Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

K-band optoelectronic oscillator based on a double-Brillouin-frequency shifter

Peng Liu
Shifeng Liu
Huashan Yang
Xiaochen Kang
Shilong Pan

SPIE.

Peng Liu, Shifeng Liu, Huashan Yang, Xiaochen Kang, Shilong Pan, "K-band optoelectronic oscillator based on a double-Brillouin-frequency shifter," *Opt. Eng.* **58**(10), 100501 (2019), doi: 10.1117/1.OE.58.10.100501.

K-band optoelectronic oscillator based on a double-Brillouin-frequency shifter

Peng Liu, Shifeng Liu, Huashan Yang, Xiaochen Kang, and Shilong Pan*
Ministry of Education, Nanjing University of Aeronautics and Astronautics, Key Laboratory of Radar Imaging and Microwave Photonics, Nanjing, China

Abstract. An optoelectronic oscillator (OEO) based on a double-Brillouin-frequency shifter (DBFS) is proposed and experimentally demonstrated. Two orders of stimulated Brillouin scattering are realized in the DBFS, and the narrow gain bandwidth of the second-order Stokes wave is utilized to implement the phase modulation to intensity modulation conversion. Only one laser is used to provide both signal and pump waves. A k-band microwave signal with a harmonic suppression ratio of 61 dB and a side-mode suppression ratio of 45 dB is experimentally generated, and 400-MHz tunability is realized by adjusting the laser wavelength. Because of the simple structure and high-frequency oscillation, the DBFS-based OEO can find applications for wireless communications and civil radar systems. [DOI: 10.1117/1.OE.58.10.100501]

Keywords: microwave photonics; optoelectronic oscillator; double-Brillouin-frequency shifter.

Paper 190728L received May 27, 2019; accepted for publication Sep. 24, 2019; published online Oct. 17, 2019.

1 Introduction

Optoelectronic oscillators (OEOs) can provide high-quality local oscillations for multifunction radars, electronic warfare systems, high-speed wireless communications, and modern instrumentation.[1–3] Yao and Maleki[4] invented the first OEO structure, which is constructed of an optoelectronic feedback loop including a laser, an electro-optic intensity modulator, a long-distance optical fiber, a photodetector (PD), an electrical amplifier (EA), and an electrical bandpass filter.[5,6] The electrical bandpass filter with a high quality-factor is one key device for the OEO to select the fewest oscillation modes at high frequency, but this kind of electrical filter is always very hard to fabricate, and the center frequency is difficult to tune. Although a yttrium-iron-garnet filter can be used in an OEO to generate tunable microwave signals,[7] it is usually unstable because of the jitter of its drive current.[8] Due to the wideband tunability of microwave photonic filters (MPFs),[9] the electrical bandpass filter in the OEO loop can be substituted. One of the effective ways to construct the MPF is using an electro-optic phase modulator (PM) followed by an optical filter,[10] a dispersive element,[11] or an optical component with stimulated Brillouin scattering (SBS),[12–15] so that phase modulation to intensity modulation conversion is realized. MPFs based on SBS have stimulated continuous research interests because of its narrow gain bandwidth and simple structure. SBS is a prominent nonlinear effect in optical fibers and can be stimulated when the pump power surpasses the SBS threshold.[16] The Stokes wave is then generated in the opposite direction with the pump wave, and the frequency difference between the pump wave and the Stokes wave is called the Brillouin frequency shift (BFS). The BFS of common optical fibers is about 10 GHz, which limits its application for OEOs to generate high-frequency microwave signals. One way to generate high-frequency microwave signals in an SBS-based OEO is using two lasers to provide signal and pump waves, respectively.[17] The oscillation frequency (OF) of the OEO is determined by the signal wave frequency, pump wave frequency, and the BFS of the optical fiber. However, two lasers in an OEO will increase the system cost, and rigorous wavelength stability of the lasers is required. Therefore, it is essential to develop the SBS-based OEO, which can generate high-frequency microwave signals directly using only one laser.

