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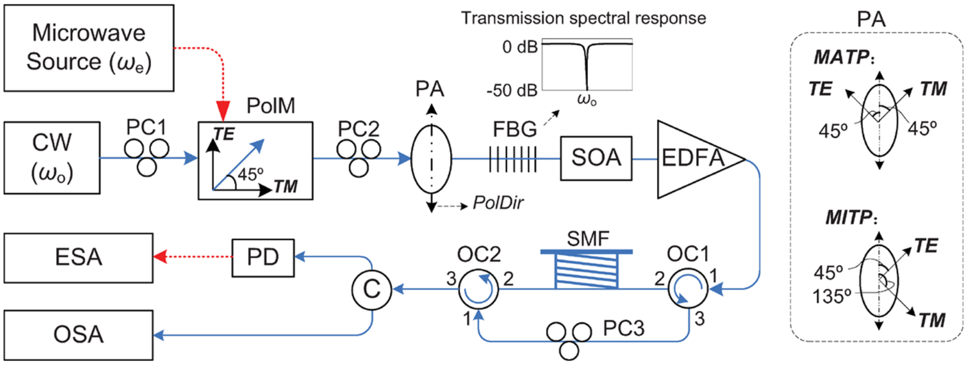

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Microwave and Terahertz Generation Based on Photonically Assisted Microwave Frequency Twelvetupling With Large Tunability

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Abstract: A novel approach to achieving photonically assisted microwave frequency twelvetupling with large frequency tunability is proposed and demonstrated. The frequency twelvetupling is realized through a joint operation of polarization modulation, four-wave mixing, and stimulated-Brillouin-scattering-assisted filtering. The key significance of the technique is that the system is capable of realizing simple frequency tuning over a wide frequency range. An experiment is performed. An electrical signal with a frequency that is tunable from 48 to 132 GHz is generated.

Index Terms: Four-wave mixing (FWM), microwave generation, microwave photonics, stimulated Brillouin scattering, Terahertz.

1. Introduction

Photonic generation of microwave and terahertz signals is attractive for numerous applications, such as spectroscopic sensing, wireless communications, radar, and modern instrumentation. The key advantages of photonics techniques for microwave and terahertz generation are the high frequency and simple and flexible tunability, which are difficult to realize using electronic techniques [1]. Among various photonics techniques [2], microwave generation based on external modulation [3]–[6] has been considered an attractive solution due to the wide frequency tunability, excellent system stability, and high spectral purity of the generated signal.

In [3] and [4], frequency doubling and quadrupling were demonstrated using a single Mach–Zehnder modulator (MZM) biased, respectively, at the minimum transmission point (MITP) and the maximum transmission point (MATP) to produce two side-bands with a frequency spacing corresponding to two and four times the frequency of the microwave drive signal. The frequency multiplication factor (FMF) can be increased to six or eight by cascading two MZMs that are biased at the MITP and the MATP [5] or both at the MATP [6]. The major limitation of the techniques in [5] and [6] is the high complexity in frequency tuning since more than two parameters are needed to be simultaneously adjusted to meet the frequency sextupling or octupling conditions.

Instead of using MZMs, frequency multiplication can also be achieved using nonlinear devices, such as nonlinear fibers or semiconductor optical amplifiers (SOAs) [7]–[9]. In [7], frequency doubling was achieved by suppressing the residual optical carrier of a phase-modulated

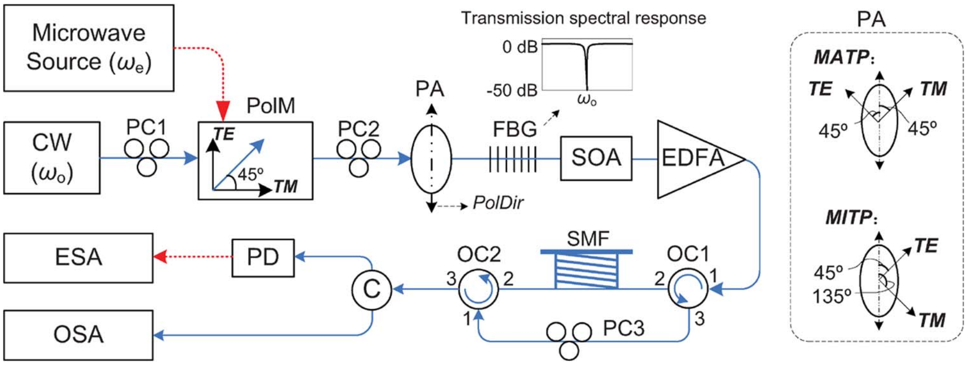

Fig. 1. Schematic of the proposed photonically assisted microwave frequency twelvetupling system. C: optical coupler; EDFA: erbium-doped fiber amplifier; ESA: electrical spectrum analyzer; OC: optical circulator; OSA: electrical spectrum analyzer; PA: polarization analyzer; PD: photodetector; PolDir: polarization direction; SMF: single mode fiber.

