Research Article | Vol. 27, No. 8 | 15 Apr 2019 | OPTICS EXPRESS 10974

Optics EXPRESS

Imaging enhancement based on stimulated Brillouin amplification in optical fiber

LIWEN SHENG,[1] DEXIN BA,[1,3] AND ZHIWEI LU[1,2,4]

[1]*National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150001, China*
[2]*School of Electronics and Information Engineering, Hebei University of Technology, Tianjin 300401, China*
[3]*dexinba@hit.edu.cn*
[4]*lvzw@hit.edu.cn*

Abstract: The detection of weak optical signals embedded in strong background illumination has broad application prospects. We propose an imaging enhancement method based on stimulated Brillouin scattering (SBS) in a single-mode fiber, which is capable of amplifying the weak optical signal while neglecting the broadband background noise because of its narrow gain bandwidth. In experiment, a high gain of 60 dB was achieved. An imaging enhancement experiment was carried out, where a target which cannot be seen because of transmission loss could be clearly captured with the amplification of SBS in the fiber. Because of the employment of continuous pump rather than a pulsed pump, this system has wide application in the monitoring of non-cooperative targets.

1. Introduction

Weak optical signal detection embedded in strong background noise remains a big challenge in optical detection, such as submarine laser communication [1], daytime operating lidar [2,3], real-time monitoring of laser welding [4] and self-propagating high-temperature synthesis [5]. In order to effectively extract the weak optical signal embedded in strong background illumination, most of the researches have focused on the employment of narrow band filter [6–8] and highly gain detector [9–11]. The high gain of the detector is realized via electrical amplification, which requires low temperature to suppress noise. What's more, the passband of optical filter generally lies in the order of 100 pm, which brings considerable background noise. Though a Faraday anomalous dispersion optical filter (FADOF) can be used to realize a narrower bandwidth (~10^{-3} nm), it is hard to tune its passband.

In recent years, researchers put forward a kind of active optical system (AOS) [12–15] for detecting weak signal from the strong lighting noise. The principle of the AOS is based on light amplification of weak signals rather than electrical amplification. Trigub *et al.* [16] proposed an AOS which employed a metal vapor brightness amplifier to visualize targets hidden in a wide-band intensive background illumination in a real-time mode. It amplified the echo beam up to thousand times for a single pass through the active medium and the filter bandwidth is in the order of the atomic linewidth (about 10^{-3} nm). Apparently, this system only operates in specific wavelengths (i.e. 510.6 nm and 578.2 nm).

Stimulated Brillouin scattering (SBS) is a simple and efficient mechanism for weak optical signals amplification. Up to now, it has been demonstrated that the operating wavelength is not limited to a particular wavelength. In this process, two beams, i.e. pump and Stokes, are injected into SBS medium from opposite directions. The Stokes beam can be amplified by the pump only when the frequency difference between the two beams matches with the Brillouin frequency shift (BFS) of the SBS medium. Therefore, the Brillouin amplification is frequency-selective. High-gain amplification via SBS using liquid medium has been studied for many years. A signal gain of ~2×10^9 was experimentally achieved with

#358534 https://doi.org/10.1364/OE.27.010974
Journal © 2019 Received 30 Jan 2019; revised 20 Mar 2019; accepted 20 Mar 2019; published 4 Apr 2019

Optics EXPRESS

an input signal energy of the order of 10^{-11} J [17]. Wei Gao *et al.* [18] proposed the use of a double-stage non-collinear Brillouin amplification system to amplify an 8.6×10^{-14} J pulse by 10^{11}. Image amplification by a factor of 300 was also demonstrated with Brillouin two-beam coupling in CS_2 medium [19]. These experiments all employed pulsed pumps to realize high peak power which enabled high Brillouin gain. However, it is hard to utilize these techniques in practical amplification, especially in the detection of non-cooperative targets which don't provide their real-time locations for the lidar, because it is almost impossible to realize the synchronization between the pulsed signal and pump.