Recently, a kind of structure called the double-Brillouin-frequency shifter (DBFS) was proposed, which attracts great research interests because it can realize about 20-GHz frequency shift using only one laser.[18–23] The DBFS has been used to construct multiwavelength fiber ring lasers,[18–20] to generate stable optical comb,[21] and to realize frequency upconversion.[22] K-band microwave signals can be generated based on the DBFS by the heterodyning of the SBS pump and its second-order sideband.[23] However, the phase-noise performance and the frequency stability of the microwave signals are not good enough to meet the requirement of practical applications. In this paper, we will use the DBFS in an OEO loop to generate k-band microwave signals using only one laser. The optoelectronic feedback loop of the OEO structure can significantly improve the signal quality and the frequency stability. OF which is equal to the doubled Brillouin frequency with high harmonic suppression ratio (HSR), high side-mode suppression ratio (SMSR), high frequency stability, and usable phase-noise performance will be obtained. This paper is organized as follows. In Sec. 2, the principle of the OEO based on DBFS is described in detail. In Sec. 3, an experiment is implemented, and the results are reported. A conclusion is drawn in Sec. 4.

2 Principle

The schematic of the DBFS-based OEO is shown in Fig. 1. A continuous-wave light emitted from a tunable laser source (TLS) passes through a polarization controller (PC1) and then launches into an electro-optic PM, in which the lightwave is phase modulated by a feedback electrical signal. The TLS provides both signal light and SBS pump so that only one laser is needed here. The phase-modulated wave is amplified by an erbium-doped fiber amplifier (EDFA), which can control the pump power into the DBFS. The sideband, which is the doubled Brillouin frequency less than the TLS frequency, is amplified by the DBFS[18,21,22] so that the phase modulation is converted to intensity modulation. The optical mechanism in the DBFS will be described later

*Address all correspondence to Shilong Pan, E-mail: pans@nuaa.edu.cn

0091-3286/2019/$28.00 © 2019 SPIE

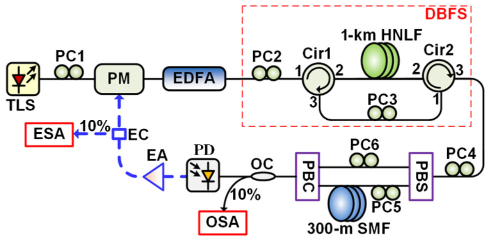

Fig. 1 Schematic of the proposed OEO based on the DBFS. TLS, tunable laser source; PC, polarization controller; PM, phase modulator; EDFA, erbium-doped fiber amplifier; Cir, circulator; HNLF, highly nonlinear fiber; SMF, single-mode fiber; PBS, polarization beam splitter; PBC, polarization beam combiner; OC, optical coupler; PD, photodetector; EA, electrical amplifier; EC, electrical coupler; OSA, optical spectrum analyzer; ESA, electrical spectrum analyzer. The black solid curve represents the optical path, and the blue dashed line corresponds to the electrical path.