continuous-wave (CW) laser light through stimulated-Brillouin-scattering (SBS)-assisted filtering. In [8], frequency sextupling was demonstrated by combining frequency doubling using an MZM and frequency tripling based on four-wave mixing (FWM) in a nonlinear fiber [8] or an SOA [9]. In [10], microwave multiplication with a FMF of 18 was achieved by a joint use of two MZMs and two SOAs. The major problem in [8]–[10] is that fiber Bragg gratings (FBG) were used as band-elimination filters, which would limit the frequency tunable range of the microwave to be generated. In addition, the employment of MZMs would suffer from the bias drifting problem, which would lead to poor stability of the microwave generation system.

In this paper, we propose and demonstrate an approach to achieving frequency-twelvetupling for microwave or terahertz generation by a combined use of a polarization modulator (PolM) for frequency quadrupling, an SOA for frequency tripling, and an SBS-assisted filter for adaptive filtering to remove unwanted spectral components. The PolM, in conjunction with two polarization controllers (PCs), operates as an equivalent MZM that is biased at the MATP, to generate even-order sidebands. By removing the optical carrier using a fixed FBG, two $\pm$ second-order sidebands with a wavelength spacing corresponding to four times the microwave drive frequency are obtained. The introduction of the $\pm$ second-order sidebands as two pump waves to the SOA would generate two idle waves due to the FWM. The two pump waves are then removed by the SBS-assisted filter. The key significance of this approach is that the SBS-assisted filtering is adaptive, which would significantly simplify the frequency tuning. In addition, the use of the wavelength-independent SBS-assisted filter would improve the frequency tunable range. Furthermore, the PolM is not dc biased; thus, the system is free from bias drifts. An experiment is performed. The generation of a microwave or terahertz signal that is tunable from 48 to 132 GHz is demonstrated.

2. Principle

The proposed system is shown in Fig. 1. The configuration includes a CW laser source, a PolM, two PCs (PC1 and PC2) before and after the PolM, a polarization analyzer (PA), a FBG notch filter, an SOA, an erbium-doped fiber amplifier (EDFA), an SBS-assisted filter, and a photodetector (PD). The key module in the system is the SBS-assisted filter, which consists of a spool of single-mode fiber (SMF), a PC (PC3), and two optical circulators (OC1 and OC2), and operates as a wavelength-independent narrow band notch filter.

As can be seen a CW light wave from the laser source is directed into the PolM via PC1, and a microwave drive signal from a microwave source is applied to the PolM via the RF port. The PolM is a special phase modulator that supports both TE and TM modes with, however, opposite phase modulation indices [11]. The polarization direction of the incident light wave to the PolM is adjusted by tuning PC1 to have an angle of 45° with respect to the two orthogonal principal axes (TE and TM modes), as shown in Fig. 1. The two light waves along the two principal axes of the PolM are then sent to the PA via PC2. By tuning PC2, the polarization directions of the phase-modulated light waves along the two principal axes of the PolM can be aligned in two ways: 1) The two orthogonal polarization directions of the phase-modulated light waves are aligned, respectively, at 45° and −45° with respect to the polarization direction of the PA; and 2) the two orthogonal polarization directions of the phase-modulated light waves are aligned, respectively, at 45° and 135° with respect to the polarization direction of the PA. Therefore, an intensity-modulated signal would be generated at the output of the PA, which is equivalent to the operation of an MZM that is biased at either the MATP or the MITP.

