandwidth of about 200 MHz is demonstrated. We also achieve a low-distortion amplification of a weak signal, whose maximum magnification is 65 dB for a −68-dBm input power signal.

Keywords: Brillouin gain spectrum, bandwidth, intensity modulation, low distortion amplification

PACS: 42.65.Es, 42.65.–k, 42.65.Yj **DOI:** 10.1088/1674-1056/28/2/024212

1. Introduction

As one of the strongest nonlinear light-matter interactions, stimulated Brillouin scattering (SBS) has been widely studied in the amplification of weak signals, pulse compression, distributed strain/temperature sensors, slow/fast-light generators, tunable optical filters, and beam shaping.[1–8] More recently, the SBS in optical fibers is found to be able to realize the high-gain amplification of weak signals embedded in strong background noise.[9] The efficient mechanism for weak signal amplification possesses many advantages, such as room temperature operation, compatibility with off-the-shelf telecom equipment and easy-to-filter out most of the background optical noise due to the narrow Brillouin resonance width (∼ 30 MHz in standard single mode optical fibers). These characteristics make the SBS a promising mechanism to be used to detect weak optical signals under extreme conditions. In view of these applications, the optimization and less time-consuming measurement of the Brillouin gain spectrum (BGS) and the low-distortion Brillouin amplification of the signal light are of great importance. In particular, low-distortion amplification with high gain based on the SBS has attracted the attention of many researchers.

In optical fibers, the SBS is a nonlinear process of three-wave coupling involving the pump field, counter-propagating Stokes field, and acoustic wave. When the angular frequency of the pump (ω_p) is the Brillouin frequency shift (BFS) of SBS medium (Ω) higher than that of the Stokes (ω_s), a positive feedback loop occurs, which leads the energy to flow from the pump to Stokes and phonon waves. A signal pulse acting as Stokes light is amplified by the pump light because of the Brillouin amplification effect. However, in the process of Brillouin amplification, only the frequency component that lies in the Brillouin amplification band (intrinsic Brillouin linewidth of SBS medium) is able to be amplified without distortion (or with very low distortion). Therefore, in the time domain, the usable signal pulse width is limited to a value larger than a certain width (generally tens of nanoseconds) due to the intrinsic narrow Brillouin bandwidth. Consequently, the SBS gain with a broad BGS is highly desirable if we are to suppress pulse distortion. For this purpose, various methods have been investigated to broaden the gain spectrum, such as by expanding the BGS through externally or internally modulating a pump source with a sinusoidal wave or Gaussian (super Gaussian) noise.[10–14]

In the internal modulation (or called direct modulation) type, the output of BGS can be viewed as a convolution between the pump spectrum and the SBS medium dependent intrinsic BGS. As reported, about 250 MHz of BGS was achieved for this case.[14] However, this proposed method is not suitable for obtaining an approximate intrinsic Brillouin gain bandwidth (dependent on the material of SBS medium). In contrast, external modulation type involves overlapping a serial of discrete Brillouin gain lines to broaden the Brillouin bandwidth. Meanwhile, there is no limit in the number of lines in theory. To realize a broader Brillouin gain bandwidth, multi-frequency phase external modulation via a phase modulator (PM) was proposed by Lu *et al.* in 2007.[15] However, this presented approach must satisfy a series of equations which are difficult to solve, and obtains an impure spectrum. It is

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not easy to obtain more than 11 discrete lines by the proposed multi-frequency phase modulation.[16] Compared with multi-frequency phase external modulation method, multi-frequency intensity modulation via an intensity modulator (IM) requires a much small quantity of calculations. Therefore, it is a good alternative to realize broader Brillouin gain bandwidth. In this paper, we extend their work to obtain an arbitrary bandwidth of BGS by using an IM instead of a phase modulator (PM) in a standard single mode fiber (SSMF). A gain spectrum with a bandwidth of about 200 MHz is obtained by using the pump with 10 equal-amplitude spectral lines. Subsequently, a low-distortion amplification of the weak signal pulse is investigated in an experiment. The maximum signal magnification with a value of 65 dB is obtained, when the input signal power is −68 dBm.