in the next paragraph. After the DBFS, the signal light passes through a polarization-multiplexed structure, which can significantly suppress the side-mode oscillation.[24,25] The polarization-multiplexed structure includes three polarization controllers (PC4, PC5, and PC6), a polarization beam splitter (PBS), a polarization beam combiner (PBC), and a 300-m single-mode fiber (SMF). The signal light out of the DBFS passes through PC4 and then is divided into two orthogonal paths with different fiber lengths by the PBS. The short path is constructed by connecting the fiber pigtails of the PBS and PBC directly, and the long path is formed by inserting a 300-m SMF between the other two pigtails of the PBS and PBC. The PBC combines the two orthogonal paths together. The power distribution between the long path and the short path can be changed by adjusting the polarization direction of the signal light using PC4. PC5 and PC6 are used in the long path and the short path to adjust the polarization directions of the light wave along the two principal axes of the PBS, respectively. Because of the well-known Vernier effect, only the modes that satisfy the oscillation condition of both the long loop and the short loop can oscillate up in the OEO. Therefore, side-mode oscillations can be significantly suppressed by the polarization-multiplexed structure. After the polarization-multiplexed structure, the signal is sent to a PD to generate a microwave signal. After amplified by an EA, the microwave signal is fed back into the radio-frequency (RF) port of the PM. The working frequency range of the EA must cover the doubled Brillouin frequency of the highly nonlinear fiber (HNLF) to ensure the oscillation of desired frequency. No electrical bandpass filter is needed here, which ensures the frequency flexibility of the OEO. If the gain of the optoelectronic feedback loop is greater than unity, the OEO begins to oscillate, and a high-quality microwave signal will be generated. About 10% of the optical power is divided from an optical coupler (OC) to monitor the optical spectrum by an optical spectrum analyzer (OSA) and 10% of the electrical power is taken out from an electrical coupler (EC) to observe the electrical spectrum and measure the phase noise by an electrical spectrum analyzer (ESA).

The DBFS contains two circulators (Cir1 and Cir2), a 1-km HNLF, and two polarization controllers (PC2 and PC3). The SBS effect can be stimulated twice in the DBFS cavity, and the mechanism is described as follows: the amplified light by the EDFA enters port 1 of Cir1 via PC2 and is then injected into the 1-km HNLF from port 2 of Cir1. When the pump power surpasses the SBS threshold, the first-order SBS will be stimulated, and the first-order Stokes wave is then generated in the opposite direction with the pump wave. The first-order Stokes wave will circulate counter-clockwise in the DBFS cavity, and the transmission route is port 2 of Cir1 to port 3 of Cir1, PC3, port 1 of Cir2, and then port 2 of Cir2, finally back into port 2 of Cir1 via the 1-km HNLF. When the power of the first-order Stokes wave surpasses the SBS threshold, the SBS effect will be stimulated again. The second-order Stokes wave will be generated, which goes into port 2 of Cir2, and transmits out of the DBFS from port 3 of Cir2. PC2 and PC3 are used to adjust the polarization state of the first SBS pump and the second SBS pump to ensure high SBS efficiency, respectively. The DBFS realizes the phase modulation to intensity modulation conversion, and the sidebands are amplified by the second-order Stokes wave in the DBFS. Therefore, the microwave signal with its frequency equal to the doubled Brillouin frequency will be generated. Generally, the BFS of a fiber is expressed as[16]

$$f_{\mathrm{BFS}} = 2nv_{\mathrm{A}}/\lambda_{\mathrm{s}}, \tag{1}$$

where n is the effective refraction index of the fiber, v_{A} is the velocity of the acoustic wave, and λ_{s} is the pump wavelength. Therefore, the oscillation frequency (OF) of the proposed OEO can be approximately given by

$$f_{\mathrm{OF}} = 4nv_{\mathrm{A}}/\lambda_{\mathrm{TLS}}, \tag{2}$$

where λ_{TLS} is the TLS wavelength.

3 Experiment and Results

An experiment based on the configuration of Fig. 1 is implemented. The wavelength tuning range of the TLS (SANTUR TL-2020-C) is 1528.77 to 1563.86 nm with a linewidth of 3 MHz. The PM (EOSPACE PM-DV5-40-PFA-PFA-LV) has a 3-dB bandwidth of 40 GHz. The PD (Finisar) has a 3-dB bandwidth of 50 GHz and a responsibility of 0.69 A/W. The EDFA (Amonics AEDFA-PA-35-B-FA) has a small signal gain of 30 dB. The EA is a low-noise one, which has an operational frequency range of 14 to 21 GHz and a gain of 40 dB. The OC has a power splitting ratio of 9:1, and the 10% port is connected to an OSA (AQ6370C, 0.02-nm resolution) to monitor the optical spectrum. The EC has a power splitting ratio of 9:1, with the 10% port connected to an ESA (Rohde & Schwarz FSWP, 1 MHz to 50 GHz) to measure the electrical spectrum and the phase-noise performance.

