Millimeter-wave subcarrier generation utilizing four-wave mixing and dual-frequency Brillouin pump suppression

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Abstract. A novel photonic technique of 60-GHz millimeter-wave subcarrier generation base on four-wave mixing effect in a semiconductor optical amplifier (SOA) and a dual-frequency Brillouin fiber laser configuration is proposed. In this system, two new harmonic components with six times spacing of the microwave source frequency are created when an optical signal, generated by carrier-suppressed intensity modulation, is launched into the SOA. The two residual modulation sidebands are then suppressed by stimulated Brillouin scattering process, and the leaved idlers provide an millimeter-wave subcarrier signal.
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Subject terms: millimeter-wave; four-wave mixing; stimulated Brillouin scattering.

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1 Introduction

In recent years, the millimeter-wave band has drawn considerable attention because it shows great potential in future broadband wireless communication systems, in which generation and distribution of millimeter-wave signals using photonics is a key technique.[1] Various methods have been used to achieve this purpose. One of the conventional ways is optical harmonic frequencies generation assisted with a proper filtering system. There are several solutions for creating optical harmonic components, such as overdriving an electrooptic modulator (intensity or phase modulator) using a microwave signal with amplitude much higher than V_π;[2] four-wave mixing (FWM) in fiber[3] or semiconductor optical amplifier (SOA).[4] Among these techniques, FWM in SOA is a good candidate due to relatively simple operation condition, small package and low optical power requirement. For selectively filtering the optical frequency components, interleaves,[5] fiber Bragg gratings,[3] or arrayed waveguide gratings[2] are widely used. However, they usually need wavelength matching between the optical sources and the filters. Furthermore, the fixed bandwidths of these filters also limit their operation ranges. Brillouin selective sideband amplification technique is another way to implement filtering function, but stable external light sources are required to provide Stokes waves. In order to solve these problems, the technique of Brillouin carrier suppression could be employed for eliminating unwanted frequencies.[6,7]

In this letter, we propose a novel technique to generate a 60-GHz millimeter-wave photonic signal with an external modulation frequency at 10 GHz. The presented scheme utilizes a Mach–Zehnder modulator (MZM), biased for carrier suppression, to create two initial modulation sidebands. New optical harmonic components (idlers), separated by six times frequency of the modulation frequency, are generated through FWM effect in SOA. When the output of SOA is launched into a Brillouin fiber laser (BFL), residual power in the initial modulation tones can be depleted and the idlers are maintained. Therefore, the optical sidebands with six times frequency of the microwave drive signal can be obtained with quality governed by the electrical modulation signal source. The experimental setup is depicted in Fig. 1.

2 Operation Principle

As shown in Fig. 1, a laser emits at a single optical frequency ν_0. When the light is modulated with a microwave signal of frequency f in a MZM, the output optical field can be expressed as[3]

$$\begin{aligned} E(t) = {} & J_0\left(\alpha\frac{\pi}{2}\right)\cos\left(\frac{\pi}{2}\varepsilon\right)\cos(2\pi\nu_0 t) \\ & - J_1\left(\alpha\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}\varepsilon\right)\cos[2\pi t(\nu_0 - f)] \\ & - J_1\left(\alpha\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}\varepsilon\right)\cos[2\pi t(\nu_0 + f)] \\ & - J_2\left(\alpha\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}\varepsilon\right)\cos[2\pi t(\nu_0 - 2f)] \\ & - J_2\left(\alpha\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}\varepsilon\right)\cos[2\pi t(\nu_0 + 2f)] + \cdots, \end{aligned} \quad (1)$$

where ε is the normalized bias point of the modulator and α is the normalized amplitude of the driving voltage. The J_n is the Bessel function of the first kind and on the order of n. If we set $\varepsilon=1$, then the optical carrier will vanish, and two strong harmonic frequencies will appear at υ_0+f and υ_0-f with the amplitude determined by $J_1[\alpha(\pi/2)]$. Starting with the two input wavelengths, which acted as two

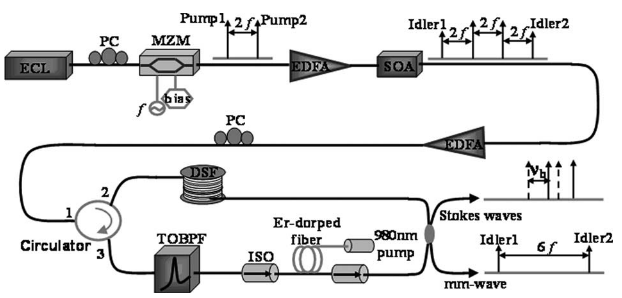

Fig. 1 Schematic diagram of mm-wave subcarrier generation.

