



Brillouin-based dual-frequency microwave signals generation using polarization-multiplexing modulation

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Abstract: Dual-frequency microwave signals have potential applications in radar and communication systems to improve system integration and signal conversion convenience. Flexible frequency tunability and low phase noise are important factors for dual-frequency microwave signals. This research focuses on improving frequency tunability of dual-frequency microwave signals meanwhile maintaining low phase noise and high spectrum purity. The outputs of two optical injection-locked slave lasers as Brillouin pump signals are employed combining with an integrated polarization-multiplexing modulator to realize orthogonal polarization multiplexing. Stable dual-frequency microwave signals are obtained in an optoelectronic oscillation loop simultaneously. The obtained microwave signals inherit the flexible frequency tunability of Brillouin effect and low phase noise of the optoelectronic oscillator at the same time.

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1. Introduction

For improving detection accuracy, communication capacity and anti-interference ability in modern radar and communication systems, the baseband signal needs to be up-converted multiple times to achieve the high operating frequency. The multi-frequency local oscillator is an effective method to achieve flexible frequency conversion of signals. Among them, dual-frequency microwave signals are widely used, especially in fields such as sensing [1,2], radar systems [3], global positioning systems [4], and wireless local area network systems [5]. All of those applications require dual-frequency signals with the characteristics of flexible frequency tunability, high amplitude, low phase noise, high spectral purity, and coherence which can improve the detection resolution greatly. The dual-frequency microwave signals are mostly generated by two voltage-controlled oscillators with a reference based on a phase-locked loop. Affected by the frequency division ratio and the loop bandwidth, the phase noise of the generated signals is greatly deteriorated especially at high frequencies. Thus, researching for new methods to generate dual-frequency microwave signals are necessary. Optoelectronic oscillator (OEO) has wide applications in the microwave photonics field due to its ultra-high spectral purity and low phase noise [6,7]. Therefore OEO based dual-frequency microwave signals generation has attracted more and more attention in recent years. On this basis, multi-format signals [8] and even chirp signals [9] generation can be realized.

Several OEO structures have been proposed to produce dual-frequency microwave signals. Using a dual-parallel Mach-Zehnder modulator and two tunable electrical bandpass filters (EBPFs), a dual-frequency OEO with 15 GHz frequency tuning range has been obtained [10]. The frequency tunability is limited by two EBPFs, and the frequency difference between two generated signals have to be larger than 70 MHz to avoid overlap. Further, a polarization multiplexed dual-frequency OEO employing a dual-polarization Mach-Zehnder modulator (DPMZM) and two tunable EBPFs has been put forward to avoid overlap [11]. The frequency tunability problem induced by the EBPFs is still not solved, which limits

the practicality of generated microwave signals greatly. Two separate lasers incorporating a polarization-maintaining fiber Bragg grating (PMFBG) with two orthogonal polarization directions have been presented in [12] to generate tunable dual-frequency microwave signals where the frequency tuning range has been limited to 7 GHz. To improve frequency tunability, stimulated Brillouin scattering (SBS) effect, having the characteristics of narrow bandwidth and flexible frequency tuning [13], gradually becomes a favorable candidate to replace EBPFs. Two separate lasers are used as Brillouin pump signals to generate dual-frequency microwave signals, as shown in [14]. However, the single-mode character of the generated signals cannot be guaranteed which is limited by the bandwidth of Stokes light, and the phase noise is relatively poor.

Obviously, while ensuring the low phase noise of the dual-frequency microwave signals, flexible frequency tunability is still a key performance worthy of improvement. Producing two polarization-orthogonal SBS pumps with flexible frequency tuning is crucial to generate dual-frequency microwave signals having flexible tunability in an SBS-based OEO system. Non-orthogonally to orthogonal-polarized optical single-sideband (OP-SSB) modulation conversion has been realized by an optical-injected semiconductor laser [15]. The generated signals have broad frequency tuning range. But the signal power is relatively low. Using two polarization modulators and electrical drive signals with 90 degrees of phase shift, OP-SSB modulation is achieved [16]. However, it is difficult to ensure an ideal 90-degree phase shift of the electrical signal, and the extinction ratio of the generated signal is insufficient.