The optical spectrum of the OEO loop is investigated first. To observe the optical mechanism of the DBFS, we opened the OEO first by disconnecting the RF port of the PM. The TLS wavelength is set to be 1550.12 nm. The SBS threshold of the HNLF is measured to be 6.9 dBm. Slowly increase the pump power by adjusting the EDFA, two orders of Stokes waves can be observed when the pump power is increased to 11 dBm, shown as the blue dotted line of Fig. 2. Three peaks can be seen in the blue dotted line; from left to right they represent the pump wave, the first-order Stokes wave, and the second-order Stokes wave, respectively. The BFS is measured to be about 9.4 GHz at a pump wavelength of 1550.12 nm, which is indicated as a red font in Fig. 2. It should be noted that the first-order Stokes wave was

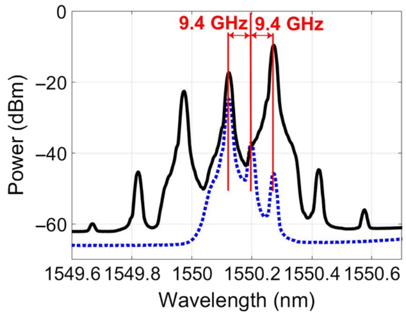

Fig. 2 The optical spectra of the proposed OEO. Blue dotted line: the opened OEO when the RF port of the PM is disconnected. Black solid line: the closed OEO loop.

supposed to circulate in the SBS cavity, but it will leak out of the DBFS cavity because of Rayleigh backscattering and reflection from the fiber end face.[26] We then connect the RF port of the PM with the EC to close the OEO loop. The electrical signal which is equal to the doubled Brillouin frequency is amplified by the EA and then feeds back into the RF port of the PM. The sidebands of the phase modulation are then amplified by the second-order Stokes wave in the DBFS, so phase modulation is converted into intensity modulation. Therefore, stable oscillation forms in the OEO loop and the OF are equal to the doubled Brillouin frequency. Seven peaks can be seen in the optical spectrum, shown as the black solid line of Fig. 2. The frequency difference between the adjacent optical peaks is about 18.8 GHz, which is the doubled Brillouin frequency of the 1-km HNLF.

Electrical spectra and the phase-noise performance of the proposed OEO are then measured by an ESA, as shown in Fig. 3. The TLS wavelength is still 1550.12 nm, the same as those in Fig. 2. Figure 3(a) shows the electrical spectrum with a span of 50 GHz and a resolution bandwidth (RBW) of 30 kHz. It can be seen that the electrical oscillation frequency of the OEO is about 18.85 GHz, shown as the highest peak in the spectrum. The oscillation frequency of 18.85 GHz is equal to the doubled Brillouin frequency, and it agrees well

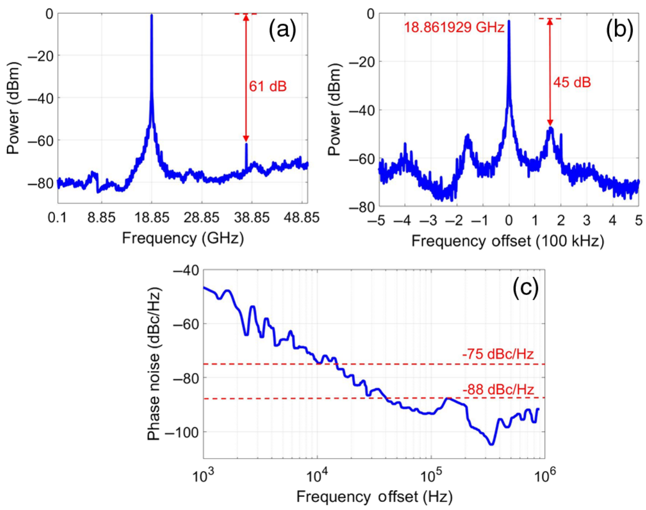

Fig. 3 Electrical spectra and phase noise of the proposed OEO. (a) Electrical spectrum with a span of 50 GHz and an RBW of 30 kHz. (b) Electrical spectrum with a span of 1 MHz and an RBW of 100 Hz. (c) Single sideband phase noise with a frequency offset ranged from 1 kHz to 1 MHz.