In this paper, a high gain amplifier based on SBS in single mode fiber (SMF) is proposed. A continuous-wave (CW) pump is utilized, so no synchronization is required. Because the length of the fiber can be much longer than that of liquid SBS media, a high gain can be realized using the pump with much lower power. The intrinsic Brillouin linewidth of SMF fiber (~30 MHz) is only one-tenth of that of liquid media, which can filter out much more background noise. In experiment, a maximum signal gain (or called magnification) of 10^6 was obtained with a signal-noise ratio of 9.7 dB. An experimental verification using the SBS amplifier to enhance imaging was also demonstrated, in which a target of interest embedded in strong background illumination was clearly viewed.

2. Principle of operation

SBS is a nonlinear interaction between counter-propagating pump and Stokes waves [20–23]. The light amplification mechanism based on SBS is schematically shown in Fig. 1. In the SBS process, the backscattered Stokes light interferes with the input pump light and generates an acoustic wave through the effect of electrostriction. The electrostrictive grating (moving grating) creates a positive feedback mechanism that rapidly depletes the forward propagating pump light to generate Stokes light. The strong attenuation of sound waves in the nonlinear medium determines the shape of the Brillouin gain spectrum (BGS). Actually, the exponential decay of the acoustic waves results in a BGS of Lorentzian shape:

$$g_{\mathrm{B}}(\nu) = g_0 \frac{(\Delta\nu_{\mathrm{B}}/2)^2}{(\nu-\nu_{\mathrm{B}})^2 + (\Delta\nu_{\mathrm{B}}/2)^2} \tag{1}$$

where ν_{B} represents the BFS, and $\Delta\nu_{\mathrm{B}}$ is the full width at half maximum (FWHM) bandwidth of the Brillouin scattering spectrum, which is relevant to the lifetime of phonons. g_0 is the gain coefficient of the SBS medium. For single-mode fiber, g_0 is 2.5 cm/GW, and $\Delta\nu_{\mathrm{B}}$ is 30 MHz [24].

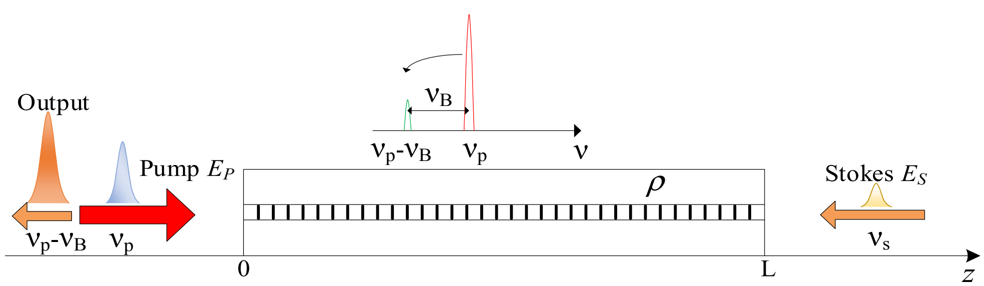

Fig. 1. The principle of the Stokes beam amplification based on SBS in optical fiber.

3. Experiment setup

A schematic diagram of the set-up is presented in Fig. 2. An ultra-narrow linewidth (~10 kHz) distributed feedback (DFB) optical fiber laser was used as the light source, which operated at the wavelength of 1550 nm and the output power of 94.2 mW. Then, a 90/10 coupler was used to split the output of DFB fiber laser into two branches. The light in the upper arm was

Optics EXPRESS

modulated into 40-ns Gaussian pulses by an electro-optic modulator (EOM2), which was driven by an arbitrary waveform generator (AWG). The 40-ns pulse width determined the spatial resolution of 4 m. The modulated pulse was amplified by an erbium-doped fiber amplifier (EDFA2) and then was collimated by an FC/APC-810 air-spaced doublet collimator (Lens2). The collimated beam was transmitted to the target. Another collimator was used as echo signal receiver. The spectrum of the lower arm was modulated into double sidebands by an intensity modulator (EOM1) which worked at the carrier suppression mode. The output of EOM1 was filtered by a fiber Bragg grating (FBG) to retain the upper sideband which was used as the pump light. The pump was amplified by an erbium doped fiber amplifier (EDFA1) to 324.7 mW. Subsequently, the amplified pump wave was injected into a 1-km-long single-mode fiber (Corning SMF-28e), where the echo signal was amplified. The amplified Stokes light was captured by a photodetector (PD) and sampled by an oscilloscope.