In this paper, a Brillouin-based dual-frequency OEO scheme incorporating a polarization multiplexing modulation is proposed to achieve microwave signals with flexible frequency tunability, low phase noise, and high spectral purity. Two slave lasers injection-locked to the same master laser are adopted as Brillouin pumps. Benefit from the injection-locking process, two SBS pumps have the characteristics of high power, flexible frequency adjustment, and high sideband suppression ratio. Through a polarization beam combiner and a polarization controller, two orthogonal-polarized pumps are obtained. Two Stokes lights with orthogonal polarization are generated which are used as the mode selection filters for OEO. An integrated polarization multiplexing modulator realizes simultaneous oscillation of two different modes in the same oscillation loop. As a result, dual-frequency microwave signals with 10 MHz fine frequency tuning resolution and up to 40 GHz tuning range are achieved, and the side mode suppression ratio maintains higher than 40 dB. The single-sideband phase noise of a 4.2 GHz signal is -119 dBc/Hz at 10 kHz offset frequency, while the 29.2 GHz signal is -117 dBc/Hz.

2. Principle

In this part, the principles of dual-frequency microwave signals generation and system phase noise analysis are introduced in detail.

2.1 Dual-frequency microwave signals generation

In a single OEO loop, using a Stokes light of SBS as the filter for mode selection, only one stable oscillation mode can be obtained due to the modes competition. In order to break this modes competition, a technology of polarization multiplexing is introduced. It requires two modes having orthogonal polarization in an OEO loop. So two orthogonal SBS pump signals are needed to generate two filters with orthogonal polarization states. Then two Stokes lights with orthogonal polarization states are generated after passing through the optical fibers in an oscillation loop. The optical carrier of the OEO loop is also polarized into two orthogonal polarization states. Then is respectively beaten with the Stokes light having the same polarization state to break the mode competition.

The schematic diagram of dual-frequency microwave signals generation based on polarization multiplexing is described in Fig. 1. A cascaded phase and intensity modulation scheme is used to generate multi sidebands. Through an intensity modulation driven by a low-

frequency electrical signal, optical pulse signals with flat top are obtained, which are then subjected to secondary phase modulation. The phase relationship between the respective sidebands is fixed. Thereby an optical frequency comb (OFC) having coherent multi-frequency combs and flat amplitudes is obtained. f_c and f_{RF} are the frequency of the optical carrier and electrical drive signal, respectively. Two different sidebands of the OFC are injected into two slave lasers (SLs), respectively. Two optical Brillouin pumps with orthogonal polarization states are realized through a polarization beam combiner (PBC) and the polarization control. Since the output lights of two SLs are coherent with the injected optical signal, two optical pumps having coherence can be obtained. The frequency stability and linewidth of SLs also can be improved by the optical injection locking (OIL) process. After passing through the optical fiber in the oscillation loop, two Stokes lights with orthogonal polarization states can be realized. An integrated dual-polarization Mach-Zehnder modulator (DPMZM) is used in the OEO loop for the electrical to optical conversion. The optical carrier is polarized by the DPMZM which contains an inherited polarization beam splitter. Therefore, the optical carrier also has two orthogonal polarization states. The carriers and the Stokes lights with the same polarization state beat each other to produce two different oscillation modes. Then, two electrical signals are input into two ports of the DPMZM respectively to form a closed OEO loop. Further, two Stokes lights have a fixed frequency shift offset to the pump in a certain environment. By flexibly controlling the frequency of the electrical drive signal and the OIL sideband order, two Stokes lights frequencies can be separately adjusted, and the flexible frequency tuning of the generated dual-frequency microwave signals can be realized. Therefore, using polarization multiplexing combining with SBS, dual-frequency microwave signals with flexible frequency tuning can be achieved.