Mathematically, the electrical field at the output of the PA can be expressed as

$$\begin{aligned} E(t) &= E_0[cos(\omega_o t + \beta cos\omega_e t + \Phi) + cos(\omega_o t - \beta cos\omega_e t)] \\ &= E_0 J_0(\beta) cos\left(\frac{\Phi}{2}\right) cos\left(\omega_o t + \frac{\Phi}{2}\right) \\ &\quad + E_0 cos\left(\frac{\Phi}{2}\right)\left\{\sum_{n=1}^{\infty}(-1)^n J_{2n}(\beta)\left\{cos\left[(\omega_o + 2n\omega_e)t + \frac{\Phi}{2}\right] + cos\left[(\omega_o - 2n\omega_e)t + \frac{\Phi}{2}\right]\right\}\right\} \\ &\quad + E_0 sin\left(\frac{\Phi}{2}\right)\left\{\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta)\left\{cos\left[(\omega_o + (2n-1)\omega_e)t + \frac{\Phi}{2}\right]\right.\right. \\ &\qquad\qquad \left.\left. + cos\left[(\omega_o - (2n-1)\omega_e)t + \frac{\Phi}{2}\right]\right\}\right\} \end{aligned} \tag{1}$$

where E_0 is the amplitude of the incident light waves along the two orthogonal polarization directions, ω_o and ω_e are, respectively, the angular frequencies of the light wave and the microwave drive signal, J_n is the nth-order Bessel function of the first kind, β is the phase modulation index, and Φ is a static phase term introduced by PC2. When Φ is equal to 0, the PolM-based MZM is biased at the MATP; when Φ is equal to π, the PolM-based MZM is biased at the MITP. When the PolM-based MZM operates at the MATP, all the odd-order sidebands would be suppressed. Under small signal modulation condition, the higher even-order sidebands are small and can be ignored. Equation (1) can be simplified to

$$E(t) = E_0\{J_0(\beta)cos(\omega_o t) - J_2(\beta)cos[(\omega_o - 2\omega_e)t] - J_2(\beta)cos[(\omega_o + 2\omega_e)t]\}. \tag{2}$$

After passing through the FBG notch filter, the optical carrier is filtered out, and only the two ± second-order sidebands $\omega_o + 2\omega_e$ and $\omega_o - 2\omega_e$ remain.

The two ± second-order sidebands are then launched into the SOA as two pump waves. According to the theory of FWM, two sidebands will interact in the SOA to produce two new idle waves with the frequencies being $\omega_o + 6\omega_e$ and $\omega_o - 6\omega_e$ and a frequency spacing corresponding to 12 times the frequency of the microwave drive signal. In addition, the powers of the pump waves are usually larger than those of the idle waves.

The two pump waves and the two idle waves are amplified by the EDFA and then routed, through OC1, to the SBS-assisted filter. The powers of the pump waves are controlled to be above the threshold of the SBS. Thus, Stokes waves would only be generated by the pump waves. The Stokes waves are re-injected into the SMF via OC2 in a direction opposite to the pump waves. The interaction of the re-injected Stokes waves with the pump waves would greatly enhance the induced acoustic grating, causing more backscattering of the pump waves into the Stokes waves, thus significantly suppressing the pump waves. The suppression ratio is determined by the power of the input light wave, regardless of the wavelength, and the suppression ratio would increase significantly as the power of the light wave increases. The SBS-assisted filter can remove the two pump waves while keeping the two idle waves. Since the output from OC2 consists of only the two idle waves $\omega_o + 6\omega_e$ and $\omega_o - 6\omega_e$, the beating of the two idle waves at the PD would generate a frequency-twelvetupled microwave signal.

Compared with the approaches in [5], [6], and [10], where two cascaded MZMs were employed for frequency multiplication, the proposed approach is much simpler for continuous frequency