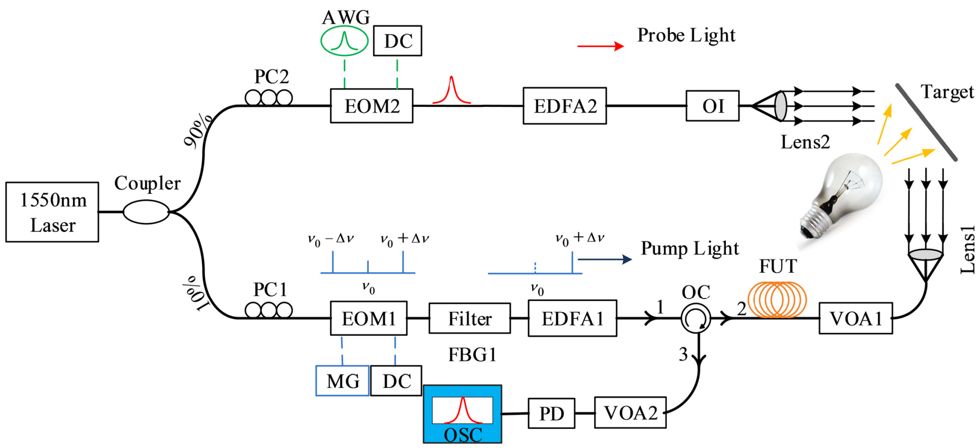

Fig. 2. Experimental setup of the laser imaging system based on SBS. PC: polarization controller; EOM: electro-optic modulator; FBG: fiber Bragg grating; EDFA: erbium doped fiber amplifier; FUT: fiber under test; AWG: arbitrary waveform generator; PD: photodetector; OSC: oscilloscope; VOA: variable optical attenuator; MG: microwave signal generator; OI: isolator.

4. Results and discussions

4.1 High gain narrowband amplification of echo signal

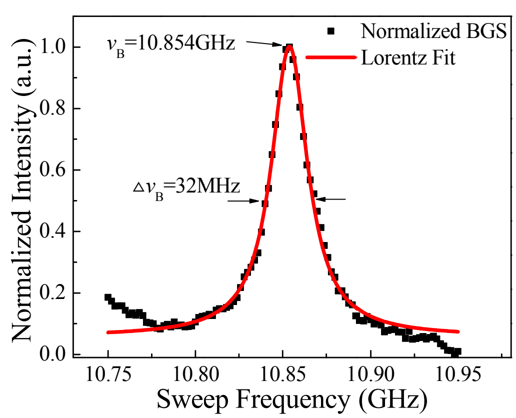

Fig. 3. Brillouin gain spectrum of the SMF-28.

Firstly, the BGS was measured by scanning the frequency difference between the pump and Stokes. The probe input power was set as 8 μW, and the pump power was set as 60 mW. The scanning range covers from 10.75 GHz to 10.95 GHz with the step of 5 MHz. Figure 3 highlights the measured BGS of the 1000-m standard SMF. The measured $\Delta\nu_B$ is 32 MHz and the BFS ν_B is 10.854 GHz in fiber medium at a wavelength of 1.55 μm. Therefore, the frequency difference between the pump and the probe was set to be 10.854 GHz in the following experiment to obtain high-gain.