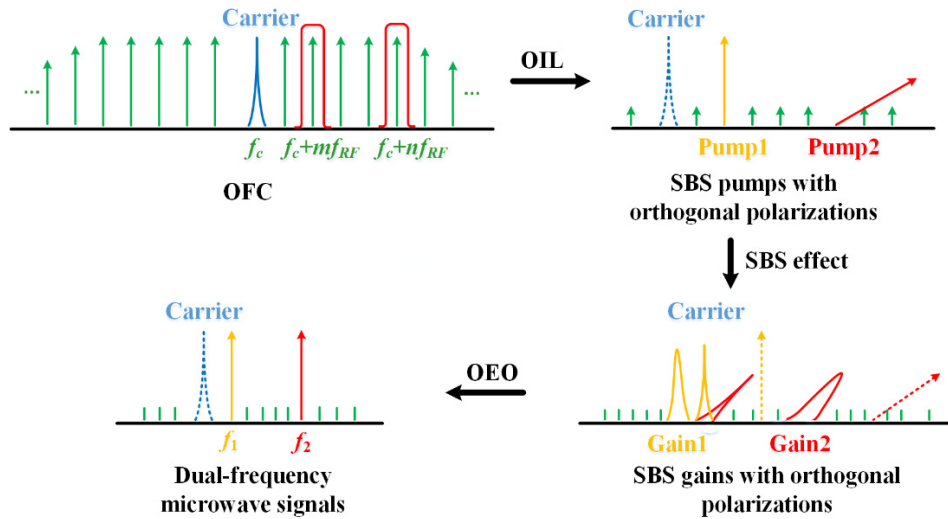


Fig. 1. Schematic diagram of dual-frequency microwave signals generation based on polarization multiplexing. OFC, optical frequency comb, OIL, optical injection locking, OEO, optoelectronic oscillator.

2.2 Phase noise analysis

The outputs of two SLs injection-locked to OFC can be written as

$$\begin{aligned} E_p &= \exp\{j[(\omega_c + m\omega_{RF})t + m\varphi_{RF} + \Delta\varphi_p(t)]\} \\ E_s &= \exp\{j[(\omega_c + n\omega_{RF})t + n\varphi_{RF} + \Delta\varphi_s(t)]\}, \end{aligned} \quad (1)$$

where ω_c is the angular frequency of the optical carrier, ω_{RF} and φ_{RF} are the angular frequency and the phase of the electrical drive signal, respectively, m and n are the m th and n th order sidebands of OFC, respectively, $\Delta\varphi_p$ and $\Delta\varphi_s$ are the phase fluctuations induced by two separate optical links which can be expressed as

$$\begin{aligned}\Delta\varphi_p(t) &= (\omega_c + m\omega_{RF}) \times \tau_p(t), \\ \Delta\varphi_s(t) &= (\omega_c + n\omega_{RF}) \times \tau_s(t)\end{aligned}\quad (2)$$

where $\tau_p(t)$ and $\tau_s(t)$ are the time delay of two optical injection-locking links, respectively. So the power spectral density (PSD) of extra frequency noise induced by two injection-locked SLs can be expressed as

$$\begin{aligned}\Delta S_p(f) &= 2f^2 \int_{-\tau}^{\tau} [\Delta\varphi_p(t) \times \Delta\varphi_p(t-\tau)] d\tau \\ \Delta S_s(f) &= 2f^2 \int_{-\tau}^{\tau} [\Delta\varphi_s(t) \times \Delta\varphi_s(t-\tau)] d\tau\end{aligned}\quad (3)$$

The close-in additive phase noise contributed by the SLs via SBS can be expressed as [17]

$$\begin{aligned}S_{SBS_p}(f) &= \left[\frac{\exp(g_B I_p L)}{1 - \exp(g_B I_p L)} \frac{g_B I_p L}{\Delta\nu_B} \right] \times [S_c(f) + S_p(f)], \\ S_{SBS_s}(f) &= \left[\frac{\exp(g_B I_s L)}{1 - \exp(g_B I_s L)} \frac{g_B I_s L}{\Delta\nu_B} \right] \times [S_c(f) + S_s(f)]\end{aligned}\quad (4)$$

where g_B is the Brillouin gain coefficient, I_p and I_s are the output power intensity of two SLs, respectively, L is the fiber length, $\Delta\nu_B$ is the SBS gain bandwidth, $S_c(f)$ is the PSD of optical frequency noise from the master laser (ML), $S_p(f)$ and $S_s(f)$ are the PSD of frequency noise from two SLs, respectively, which can be rewritten as

$$\begin{aligned}S_p(f) &= S_c(f) + mS_{RF}(f) + \Delta S_p(f), \\ S_s(f) &= S_c(f) + nS_{RF}(f) + \Delta S_s(f)\end{aligned}\quad (5)$$