2. Theory

Figure 1 illustrates the principle of broadening the gain bandwidth of SBS by using a discrete multi-line pump. We assume that the initial input pump beam is a continuous and monochromatic, in the time domain it can be expressed as

$$E_{\mathrm{p}}(t) = \cos(\omega_{\mathrm{p}} t + \varphi_{\mathrm{p}}), \tag{1}$$

where ω_{p} and φ_{p} are the frequency and phase of the pump beam, respectively. To obtain more discrete gain spectrum lines of SBS, a multi-frequency intensity modulation signal is used to modulate the pump beam. The modulated field is written as

$$E_{\mathrm{m}}(t) = \sum_{i=1}^{n} A_i \cos\left[(i-0.5)\,\omega_{\mathrm{m}} t + \varphi_i\right], \tag{2}$$

where A_i is the amplitude of the component of the i-th harmonic wave, and φ_i is the initial phase of the i-th harmonic wave. Notice that the single-frequency intensity modulation corresponds to the case of $i = 1$ under the assumption of $\varphi_i = 0$. Therefore, for simplicity, the final modulated output of pump beam can be described as

$$\begin{aligned} E(t) &= E_{\mathrm{p}}(t) E_{\mathrm{m}}(t) \\ &= \cos\left(\omega_{\mathrm{p}} t + \varphi_{\mathrm{p}}\right) \left[\sum_{i=1}^{n} A_i \cos\left[(i-0.5)\,\omega_{\mathrm{m}} t + \varphi_i\right]\right] \\ &= \sum_{i=1}^{n} \frac{A_i}{2} \Big\{ \cos\left[\left(\omega_{\mathrm{p}} + (i-0.5)\,\omega_{\mathrm{m}}\right) t + \varphi_i + \varphi_{\mathrm{p}}\right] \\ &\quad + \cos\left[\left(\omega_{\mathrm{p}} - (i-0.5)\,\omega_{\mathrm{m}}\right) t + \varphi_{\mathrm{p}} - \varphi_i\right] \Big\}. \end{aligned} \tag{3}$$

The output spectrum is composed of $2n$ lines. By setting $A_i = 2A$, all the lines are of equal intensity (i.e. equal-amplitude lines). Thus, the effective BGS is given by overlapping the gain spectra induced by each pump spectral line. Therefore, the total gain $g(v)$ can be expressed as[17]

$$\begin{aligned} g(v) = \frac{1}{2n} \sum_{i=1}^{n} \Bigg\{ & \frac{\kappa_i g_0 (\Delta v_{\mathrm{B}})^2}{(\Delta v_{\mathrm{B}})^2 + 4\left[v + (i-0.5)\,\delta\right]^2} \\ & + \frac{\kappa_i g_0 (\Delta v_{\mathrm{B}})^2}{(\Delta v_{\mathrm{B}})^2 + 4\left[v - (i-0.5)\,\delta\right]^2} \Bigg\}, \end{aligned} \tag{4}$$

where g_0 is the line-center SBS gain coefficient for a monochromatic pump field, v is the detuning from the line center, Δv_{B} is the BGS bandwidth, and δ is the frequency separation between adjacent spectral lines, and κ_i is the modulation index ($\kappa_i = 1$ for equal amplitude modulation).

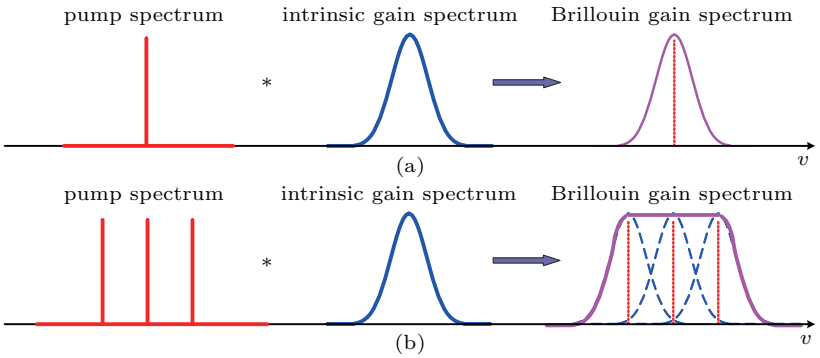


Fig. 1. (a) Gain spectrum of one-line pump and (b) sketch map of bandwidth broadening using three-line pump.