with the prediction from the optical spectrum of Fig. 2. Another peak can be observed at about 37.7 GHz, which is the harmonic of the OEO. The HSR is 61 dB, shown in Fig. 3(a). To study the OF in detail, the electrical spectrum with a span of 1 MHz and an RBW of 100 Hz is measured, as shown in Fig. 3(b). The precise oscillation frequency of the OEO is 18.861929 GHz, and the SMSR is 45 dB. We observed the electrical spectrum for half an hour, and there was no evident frequency jitter of the oscillation modes, which verifies the frequency stability of the OEO structure. It should be noted that although the SMSR is poor as compared with the OEO that uses an intensity modulator and a microwave filter,[24] it is almost the same as the OEO that uses the first-order SBS.[17,25] To further increase the SMSR, one may carefully select the fiber lengths in the polarization-multiplex structure. Figure 3(c) exhibits the single sideband phase noise of the proposed OEO with the frequency offset from 1 kHz to 1 MHz. The phase noise at 10-kHz frequency offset is -75 dBc/Hz, and the maximum phase noise of the side mode is -88 dBc/Hz. The noise floor of the phase noise analyzer is -122 dBc/Hz at 10-kHz frequency offset, which is far below the phase noise of the generated microwave signal. This can ensure the accuracy of the measured phase-noise value. The phase noise is a bit higher than the OEOs based on the SBS reported in other papers,[17,25] which is about -90 dBc/Hz at 10-kHz offset for 10-GHz OF. We attribute this high phase noise to the following factors: (1) the OF is 18.86 GHz here, which is nearly two times of 10 GHz, leading to ~6 dB-phase-noise degradation; (2) two orders of SBS are stimulated in the proposed OEO, which enlarge the gain bandwidth of the SBS effect and introduce much more noise; (3) our OEO loop is much shorter, which has a reduced energy storage capability. It should be noted that, because the DBFS has a cavity structure, it is sensitive to the environment vibration and temperature variation. Therefore, if the HNLF is placed in a temperature-stabilized condition and isolated from vibration and acoustic influence, the phase-noise performance of the OEO may be improved. Other methods, such as using long OEO loops or incorporating a frequency discriminator,[8] can also reduce the phase noise of the generated microwave signal. Nevertheless, the microwave signal generated by the OEO based on DBFS can be applied in short-distance wireless communications, civil radars, and other areas in which medium phase-noise performance is acceptable.

The frequency tunability of the proposed OEO is studied by changing the TLS wavelength. Figure 4(a) illustrates the electrical spectra of oscillation frequencies when the TLS wavelength decreases from 1561.02 to 1529.56 nm. The spectral span is 1 GHz, and the RBW is 30 kHz. From left to right, the spectral peaks locate at 18.72, 18.77, 18.82, 18.87, 18.92, 18.97, 19.02, 19.07, and 19.12 GHz, corresponding to the TLS wavelength of 1561.02, 1557.37, 1553.34, 1549.33, 1545.33, 1541.36, 1537.41, 1533.47, and 1529.56 nm, respectively. The phase-noise performances of these microwave signals were also measured in our experiment, and they do not show distinct changes. The phase-noise differences at 10-kHz offset are <1 dBc/Hz. Figure 4(b) gives the curve of the OF with the function of TLS wavelength, and a linear variation relationship can be seen. This result is in good agreement with the theoretical prediction by Eq. (2). The OF increases from 18.72 to 19.12 GHz when the TLS