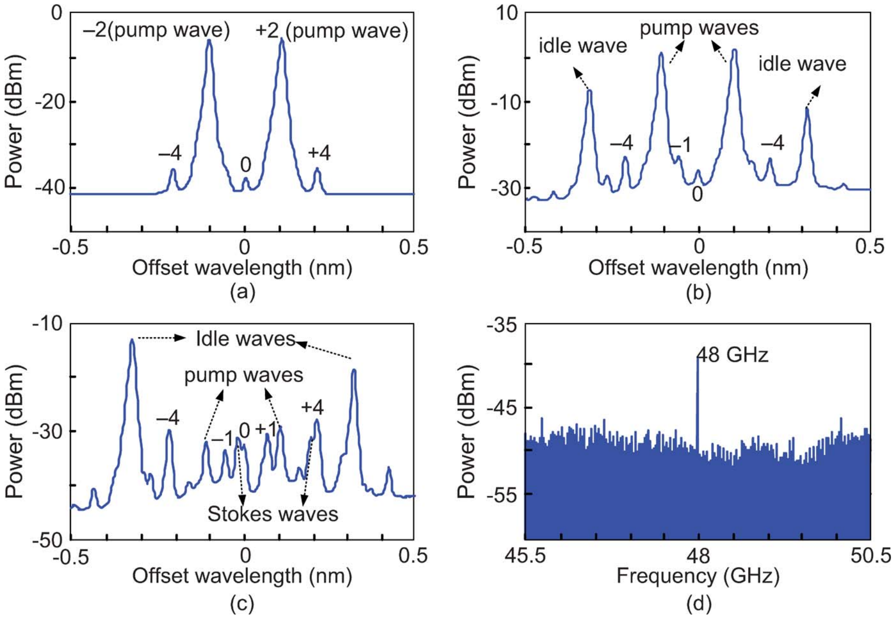

Fig. 2. Measured optical spectra at the outputs of (a) the FBG notch filter, (b) the SOA, and (c) the second OC; (d) measured electrical spectrum of the generated frequency twelvetupled microwave signal with a frequency span of 5 GHz and a resolution bandwidth (RBW) of 3 MHz.

tuning, since only the microwave drive frequency needs to be tuned, while in [5], [6], and [10], the phase and phase-modulation index conditions must be simultaneously met, which involve the tuning of multiple parameters. Since the FMF is 12, theoretically, the frequency tuning step and tuning range of the system are both 12 times those of the microwave source; the phase noise of the frequency-multiplied microwave would be increased by $20\log_{10}(12) \approx 21$ dB from that of the microwave drive signal [10], [12]. In addition, since no dc bias is needed, the PolM-based system is free from the bias drifting problem.

3. Experimental Results

An experiment based on the setup shown in Fig. 1 is performed. In the experiment, the wavelength of the CW laser source is set at 1556 nm to make it coincide with the center wavelength of the FBG notch filter. The power of the microwave drive signal is about 20 dBm. Considering that the half-wave voltage of the PolM is 6.5 V, the phase modulation index is calculated to be about 1.5. The powers of the light waves sent to the SOA and the SBS-assisted filter are about 6 and 16 dBm, respectively. The length of the SMF is about 24 km with a loss of about 7 dB. First, we adjust PC1 and PC2 to make the PolM operate as an equivalent MZM that is biased at the MATP. We also adjust PC3 to maximize the suppression ratio of the pump waves by the SBS-assisted filtering.

The optical spectra at the outputs of the FBG, the SOA, and the SBS-assisted filter, and the electrical spectrum of the beat note at the output of the PD are shown in Fig. 2, for which the frequency of the microwave drive signal is set at 4 GHz. From Fig. 2(a), we can clearly see that a symmetric optical spectrum consisting of only the two ± second-order sidebands is generated, and the optical carrier and other sidebands are significantly suppressed. Fig. 2(b) shows the optical spectrum of the signal after the SOA. Thanks to the FWM, two idle waves are generated. Due to the non-flat gain spectrum of the SOA, the spectral symmetry becomes poor. The spectral symmetry is critical to ensure an efficient SBS-assisted filtering to suppress the two pump waves since its suppression ratio is power-dependent. Fig. 2(c) shows the spectrum at the output of the SBS-assisted filter. As can be seen, the pump waves are suppressed, and only the idle waves are kept.

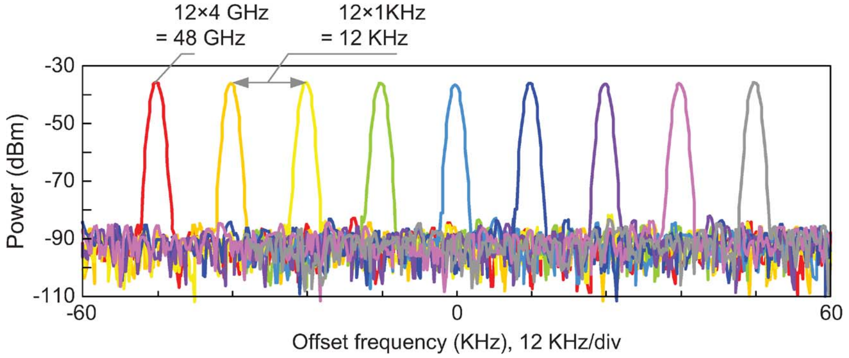

Fig. 3. Superimposed spectra of the generated frequency twelvetupled microwave signals with a 120-kHz spectral span when the frequency of the microwave drive signal is tuned from 4 to 4.000008 GHz with a 1-kHz interval. The RBW is 1.1 kHz.