where $S_{RF}(f)$ is the PSD of optical frequency noise from the electrical drive signal. According to our previous research, compared to the frequency noise of ML, the frequency noise from the electrical drive signal can be ignored [18]. Because the PSD of optical frequency noise is much higher than the electrical frequency noise, Eq. (1) can be rewritten as

$$\begin{aligned}S_{SBS_p}(f) &= \left[\frac{\exp(g_B I_p L)}{1 - \exp(g_B I_p L)} \frac{g_B I_p L}{\Delta\nu_B} \right] \times [2S_c(f) + \Delta S_p(f)] \\ S_{SBS_s}(f) &= \left[\frac{\exp(g_B I_s L)}{1 - \exp(g_B I_s L)} \frac{g_B I_s L}{\Delta\nu_B} \right] \times [2S_c(f) + \Delta S_s(f)]\end{aligned}\quad (6)$$

Ideally, the phase difference between any two sidebands in the OFC is constant. After injection-locked to two different sidebands of the OFC, two optical links of separate SLs have an equal time delay. The value $\Delta S_p(f)$ is equal to $\Delta S_s(f)$. When the SL is injection-locked to the ML, the phase noise of the SL is inherited from the phase noise of the ML. At this point, there is only a small amount of frequency jitters coming from the SL at low offset frequencies which can be ignored. Then two Stokes lights with orthogonal polarization states transmit in the OEO loop will generate two different modes. However, the time delay between two optical links cannot be exactly the same. Two separate optical fiber links of two

SLs will lead to extra phase noise into the OEO loop so as to deteriorate signal stability. By introducing an optical phase-locked loop (PLL), it is possible to compensate for the extra phase noise induced by the separated optical links [19]. The low-frequency jitters from the SLs can also be compensated in this way. Besides, by using an integrated dual-wavelength laser as injection-locking SLs, optical link separation can be effectively avoided to improve the coherence of two Brillouin pumps [20].

3. Experimental setup

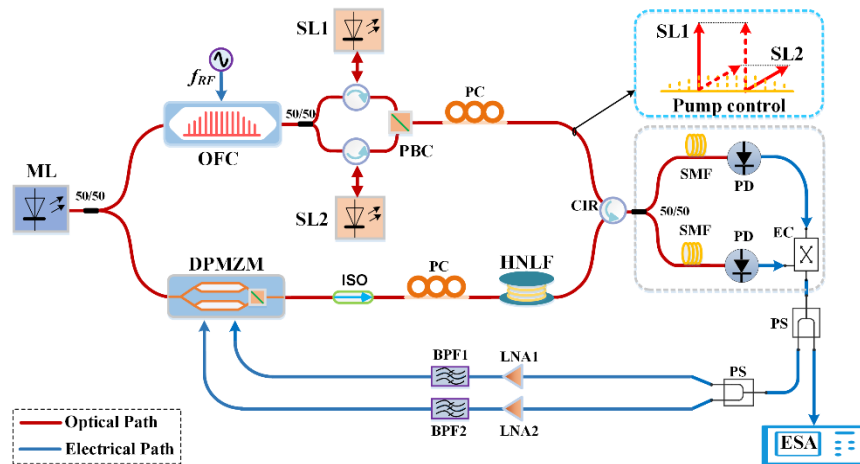


Fig. 2. Experimental setup of the SBS based dual-frequency OEO. ML, master laser, OFC, optical frequency comb, CIR, circulator, SL, slave laser, PBC, polarization beam combiner, PC, polarization controller, DPMZM, dual-polarization Mach-Zehnder modulator, ISO, isolator, HNLF, high nonlinear fiber, SMF, single-mode fiber, PD, photodiode, EC, electrical coupler, PS, power splitter, LNA, low noise amplifier, BPF, bandpass filter, ESA, electrical spectrum analyzer.