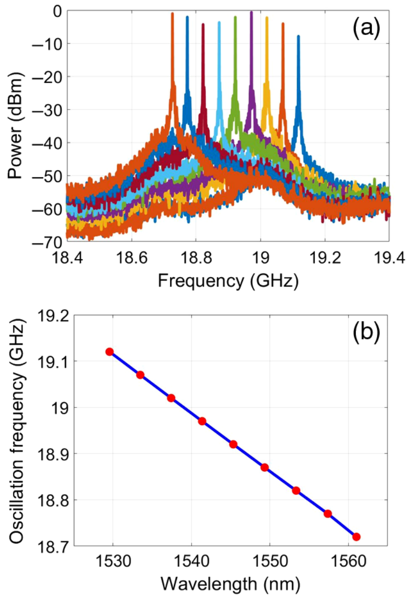

Fig. 4 Frequency tunability of the proposed OEO. (a) Electrical spectra with a span of 1 GHz and an RBW of 30 kHz when the TLS wavelength decreases from 1561.02 to 1529.56 nm. (b) Relationship between the OF and the TLS wavelength.

wavelength decreases from 1561.02 to 1529.56 nm, so the tuning efficiency of the TLS wavelength is −12.7 MHz/nm. The tuning efficiency is twice as high as the OEOs based on the first-order SBS.[27] The linear relationship between the OF and the laser wavelength is very useful for precise tuning of the OEOs and also can be applied to frequency synthesizers to obtain desired local oscillation easily. It should be noted that the oscillation frequency of the proposed OEO is fixed at the double of the BFS of the HNLF, so the frequency tunability is restricted in a relatively narrow band according to Eq. (2). Other frequencies out of the tuning range can be obtained using a frequency synthesizer driven by the proposed OEO.

4 Conclusion

We proposed and experimentally demonstrated an OEO based on the DBFS. The second-order Stokes wave in the DBFS realized the phase modulation to intensity modulation conversion, so only one laser is used in the OEO. An 18.86-GHz microwave signal with an HSR of 61 dB, an SMSR of 45 dB, and a phase noise of −75 dBc/Hz at 10-kHz offset is experimentally generated. The 400-MHz tunability of the OEO is realized by adjusting the laser wavelength, and linear relationship between the OF and the laser wavelength is experimentally verified. Higher than 20-GHz microwave signal can be generated if long-distance SMF is used instead of the HNLF. Because of its simple structure, the proposed OEO can be easily integrated on a chip to provide k-band local oscillations for short-distance wireless communications and civil radar systems.