Based on this theory, we first numerically study the conditions of obtaining arbitrary bandwidth of BGS for multi-frequency modulation. The 2 and 30 spectral lines with $\delta = 10$ MHz can be obtained as shown in Fig. 2. The total gain spectra are denoted by red and blue solid line, respectively. It is obvious that the gain profile is broadened by the pump with different numbers of lines. Moreover, the shape of BGS is also changed with the interval between adjacent spectral lines δ. For $2n = 30$, figures 3(a)–3(f) show the simulation results of BGS for $\delta = 1$, 5, 10, 20, 30, and 60 MHz, respectively. It can be seen that the fluctuation in resulting gain increases with the frequency separation increasing, which leads to great pulse distortion. Therefore, there is an optimal δ for a constrained pulse distortion. The previous experiments on SBS slow light proved that the optimal separation, which equals the gain linewidth, can significantly suppress the pulse

distortion.[17] The present simulations prove that the bandwidth of BGS can be increased by multi-line pump.

We take the $2n = 10$ for example. When frequency separation is fixed at 10 MHz, the corresponding Brillouin gain profile is obtained. The gain spectrum of the pump, plotted in black dash curve, is shown in Fig. 4(a). There is no doubt that the BGS is a bell-shaped profile. However, when none of the modulation indexes are identical, *i.e.*, $\kappa_1 = \kappa_2 = \kappa_3 = \kappa_4 = 0.5$, and $\kappa_5 = 1$, the unequal-amplitude spectral lines appear as shown in Fig. 4(b). It can be seen that the corresponding BGS presents a flat-top-shaped profile. Therefore, we can choose the suitable modulation parameters (*i.e.*, δ, κ_i, n) to achieve a flat-top Brillouin gain spectrum with different bandwidths under the condition of multi-frequency modulation via an intensity modulator.

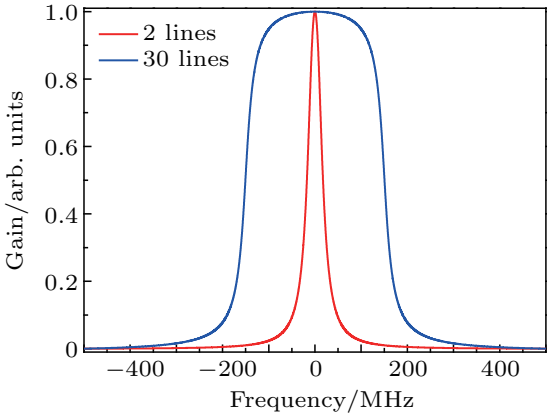


Fig. 2. Gain spectra induced by multi-line pumps.