The experimental setup of the dual-frequency OEO scheme based on SBS and polarization multiplexing is shown in Fig. 2, which is mainly constituted of injection-locked pump signal generation, optoelectronic oscillation loop, and single-mode selection part. The first part is used to generate two optical pump signals with shifted frequency from the optical carrier. Dual-frequency signals are obtained through continuous electric-optical feedback in the OEO loop. A mode selection part is involved to maintain a single-mode oscillation [21]. A continuous wave signal from an ML with fixed power of 16.8 dBm and a linewidth of 1 kHz operating at 1550.7 nm is separated into two branches by a 50:50 optical coupler (OC). In the upper branch, the output from the ML is act as an optical carrier to generate OFC based on a 10 GHz phase modulator and a 20 GHz intensity modulator driven by a low-frequency microwave source. The obtained OFC is divided into two parts with equal power as the optical injection signals of two SLs, respectively. Two distributed feedback (DFB) lasers having a linewidth of about 4 MHz without isolators are chosen as the SLs. The corresponding central wavelength can be adjusted within 2 nm centered at 1550 nm. By precisely controlling the temperature and current of two SLs independently, the center wavelengths of two SLs can be injection-locked to any sideband of OFC. The outputs from two injection-locked SLs are combined together by a PBC, then are sent into a 1 km length high nonlinear fiber (HNLF) as the SBS pumps through an optical circulator (CIR). For the ML, phase and amplitude modulator, OC, CIR, and two SLs used in this part are polarization-maintained, only one PBC is needed to realize two polarization-orthogonal pumps. The HNLF used is a single-mode fiber because the SBS effect is polarization-dependent. In the lower branch, the ML output is used as the optical carrier of the DPMZM. The DPMZM output passes through an optical isolator (ISO) and the HNLF, then transmits into the CIR.

Two of the DPMZM sidebands are amplified by the Stokes lights in the HNLF. To maintain the maximum Stokes lights and polarization matching, two polarization controllers (PCs) are inserted at two branches respectively. The port 3 output of the CIR is sent into two separate optical fiber links by a 50:50 OC. One link is composed by a 1 km single-mode fiber (SMF) and a 40 GHz photodiode (PD), whereas the other one has a 1.1 km SMF and a 40 GHz PD. Two electrical signals from PDs are combined together by a 40 GHz electrical coupler (EC), then are divided into two equal parts and sent into two electrical drive ports of the DPMZM after being amplified by two electrical low noise amplifiers (LNAs), respectively. Two electrical bandpass filters (BPFs) with broad bandwidth are added to separate two microwave frequencies. The specific parameters of BPFs can be seen in the experimental results section. When the two modes oscillating in the loop reach a steady state, stable dual-frequency microwave signals can be observed by an electrical spectrum analyzer (ESA).

4. Experimental results

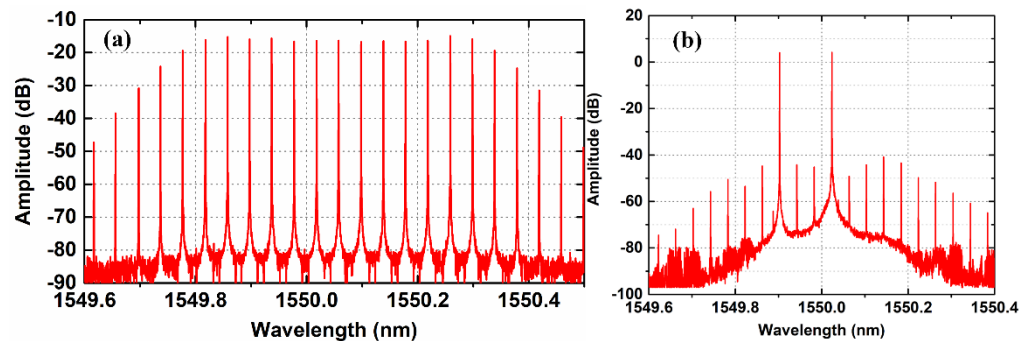


Fig. 3. (a) The optical spectrum of OFC with a 5 GHz electrical drive signal. (b) The optical spectrum of two injection-locked SBS pumps.