Subsequently, an experiment was carried out to determine the maximum gain that an echo signal can achieve in the FUT. A tungsten filament lamp was employed to introduce wide-band background noise. The influence of pump power on the amplification is shown in Fig. 4. The red dots represent the data measured when the lamp was turned off, while the blue dots correspond the data obtained when the lamp was turned on. The maximum magnification can reach 5×10^6. But the signal magnification in the presence of stray lighting decreases slightly, which comes from pump power depleted by the wide-band intensive background lighting. At the maximum echo signal gain, the pump power is 324.7 mW. The gain factor *gIL* in this experiment is larger than 20. However, the generation process of SBS was not observed, because of the competition between the generation process and the amplification of the leaked CW-Stokes of EOM2.

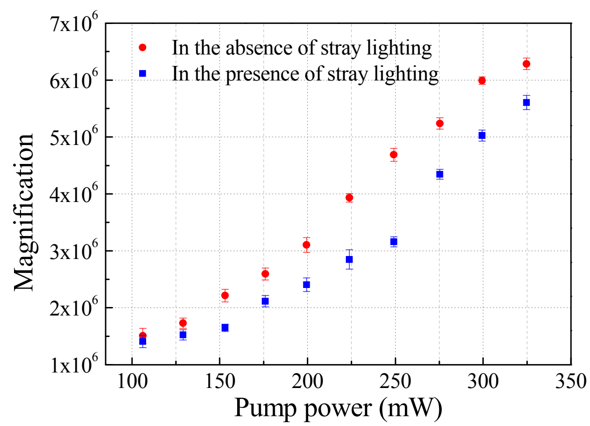

Fig. 4. In the absence/presence of stray lighting of the magnification as a function of the pump power.

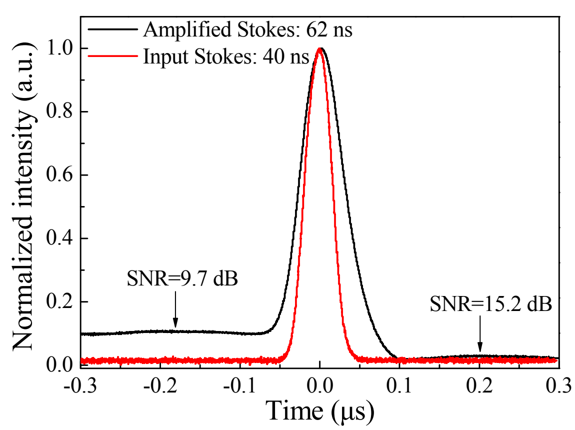

Fig. 5. The normalized of input and amplified Stokes pulses.

The profiles of the input Stokes signal and the amplified echo by the Brillouin fiber amplifier (BFA) with background illumination are shown in Fig. 5. The amplified leakage of EOM2 results in a CW trace in front of the signal, thus it degrades the system's signal noise ratio (SNR). The minimum SNR of the amplified signal is ~9.7 dB. The power behind the signal was lower because the pump was depleted by the signal pulse, so the SNR is higher and reaches 15.2 dB. The width of the amplified Stokes signal changes from 40-ns to 62-ns. At the early stage of the amplification, the pulse was broadened to 83-ns. Then it was compressed when increasing the pump power. The pulse broadening is the result of the limitation of the gain bandwidth of SBS [25,26], while the compression derives from the asymmetry of amplification at the front and tail parts of the Stokes pulse [27–29]. For high-gain Brillouin amplification case, the noise mainly derives from the unwanted coupling between photons and spontaneous non-coherent phonons, which limits the amplifier's performances. The signal-noise ratio can be increased through orbital angular momentum mode division filtering [30]. In addition, the use of EOM2 with higher extinction ratio or polarization-maintaining fiber can also improve the SNR of the proposed method.