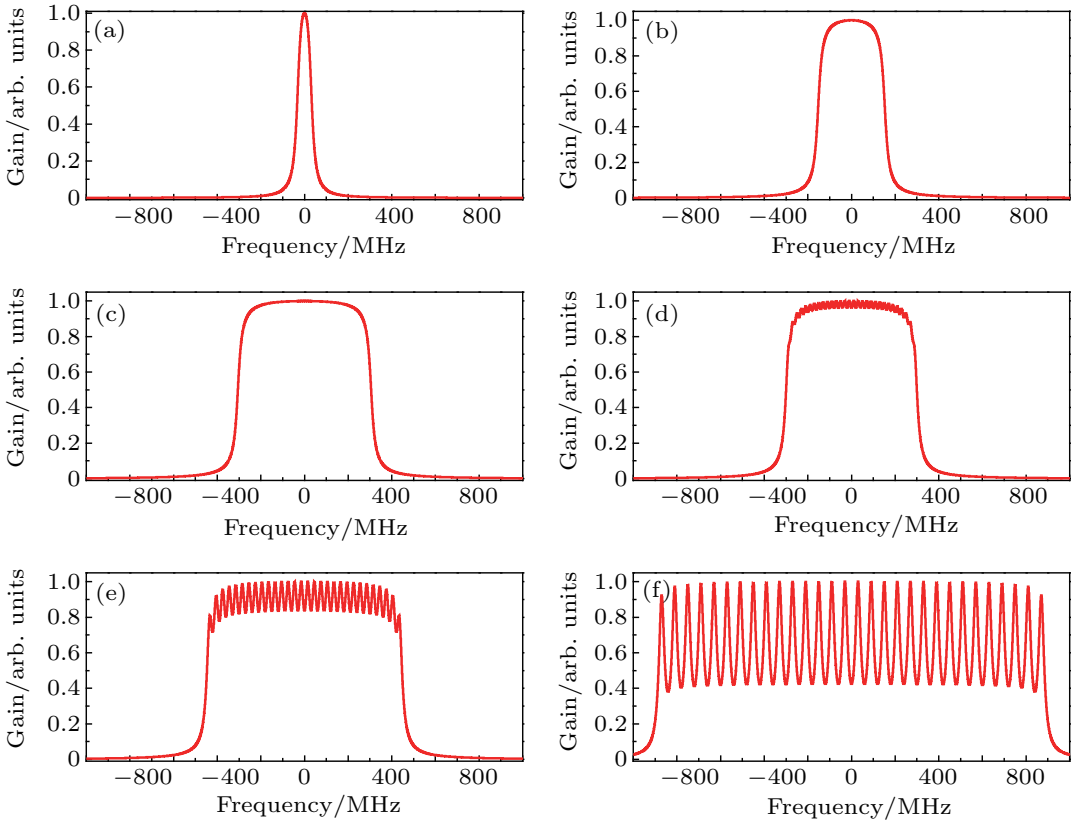


Fig. 3. Brillouin spectra under the pump with multi-line spectrum separated in different intervals for frequencies of (a) 1 MHz, (b) 5 MHz, (c) 10 MHz, (d) 20 MHz, (e) 30 MHz, and (f) 60 MHz.

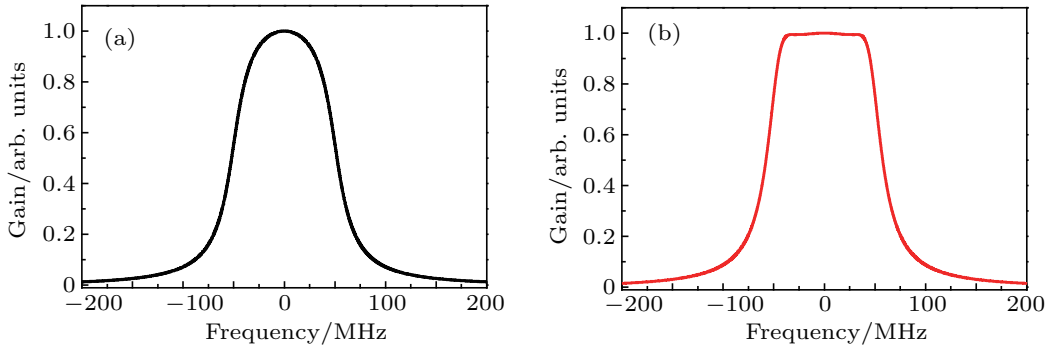


Fig. 4. (a) Bell-shaped BGS and (b) flat-top-shaped BGS.

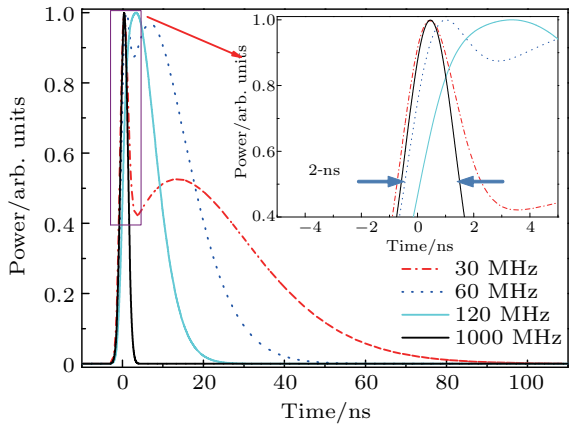


Fig. 5. Amplified waveforms for various pump bandwidths.

Finally, the simulation is carried out to demonstrate the capability of the multi-line pump beam to amplify weak signals with low distortion. In the simulation, the original signal is a 2-ns Gaussian pulse. The pump bandwidths are set to be 30, 60, 120, and 1000 MHz, respectively. The corresponding amplification results are shown in Fig. 5 (see also inset). It can be seen that the distortion decreases with the bandwidth increasing. Therefore, this is a promising method to achieve low distortion amplification, and hence to greatly expand its application scope.