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pump waves, idlers are produced by a FWM effect in SOA with frequencies of υ_0-3f and υ_0+3f.

For filtering the two residual pump waves, the stimulated Brillouin scattering (SBS) mechanism is introduced to deplete their power in a BFL cavity. It is well known that a pump wave with a frequency ν_0 is able to stimulate a moving acoustic grating in the transmission direction of the pump, which can reflect the pump wave by Bragg diffraction and with frequency-downshifted from the pump by ν_b. In this process, the pump power is transferred to the reflected light (Stokes wave); therefore, the pump attenuation is realized. According to this fact, one can design a BFL configuration, where the spontaneous Stokes waves are amplified and counterpropagated with the original signal. In this case, the corresponding pumps are greatly depleted and other components keep unchanged since Brillouin gain spectrum has very narrow bandwidth (dozens of megahertz).[6] It should be emphasized that the wavelength of the light source has no requirement because the wavelength spacing between Stokes waves and pumps is self-locked.

3 Experimental Results and Discussion

In our experiment, an external cavity laser output is at 1550.6 nm with a linewidth of ~100 kHz, which is amplitude modulated with a 10-GHz bandwidth $LiNbO_3$ MZM. Through optimizing the modulator bias and controlling the input polarization with a polarization controller (PC), the optical carrier is maximum suppressed and two first-order sidebands, separated by 20 GHz, are generated when a 10-GHz microwave signal is applied to the MZM. The resulting output spectrum is given by Fig. 2(a). Because of the optical insertion loss of the MZM, an isolated Er-doped fiber amplifier (EDFA) is employed and the power launched into SOA (I_{bias}=300 mA) is set at 3 dBm. According to the FWM effect in SOA, idlers are produced with the frequency difference of 60 GHz, which is shown in Fig. 2(b). The spectrum is asymmetric, owing to the existence of several nonlinear mechanisms in SOA, such as cross-gain modulation, spectral hole burning, and carrier heating,[8] but the two first-order idlers have an almost equal power level.

The output of SOA is amplified by an EDFA and enters port 1 of a circulator after a PC because of the polarization dependence of the SBS effect in fiber. The average optical power measured at port 2 is 17 dBm, which enables the pumps (two first-order sidebands) to generate spontaneous Stokes waves in 10-km-long dispersion shift fiber (DSF), and the Stokes waves will enter the port 3 of the circulator. A tunable optical bandpass filter (TOBPF) with a bandwidth of 0.2 nm is used for selecting the Stokes waves corresponding to the pumps and rejecting other components. According to the SBS mechanism that the higher the Stokes power is, the higher the pump attenuation is,[6] a 980-nm pumped EDFA is next to the TOBPF. After the Stokes waves coupled into the DSF from the opposite end of the pumps, a dual-frequency BFL is composed, where the loop gain is provided by EDFA and the Brillouin amplification.

Figure 2(c) presents the output of the SOA and the Stokes waves from the BFL. It is clear to see that two Stokes waves are generated, which are corresponding to the