4.2 Imaging use the SBS amplifier

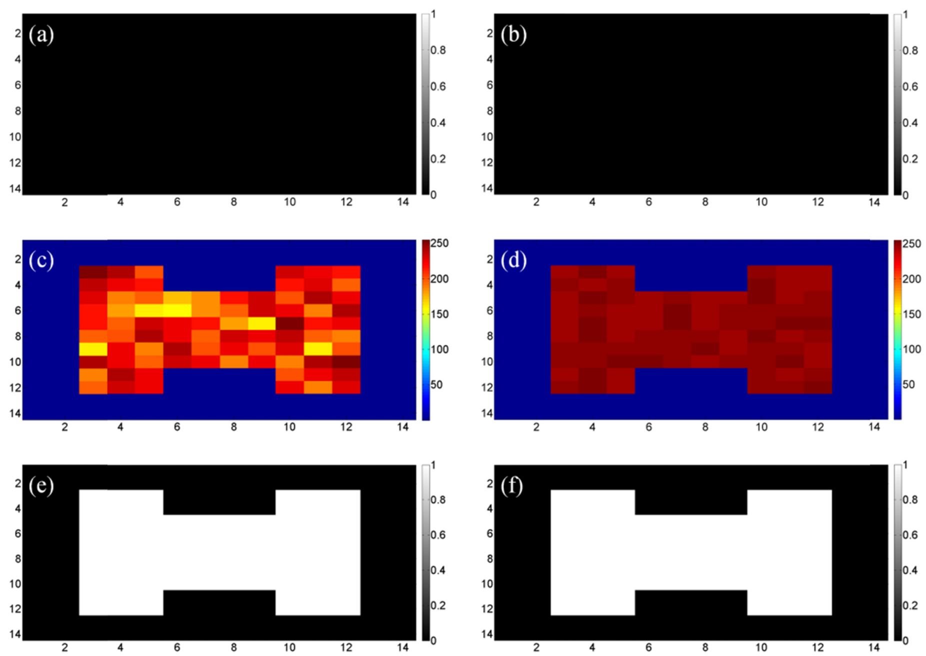

Fig. 6. Test-object experiment. (a) Image of the object without SBS amplifier under the condition of stray lighting. (b) Image of the object without SBS amplifier under the condition of no stray lighting. (c) Image of the object with the SBS amplifier under the condition of stray lighting. (d) Image of the object with the SBS amplifier under the condition of no stray lighting. (e) the binary image processing of Panel (c). (f) the binary image processing of Panel (d).

Finally, an experiment of SBS enhanced imaging was carried out. In this experiment, a letter H was used as target. This target was placed in a moving stage (Thorlabs LTS150), which enabled a two-dimensional position scanning for imaging. In the experiment, the data of one pixel was achieved by a single pulse. The repetition rate of the probe pulses was 1000 Hz. So the pixel-dwell time was 1 ms. The experimental results are shown in Fig. 6. The same lamp above was used to simulate the intensive solar background lighting noise. In the beginning, VOA1 was adjusted to load additional loss on the received optical signal. The loss was

Optics EXPRESS

increased until nothing could be seen from CCD when there was no pump. The images corresponding to lamp off and on are shown in Figs. 6(a) and 6(b), respectively. Next, the pump was injected into the FUT and the images were recorded again, as shown in Figs. 6(c) and 6(d). We denoised the gray-scale images after binary processing so as to filter the noise regions. In order to obtain clear image, the collected original data were firstly normalized. All the original data were transformed based on 256 gray levels. Then, the normalized data were binarized. In the threshold binarization processing, a threshold of 150 gray level was employed. The value above the threshold was set to 1, and the value below the threshold was set to 0. Besides, various image processing methods can also be used to enhance imaging together with the proposed Brillouin amplification. The final results were depicted in Figs. 6(e) and 6(f), respectively. The letter H can be clearly viewed because of SBS amplification even when the lamp was on. Furthermore, we checked the image when the pump was on but the probe was off to guarantee that the validity of the image enhancement. All these results prove that the SBS amplification system can be effectively applied to image enhancement.