3. Experimental results and discussion

Based on this theoretical analysis, we build an experimental setup as shown in Fig. 6. Pump from a 100-mW, 40-kHz linewidth, 1550-nm wavelength distributed feedback laser (DFB) is split into two parts by an optical coupler (C1, 90:10). The upper branch is used as the pump light, which passes through an electro-optic modulator (IM3) connected with an erbium doped fiber amplifier (EDFA1), and then injected into an SBS medium of optical fiber (fiber under test, FUT) with 1 km in length. The other branch is injected into an IM1 driven by a microwave generator (MG), generating two modulation sidebands. After being filtered by an optical Bragg grating filter (FBG), the lower sideband is obtained, which is used as the probe light. The shifted probe beam is then injected into the opposite end of the SBS medium, where the SBS effect will happen. An oscilloscope is used to record the amplified probe beam.

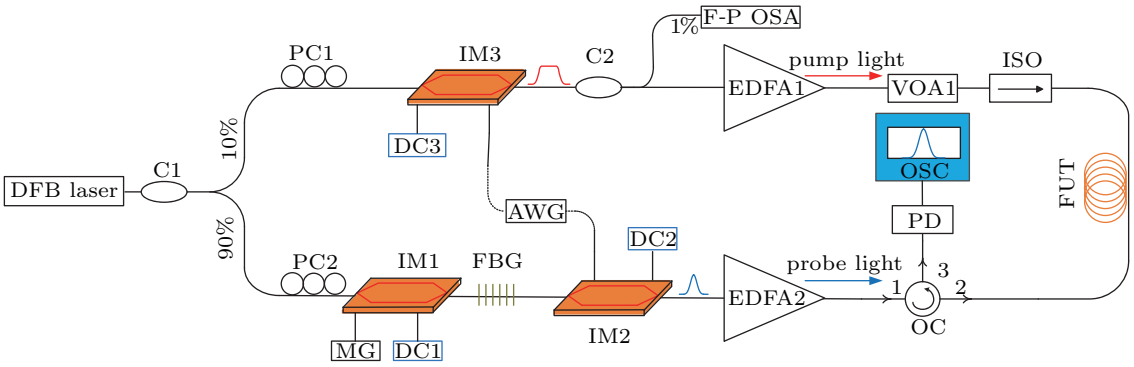


Fig. 6. Schematic diagram of experimental setup. IM: electro–optic modulator; EDFA: erbium-doped fiber amplifier; FUT: fiber under test; PC: polarization controller; AWG: arbitrary waveform generator; ISO: optical isolator; PD: photodetector; MG: microwave generator; FBG: fiber Bragg grating; VOA: variable optical attenuator; OSC: oscilloscope; OC: circulator.

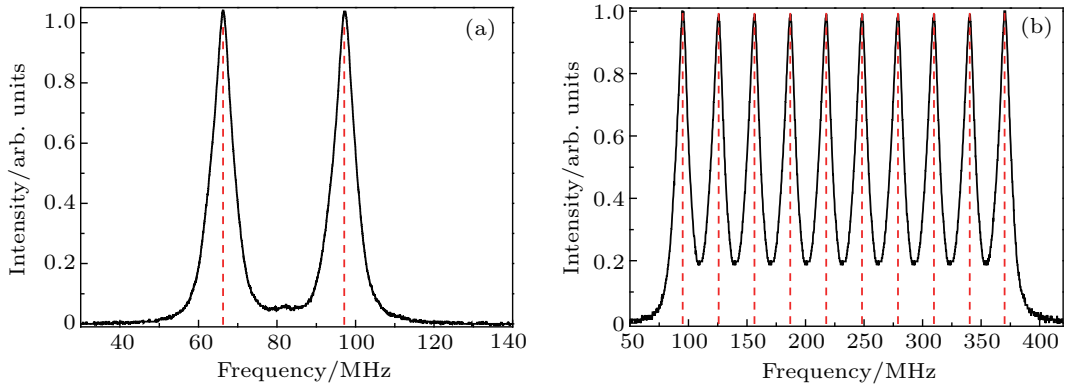


Fig. 7. (a) Spectrum of two equal-amplitude pump lines and (b) spectrum of ten equal-amplitude pump lines.