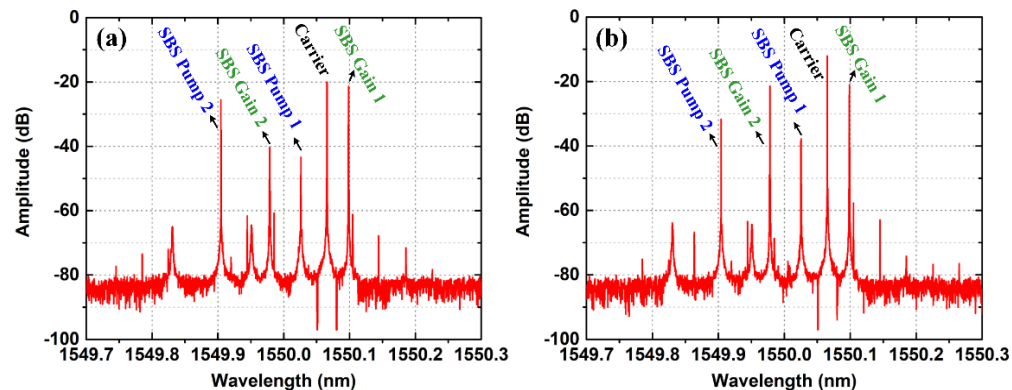


Fig. 4. Optical spectra of injection-locked SBS pumps and corresponding Stokes lights. (a) Two SBS pumps have non-orthogonal polarization states. (b) Two SBS pumps have orthogonal polarization states.

The polarization-multiplexed modes oscillation, single-mode performance, flexible frequency tunability, and phase noise of the generated dual-frequency microwave signals are measured in this section. The electrical drive signal frequency of OFC is set at 5 GHz. By adjusting the delay of the phase modulator and the bias of the intensity modulator, the obtained optical spectrum of OFC is shown in Fig. 3(a). There are about 14 sidebands with almost equal amplitude. When two SLs are injection-locked to the first and fourth-order right sidebands of OFC separately, the optical spectrum of combined output signals is shown in Fig. 3(b), which act as the optical SBS pumps. As can be seen, the sideband suppression ratio is higher than 40

dB, and the sideband power is much lower than the SBS threshold. Through tuning the polarization states of two branches in Fig. 2, the amplitudes of two polarization-multiplexing modes can be changed. Optical spectrums of injection-locked SBS pump signals and the corresponding Stokes lights at different polarization states can be seen in Fig. 4(a) and 4(b). The pumps and Stokes lights of SBS are not equal in Fig. 4(a). When two polarization modes reach orthogonal state, two maximum SBS gains with equal amplitudes can be obtained as shown in Fig. 4(b). Because the Stokes light is polarization-dependent. In order to reduce the influence of polarization drifting, polarization-maintaining devices are adopted at the pump generation part of SBS. All of the transmission fibers used in the experiment are packaged in the vibration-isolated boxes. The remaining fiber links and devices are also fixed at the optical platform. In this way, the polarization state drifting of the OEO system is minimized.

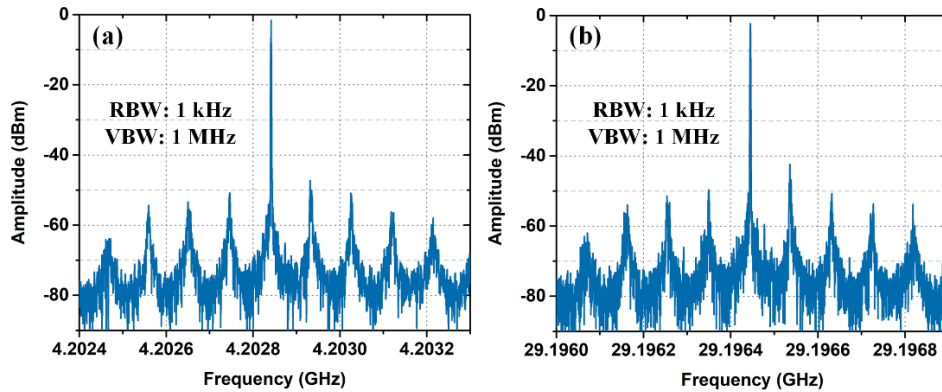


Fig. 5. The electrical spectrums of OEO generated dual-frequency microwave signals at the frequency of (a) 4.2 GHz, and (b) 29.2 GHz.