5. Conclusions

In this work, a weak optical signal detecting approach for imaging enhancement using Brillouin fiber amplifier (BFA) in a single mode optical fiber was proposed. A signal amplification of 10^6 was obtained in the presence of background noise. The minimum signal-noise ratio (SNR) is larger than 9.7 dB, which satisfies the minimum requirement on SNR to obtain clear images (2.5 dB). The presented results in this paper show that the laser imaging enhancement method based on the BFA can be used to visualize objects hidden by intensive stray lighting. It should be noted that the Stokes pulse width we used in experiment was 40-ns, which made the spatial resolution far from the traditional pulse lidar. Therefore, the capacity of imaging enhancement for short pulses based on BFA should be studied in the future. Various researches on the Brillouin bandwidth broadening can be employed in this imaging enhancement system [31–33].

Funding

National Natural Science Foundation of China (NSFC) (61605034).

Disclosures

The authors declare that there are no conflicts of interest related to this article.

References

1. J. Xu, M. Kong, A. Lin, Y. Song, J. Han, Z. Xu, B. Wu, S. Gao, and N. Deng, "Directly modulated green-light diode-pumped solid-state laser for underwater wireless optical communication," Opt. Lett. **42**(9), 1664–1667 (2017).
2. L. Mei and M. Brydegaard, "Atmospheric aerosol monitoring by an elastic Scheimpflug lidar system," Opt. Express **23**(24), A1613–A1628 (2015).
3. W. Gao, Z. W. Lu, Y. K. Dong, and W. M. He, "A new approach to measure the ocean temperature using Brillouin lidar," Chin. Opt. Lett. **4**(7), 428–431 (2006).
4. A. Ancona, V. Spagnolo, P. M. Lugarà, and M. Ferrara, "Optical sensor for real-time monitoring of CO2 laser welding process," Appl. Opt. **40**(33), 6019–6025 (2001).
5. A. G. Merzhanov, "SHS technology," Adv. Mater. **4**(4), 294–295 (1992).
6. X. Xue, C. Janisch, Y. Chen, Z. Liu, and J. Chen, "Low-frequency shift Raman spectroscopy using atomic filters," Opt. Lett. **41**(22), 5397–5400 (2016).
7. X. B. Xue, D. Pan, X. G. Zhang, B. Luo, J. B. Chen, and H. Guo, "Faraday anomalous dispersion optical filter at 133Cs weak 459 nm transition," Photon. Res. **3**(5), 275–278 (2015).
8. B. Luo, L. Yin, J. Xiong, J. Chen, and H. Guo, "Signal intensity influences on the atomic Faraday filter," Opt. Lett. **43**(11), 2458–2461 (2018).
9. M. DaneshPanah, B. Javidi, and E. A. Watson, "Three dimensional object recognition with photon counting imagery in the presence of noise," Opt. Express **18**(25), 26450–26460 (2010).
10. G. Yang, R. Billmers, P. R. Herczfeld, and V. M. Contarino, "Temporal characteristics of narrow-band optical filters and their application in lidar systems," Opt. Lett. **22**(6), 414–416 (1997).