We experimentally demonstrate that the multi-frequency intensity modulation is able to achieve a broad gain spectra. One percent of the pump beam is extracted with a C2 (1:99), and then detected by a confocal scanning F–P optical spectrum analyzer (OSA) with a free spectrum range (FSR) of 2 GHz. For simplicity, by using the required modulation signal, we

obtain two equal-amplitude spectral lines shown in Fig. 7(a), and 10 equal-amplitude spectral lines shown in Fig. 7(b) with the same frequency separation (30 MHz). It is evident that the experimental results accord well with the simulation results. The BGS is measured by sweeping around the BFS of fiber medium. A Brillouin gain bandwidth of ~ 200 MHz is obtained. The corresponding gain profile is shown in Fig. 8. It is worth noting that if one wants to achieve a wider gain spectrum, then the modulation signals including more discrete lines are necessary.

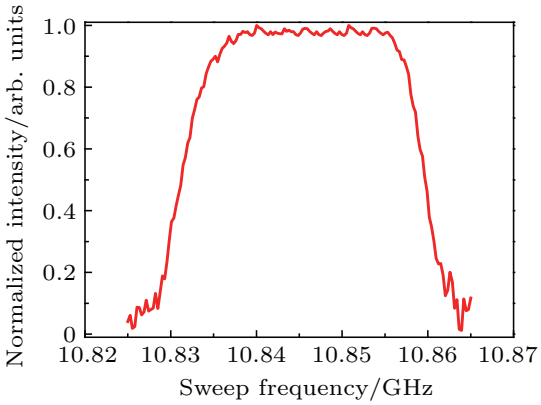


Fig. 8. Brillouin gain spectrum of 10-line spectral pump.

Another experiment based on Brillouin amplification in fiber is carried out to demonstrate its low distortion amplification capability. The pump beam then is modulated by an IM3 to form 10 lines or one line (no modulated), which results in a broadened BGS. The other branch is used as a probe (Stokes) beam, which is modulated into a Gaussian-shaped 50-ns pulse by a pulse generator (IM2). Figure 9 shows the comparison between the probe input and its amplified output pulses under the different pump conditions. The input of pump power density needs controlling to keep the same signal magnification (30 dB) in these cases. Obviously, the shape and width of the amplified probe pulse are almost consistent with those of the origin probe input pulse under the condition of multi-line pump. By contrast, the experimental result without pump modulation is also shown in Fig. 9 (blue dash line). This highlights that a serious broadening and a distortion occur. The experimental results suggest that a low distortion amplification can be obtained. More interestingly, the low distortion Brillouin amplification with high-gain paves the way for a range of weak optical detection embedded in strong background noise including laser communication, laser lidar, real-time monitoring of laser welding and intelligent driving.[18–21]

Finally, an experiment is conducted to measure the magnification that a signal can be achieved in the fiber medium. In the experiment, the pump power is fixed at 300 mW and the seed power is set to be in a range of 30 dBm to -70 dBm. Figure 10 shows the signal magnification versus seed power. It can be seen that the maximum magnification (signal gain) is about 65 dB. The maximum magnification of the signal decreases with its power increasing because of the gain saturation. This happens because a higher input signal power more easily depletes the pump power. It is evident that the generation of multi-line spectrum via intensity modulation for broadening the Brillouin gain bandwidth is able to realize high magnification.

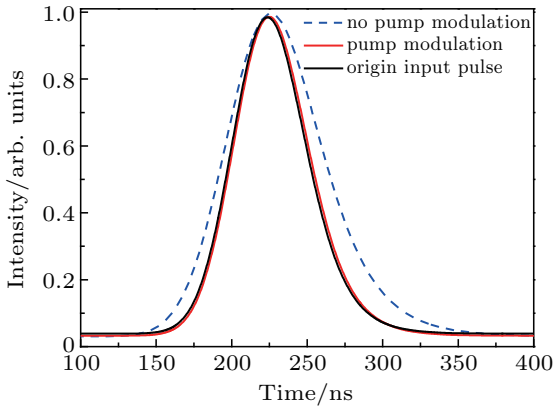


Fig. 9. Comparison between probe input and its amplified output pulses under different pump conditions.

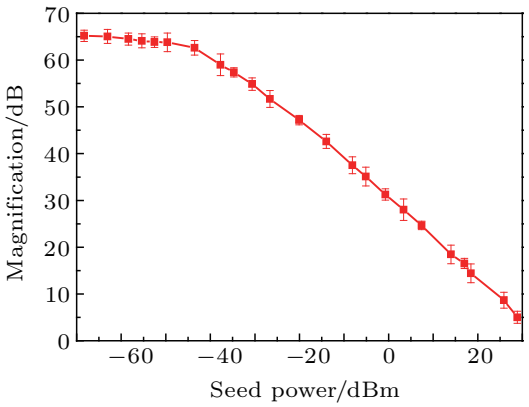


Fig. 10. Plot of signal magnification versus seed power.