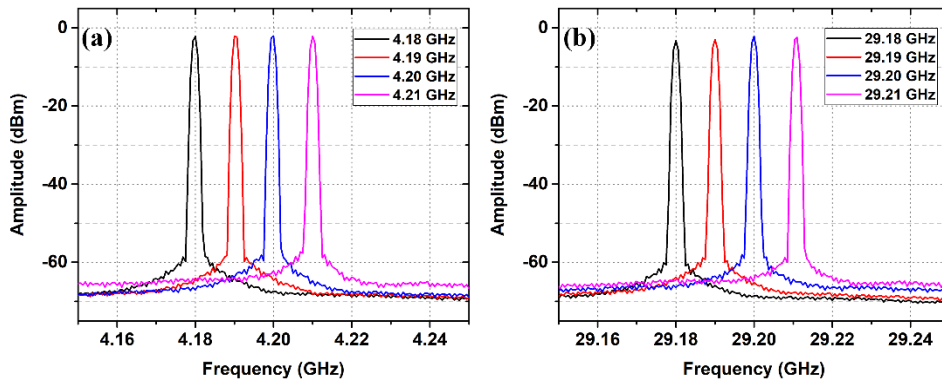


Fig. 6. Fine frequency tuning of the obtained dual-frequency microwave signals with the step of 10 MHz around the frequency of (a) 4.2 GHz, and (b) 29.2 GHz.

In order to demonstrate the single-mode performance of the generated signals at different frequencies, the two SLs are injection-locked to the first sideband on the left and the fourth sideband on the right of OFC, respectively. A low-pass electrical filter with a bandwidth of 6 GHz and a BPF with passband from 25 GHz to 35 GHz are used to separate two microwave signals in Fig. 2. The inherent SBS gain spectrum bandwidth of the HNLF used at room temperature is about 20 MHz. The mode space of an OEO loop with 2 km loop length is about 100 kHz. As a result, there are several modes oscillate simultaneously. When another OEO loop with different loop length is added, the mode competition in the two loops will lead to one stable oscillation mode, as explained in our previous work [18]. The fiber lengths of two OEO loops used in the experiment are 2 km and 2.1 km, respectively. The side-mode

suppression ratio (SMSR) obtained is reduced by 30 dB. The zoom-in electrical spectrums of generated dual-frequency microwave signals at 4.2 GHz and 29.2 GHz are shown in Fig. 5(a) and 5(b), respectively. The view bandwidth (VBW) of ESA is 1 MHz with a resolution bandwidth (RBW) of 1 kHz. The 4.2 GHz and a 29.2 GHz electrical signal are obtained simultaneously with the SMSR higher than 40 dB, which fully demonstrates the single-mode and high spectral purity of the generated dual-frequency signals. Influenced by the environment, the slow frequency drifting of the generated signal is about several kHz in 1 h. To ensure the frequency accuracy, the final measured minimum frequency tuning step is 10 MHz, which is much higher than the slow frequency drift. By precisely controlling the frequency of the electrical drive signal, the accurate frequency tuning of above dual-frequency microwave signals can be shown in Fig. 6(a) and 6(b). If the electrical drive signal is tuned within the locking bandwidth of the SLs, the frequency of the output signal can be quickly changed. For the response time of the devices used is on the order of ns, the total frequency tuning speed also can reach the order of ns.

By changing the electrical drive signal frequency of OFC and the injection-locking orders of SLs, the frequencies of the obtained dual-frequency signals can be flexibly adjusted as illustrated in Fig. 7(a). The signals with lower frequencies are changed from 4.2 GHz to 10.8 GHz, while the higher frequencies are tuned from 15.8 GHz to 39.2 GHz. In addition to the above two BPFs, a BPF with the passband from 10 GHz to 20 GHz is used to select signals in this frequency range. So the proposed SBS-based dual-frequency OEO can generate dual-frequency signals with a maximal tuning range of around 40 GHz. When the frequency of the drive signal is set to be 5 GHz, the minimum frequency achieved is 0.8 GHz when the SL is injection-locked to the 2nd right sideband of OFC. The OIL process is stable during the experiment. Unless there were significant changes in external conditions, the SL can maintain phase-locked to the ML in at least a few hours. Ideally, if the two SBS pumps maintain a perfectly orthogonal polarization state during the generation and transmission process, the frequency spacing of the two microwave signals can be infinitely small. The maximum frequency tuning range of generated signal is limited by the response bandwidth of optical and electrical devices such as modulator, PD, and LNA. The single-sideband (SSB) phase noise of the generated dual-frequency signal with frequencies of 4.2 GHz and 29.2 GHz is measured by a phase noise analyzer (PNA) as shown in Fig. 7(b). Two signals have almost coincident phase noise traces. The SSB phase noise of the 4.2 GHz signal is -119 dBc/Hz at 10 kHz offset frequency, while the 29.2 GHz signal is -117 dBc/Hz. The 2 dB difference mainly comes from the response difference of LNA at different frequencies.