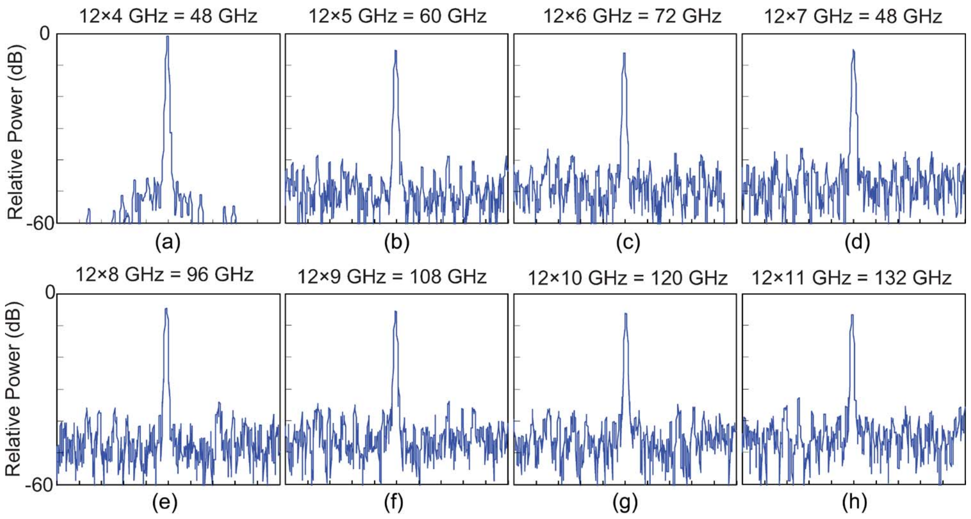

Fig. 4. Spectra of the generated frequency twelvetupled signals with a 1-kHz spectral span when the frequency of the microwave drive signal is tuned from 4 to 11 GHz with a 1-GHz interval. The RBW is 9.1 Hz.

The small peaks between the two idle waves are 1) the residual ± first- and ± fourth-order sidebands, which can be reduced by decreasing the phase-modulation index or by increasing the extinction ratio of the PolM and the notch depth of the FBG; 2) the residual pump waves, which can be further suppressed by increasing their powers before being injected into the SMF; and 3) the Stokes waves, which can be removed by reducing the end face reflections between the OCs and the SMF. In Fig. 2(d), a frequency-twelvetupled microwave signal by beating the two idle waves at the PD is generated.

The frequency tuning capability of the technique is evaluated. In the experiment, we tune the frequency of the microwave drive signal with two different tuning steps and record the electrical spectra of the generated frequency-twelvetupled microwave signals, which are shown in Figs. 3 and 4. When the frequency of the microwave drive signal is tuned from 4 to 4.000008 GHz with a tuning step of 1 kHz, a frequency twelvetupled signal from 48 to 48.000096 GHz is generated, as shown in Fig. 3. When the frequency of the microwave drive signal is tuned from 4 to 11 GHz with a tuning step of 1 GHz, a frequency twelvetupled signal from 48 to 132 GHz is generated.

The spectra of the generated microwave signals are also measured. As can be seen from Fig. 4, very narrow spectral peaks with a frequency span of only 1 kHz are observed.

4. Discussions and Conclusion

In the experiment, the notch width of the FBG and the bandwidth of the PD used are two factors that limit, respectively, the minimum (48 GHz) and the maximum (132 GHz) frequencies of the generated microwave signals. The notch width of the FBG is about 10 GHz. If the frequency of the microwave drive signal applied to the PolM is too low (< 4 GHz), not only the optical carrier but, in addition, the two ± second-order sidebands will be suppressed by the FBG notch filter. Therefore, the minimum frequency of the generated signal is about 48 GHz in this experiment; however, if we can replace the FBG notch filter with another adaptive wavelength-independent SBS-assisted filter, the limit on the minimum frequency would be eliminated.

The bandwidth of the PD is about 100 GHz in the experiment. When the frequency spacing between the two idle waves is larger than 100 GHz, the PD will not respond efficiently to the beat signal, and the power of the generated microwave signal would be extremely low. In the experiment, we can only detect the frequency up to 132 GHz. A photomixer with a bandwidth up to about 1 THz is now commercially available. The use of such a photomixer would enable our scheme to generate a signal with the highest frequency up to 1 THz.

In conclusion, an approach to achieving frequency-twelvetupling with large tunability was proposed and experimentally demonstrated. By a joint use of a PolM, an SOA, and an SBS-assisted filter, a frequency-twelvetupled microwave signal was generated. The key significance of the proposed approach is the simple frequency tuning and the large tunable range, which was enabled by the adaptive nature of the SBS-assisted filtering. The proposed system could be used for high-frequency electrical signal generation up to terahertz if a PD with a bandwidth extending to terahertz range is employed.

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