Optics EXPRESS

11. A. McCarthy, R. J. Collins, N. J. Krichel, V. Fernández, A. M. Wallace, and G. S. Buller, "Long-range time-of-flight scanning sensor based on high-speed time-correlated single-photon counting," Appl. Opt. **48**(32), 6241–6251 (2009).
12. K. I. Zemskov, A. A. Isaev, M. A. Kazaryan, S. V. Markova, and G. G. Petrash, "Active optical systems with brightness amplification by pulsed metal vapor lasers," Opt. Commun. **18**(1), 144 (1976).
13. R. L. Espinola, E. L. Jacobs, C. E. Halford, R. Vollmerhausen, and D. H. Tofsted, "Modeling the target acquisition performance of active imaging systems," Opt. Express **15**(7), 3816–3832 (2007).
14. Y. Liu, J. Shi, and G. Zeng, "Single-photon-counting polarization ghost imaging," Appl. Opt. **55**(36), 10347–10351 (2016).
15. Z. Chen, H. Gao, and G. Barbastathis, "Background suppression in long-distance imaging using volume hologram filters," Opt. Express **22**(25), 31123–31130 (2014).
16. M. V. Trigub, G. S. Evtushenko, S. N. Torgaev, D. V. Shiyanov, and T. G. Evtushenko, "Copper bromide vapor brightness amplifiers with 100 kHz pulse repetition frequency," Opt. Commun. **376**, 81–85 (2016).
17. I. M. Bel'dyugin, V. F. Efimkov, S. I. Mikhailov, and I. G. Zubarev, "Amplification of weak Stokes signals in the transient regime of stimulated Brillouin scattering," J. Russ. Laser Res. **26**(1), 1–12 (2005).
18. Z. Lu, W. Gao, W. He, Z. Zhang, and W. Hasi, "High amplification and low noise achieved by a double-stage non-collinear Brillouin amplifier," Opt. Express **17**(13), 10675–10680 (2009).
19. S. Sternklar, S. Jackel, D. Chomsky, and A. Zigler, "Coherent beam and image amplification by Brillouin two-beam coupling in CSS2," Opt. Lett. **15**(11), 616–618 (1990).
20. M. V. Chekhova and Z. Y. Ou, "Nonlinear interferometers in quantum optics," Adv. Opt. Photonics **8**(1), 104–154 (2016).
21. R. W. Boyd, *Nonlinear optics,* 3rd ed. (Academic, 2008), Chap. 9.
22. E. L. Buckland and R. W. Boyd, "Measurement of the frequency response of the electrostrictive nonlinearity in optical fibers," Opt. Lett. **22**(10), 676–678 (1997).
23. J. H. Lee, Z. Yusoff, W. Belardi, M. Ibsen, T. M. Monro, and D. J. Richardson, "Investigation of Brillouin effects in small-core holey optical fiber: lasing and scattering," Opt. Lett. **27**(11), 927–929 (2002).
24. M. Niklès, L. Thévenaz, and P. A. Robert, "Brillouin gain spectrum characterization in single-mode optical fibers," J. Lightwave Technol. **15**(10), 1842–1851 (1997).
25. Y. K. Dong, Z. W. Lu, Q. Li, and W. Gao, "Controllable optical delay line using a Brillouin optical fiber ring laser," Chin. Opt. Lett. **4**(11), 628–630 (2006).
26. Z. Lu, Y. Dong, and Q. Li, "Slow light in multi-line Brillouin gain spectrum," Opt. Express **15**(4), 1871–1877 (2007).
27. C. B. Dane, W. A. Neuman, and L. A. Hackel, "High-energy SBS pulse compression," IEEE J. Quantum Electron. **30**(8), 1907–1915 (1994).
28. Z. Liu, Y. Wang, Z. Bai, Y. Wang, D. Jin, H. Wang, H. Yuan, D. Lin, and Z. Lu, "Pulse compression to one-tenth of phonon lifetime using quasi-steady-state stimulated Brillouin scattering," Opt. Express **26**(18), 23051–23060 (2018).
29. Z. Liu, Y. Wang, Y. Wang, S. Li, Z. Bai, D. Lin, W. He, and Z. Lu, "Pulse-shape dependence of stimulated Brillouin scattering pulse compression to sub-phonon lifetime," Opt. Express **26**(5), 5701–5710 (2018).
30. Z. H. Zhu, L. W. Sheng, Z. W. Lv, W. M. He, and W. Gao, "Orbital angular momentum mode division filtering for photon-phonon coupling," Sci. Rep. **7**(1), 40526 (2017).
31. H. Li, N. Chang, H. Zhang, B. Wang, W. Gao, and Z. Zhu, "Frequency domain staring pump-probe technique for Brillouin gain/loss spectrum measurement," Appl. Opt. **56**(20), 5745–5750 (2017).
32. L. W. Sheng, D. X. Ba, and Z. W. Lv, "High-gain and low-distortion Brillouin amplification based on pump multi-frequency intensity modulation," Chin. Phys. B **28**(2), 024212 (2019).
33. M. Shi, L. Yi, W. Wei, and W. Hu, "Generation and phase noise analysis of a wide optoelectronic oscillator with ultra-high resolution based on stimulated Brillouin scattering," Opt. Express **26**(13), 16113–16124 (2018).