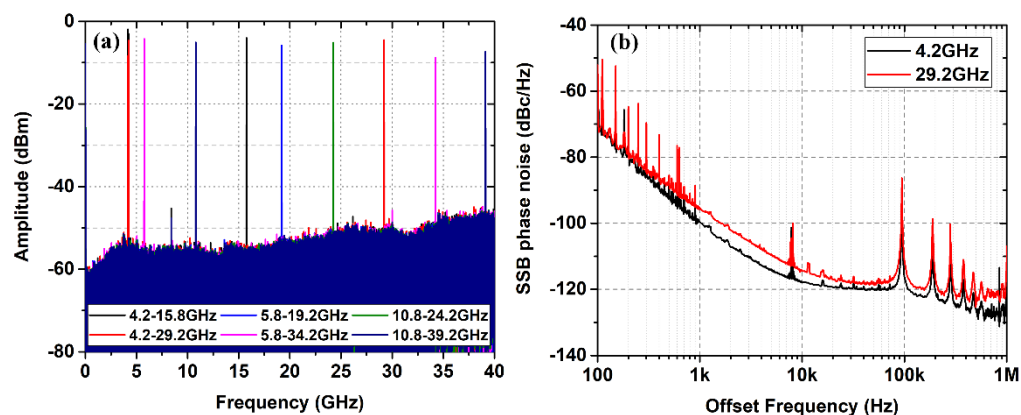


Fig. 7. (a) Electrical spectrum of OEO generated dual-frequency microwave signals with frequency tuning range up to 40 GHz. (b) SSB phase noise of OEO generated dual-frequency signals with frequencies of 4.2 GHz and 29.2 GHz, respectively.

Affected by temperature, environmental jitters and so on, the SSB phase noise at the low offset frequency of the microwave signals generated by OEO is relatively poor, that is, there is a long-term slow frequency drift. In order to ensure the stability of the entire loop, the PLL technique can be adopted. The generated microwave signal can be compared with an external electrical reference signal to generate an error signal. Then is fed back to the OEO loop to compensate for the phase jitters [22]. There are many factors that affect the coherence of the generated dual-frequency signals, including laser noise, separate pump links, loop jitters, polarization rotations, and other factors. Under the influence of all these factors, the OEO system has fast frequency jitters and slow frequency drifting simultaneously. By dividing the high-frequency signal generated by OEO, a signal with the frequency close to the low-frequency signal is obtained. The phase of above two signals can be detected to obtain an error signal which includes incoherent noise. Because the frequency of Stokes light can be controlled by changing the pump frequency. The error signal can be fed back to the electrical drive signal of the OFC through a PLL to compensate for the frequencies of two pumps simultaneously. The frequencies of Stokes lights are also controlled. Thereby the incoherent noise of dual-frequency microwave signals generated by OEO can be compensated to an extent, and the coherence of the two signals can be improved. Benefiting from the advantage that OEO signals at different frequencies have the same phase noise, the signal frequency generated under this scheme can be extended to millimeter waves.

5. Summary

As a conclusion, a dual-frequency microwave signals generation scheme based on Brillouin optoelectronic oscillator is proposed. Flexible frequency tuning, low phase noise, the high spectral purity of the obtained microwave signals are maintained simultaneously. The frequencies of two generated microwave signals can be independently adjusted within 40 GHz, and the side mode suppression ratio is higher than 40 dB. The SSB phase noise of the generated signals at different frequencies is about -117 dBc/Hz at 10 kHz offset frequency. In addition, an optical phase-locking technique for stabilizing two separated Brillouin pump signals can be adopted to improve the coherence of the generated dual-frequency microwave signals. This study put forward a technique for generating coherent dual-frequency microwave signals with flexible frequency tunability, which is of great significance for realizing high-precision target detection in radar systems.

Funding

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