References

1. S. Pan et al., "Optoelectronic oscillator based on polarization modulation," *Fiber Integr. Opt.* **34**(4), 185–203 (2015).
2. S. Liu et al., "Wideband microwave frequency division based on an optoelectronic oscillator," *IEEE Photonics Technol. Lett.* **31**(5), 389–392 (2019).
3. X. Ye et al., "Photonics-based radar with balanced I/Q de-chirping for interference-suppressed high-resolution detection and imaging," *Photonics Res.* **7**(3), 265–272 (2019).
4. X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," *J. Opt. Soc. Am. B* **13**(8), 1725–1735 (1996).
5. S. Pan and J. Yao, "A frequency-doubling optoelectronic oscillator using a polarization modulator," *IEEE Photonics Technol. Lett.* **21**(13), 929–931 (2009).
6. T. Du, D. Zu, and S. Pan, "Polarization-maintained coupled optoelectronic oscillator incorporating an unpumped erbium-doped fiber," *Chin. Opt. Lett.* **16**(1), 010604 (2018).
7. D. Eliyahu and L. Maleki, "Tunable, ultra-low phase noise YIG based opto-electronic oscillator," in *IEEE MTT-S Int. Microwave Symp. Digest* (2003).
8. N. Kuse and M. E. Fermann, "A photonic frequency discriminator based on a two wavelength delayed self-heterodyne interferometer for low phase noise tunable micro/mm wave synthesis," *Sci. Rep.* **8**(1), 13719 (2018).
9. J. Capmany, B. Ortega, and D. Pastor, "A tutorial on microwave photonic filters," *J. Lightwave Technol.* **24**(1), 201–229 (2006).
10. X. Xie et al., "Wideband tunable optoelectronic oscillator based on a phase modulator and a tunable optical filter," *Opt. Lett.* **38**(5), 655–657 (2013).
11. B. Yang et al., "A tunable optoelectronic oscillator based on a dispersion-induced microwave photonic filter," *IEEE Photonics Technol. Lett.* **25**(10), 921–924 (2013).
12. H. Tang et al., "Wideband tunable optoelectronic oscillator based on a microwave photonic filter with an ultra-narrow passband," *Opt. Lett.* **43**(10), 2328–2331 (2018).
13. H. S. Wen et al., "Ultrahigh-Q and tunable single-passband microwave photonic filter based on stimulated Brillouin scattering and a fiber ring resonator," *Opt. Lett.* **43**(19), 4659–4662 (2018).
14. D. Zhu et al., "Tunable up-converting optoelectronic oscillator based on stimulated Brillouin scattering," in *IEEE MTT-S Int. Microwave Symp. Digest (MTT)*, pp. 1–4 (2013).
15. P. Zhou, F. Zhang, and S. Pan, "A tunable multi-frequency optoelectronic oscillator based on stimulated Brillouin scattering," in *14th Int. Conf. Opt. Commun. and Networks (ICOCN)*, pp. 1–3 (2015).
16. A. Kobyakov, M. Sauer, and D. Chowdhury, "Stimulated Brillouin scattering in optical fibers," *Adv. Opt. Photonics* **2**(1), 1–59 (2010).
17. H. Peng et al., "Tunable DC-60 GHz RF generation utilizing a dual-loop optoelectronic oscillator based on stimulated Brillouin scattering," *J. Lightwave Technol.* **33**(13), 2707–2715 (2015).
18. Y. G. Shee et al., "Multiwavelength Brillouin-erbium fiber laser with double-Brillouin-frequency spacing," *Opt. Express* **19**(3), 1699–1706 (2011).
19. K. Hu et al., "Hybrid Brillouin/thulium multiwavelength fiber laser with switchable single- and double-Brillouin-frequency spacing," *Opt. Express* **22**(26), 31884–31892 (2014).
20. X. Zhou et al., "Multi-wavelength Brillouin fiber laser with triple Brillouin frequency spacing," *IEEE Photonics Technol. Lett.* **28**(21), 2379–2382 (2016).
21. J. Tang et al., "A stable optical comb with double-Brillouin-frequency spacing assisted by multiple four-wave mixing processes," *Opt. Fiber Technol.* **17**(6), 608–611 (2011).
22. C. Du et al., "Photonic millimeter-wave ultrawideband signal generation using frequency upconversion based on the stimulated Brillouin scattering effect," *Opt. Lett.* **43**(20), 4915–4918 (2018).
23. Y. G. Shee et al., "All-optical generation of a 21 GHz microwave carrier by incorporating a double-Brillouin frequency shifter," *Opt. Lett.* **35**(9), 1461–1463 (2010).
24. J. Yang et al., "An optical domain combined dual-loop optoelectronic oscillator," *IEEE Photonics Technol. Lett.* **19**(11), 807–809 (2007).
25. X. Han et al., "Polarization multiplexed dual-loop optoelectronic oscillator based on stimulated Brillouin scattering," *Opt. Commun.* **383**, 138–143 (2017).
26. T. Zhu et al., "Experimental study on stimulated Rayleigh scattering in optical fibers," *Opt. Express* **18**(22), 22958–22963 (2010).
27. Y. Jiang et al., "All-optical microwave oscillator based on semiconductor optical amplifier and stimulated Brillouin scattering," *Opt. Lett.* **43**(8), 1774–1777 (2018).