4. Conclusions

In this work, we theoretically analyze and experimentally verify the ability to achieve the broadband BGS based on multi-frequency intensity modulation via an IM. The results show that different bandwidths of the gain spectrum can be easily achieved. A BGS with a bandwidth of about 200 MHz is obtained by the proposed effective approach in the experiment. Subsequently, we demonstrate that Brillouin amplification in a single-mode fiber can be used to obtain low distortion amplification with high magnification, and the maximum magnification is around 65 dB. With appropriate optimization, the application scope of low distortion of weak signals with high gain is greatly expanded. Such an imaging enhancement may play an important role in an image sensor where the target is embedded in strong noise. Further work will focus on further

exploring the performances of bandwidth Brillouin amplification, including signal-to-noise, higher magnification, quicker measurement of BGS, and simple structure.

References

[1] Zhu Z H, Gao W, Mu C Y and Li H Y 2016 *Optica* **3** 212
[2] Yuan H, Wang Y L, Lu Z W and Zheng Z X 2015 *Chin. Phys. B* **24** 094210
[3] Liu G B, Yang Y F, Wang J H, Zheng Y, Chen X L, Liu K, Zhao C, Qi Y F, He B and Zhou J 2016 *Chin. Phys. Lett.* **33** 074207
[4] Bai Z X, Yuan H, Liu Z H, Xu P B, Gao Q L, Williams R J, Kitzler O, Mildren R P, Wang Y L and Lu Z W 2018 *Opt. Mater.* **75** 626
[5] Zhou D W, Dong Y K, Wang B Z, Pang C, Ba D X, Zhang H Y, Lu Z W, Li H and Bao X Y 2018 *Light: Sci. & Appl.* **7** 32
[6] Kang Z J, Fan Z W, Huang Y T, Zhang H B, Ge W Q, Li M S, Yan X C and Zhang G X 2018 *Opt. Express* **26** 6560
[7] Wei W, Yi L L, Jaouen Y and Hu W S 2014 *Opt. Express* **22** 23249
[8] Zhu Z H, Chen P, Li H W, Zhao B, Zhou Z Y, Hu W, Gao W, Lu Y Q and Shi B S 2018 *Appl. Phys. Lett.* **112** 161103
[9] Zhu Z H, Sheng L W, Lu Z W, He W M and Gao W 2017 *Sci. Rep.* **7** 40526
[10] Yi L L, Jaouën Y, Hu W S, Su Y K and Bigo S 2007 *Opt. Express* **15** 16972
[11] Shi M Y, Yi L L, Wei W and Hu W S 2018 *Opt. Express* **26** 16113
[12] Zheng D, Pan W, Yan L S, Luo B, Zou X H, Liu X K and Yi A L 2014 *Acta Phys. Sin.* **63** 154214 (in Chinese)
[13] Zadok A, Eyal A and Tur M 2007 *J. Lightwave Technol.* **25** 2168
[14] Li H W, Chang N, Zhang H Y, Wang B, Gao W and Zhu Z H 2017 *Appl. Opt.* **56** 5745
[15] Lu Z W, Dong Y K and Li Q 2007 *Opt. Express* **15** 1871
[16] Dong Y K, Lu Z W, Li Q and Liu Y F 2008 *J. Opt. Soc. Am. B* **25** C109
[17] Ba D X 2013 "Research on Techniques of Optical Delay Based on Slow Light of Stimulated Brillouin Scattering in Optical Fibers", Ph. D. Dissertation (Harbin: Harbin Institute of Technology) (in Chinese)
[18] Sun Y F, Zhang Z J, Zhao L Y, Sun W M and Zhao Y 2018 *Chin. Phys. B* **27** 094213
[19] Xu F and Wang Y Q 2015 *Chin. Phys. B* **24** 104214
[20] Massot-Campos M and Oliver-Codina G 2015 *Sensors* **15** 31525
[21] Li Y and Ruichek Y 2014 *Sensors* **14** 10454