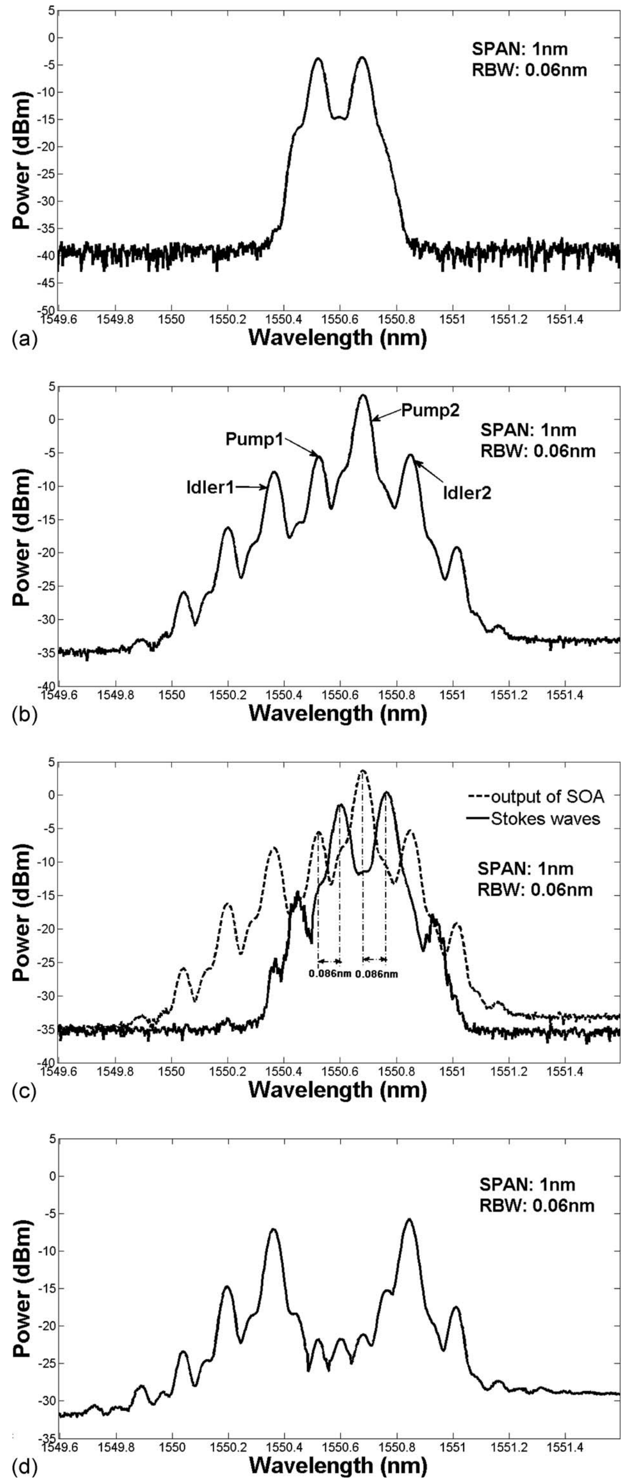

Fig. 2 Measured optical spectra: (a) The signal after MZM, (b) after SOA with FWM, (c) contrast between the Stokes waves from BFL and the output from SOA, and (d) the generated mm-wave after pump suppression in the BFL.

original modulation sidebands with ν_b of 10.7 GHz. Figure 2(d) shows the output optical spectrum of millimeter-wave subcarrier. In comparison to Fig. 2(b), it can be found that the two pump components are suppressed by about 16 and 20 dB, respectively, which have power about 15 dB lower

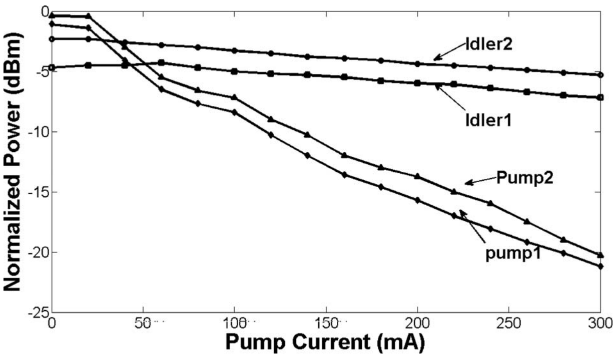

Fig. 3 Dependence of pumps; idlers on EDFA pump current.

than those of the two idlers. Therefore, the pump components will not provide significant contribution to further applications.

As was mentioned before, the pumps attenuation is dependent on the power of the Stokes waves; in other words, it is interrelated with the pump current of the 980-nm pump inside the BFL cavity. Figure 3 shows the dependence of pumps, idlers on the EDFA pump current of the BFL. Although the power of pump 2 is ~8 dB higher than that of pump 1 at the end of SOA, pump 2 will suffer greater attenuation by the spontaneous SBS process at zero pump current in the cavity, which leads to close power level between pump 1 and pump 2 at the beginning point of the measurement.

It is not demonstrated in this letter, however, an optical bandpass filter can be inserted after the SOA to eliminate the amplified spontaneous noise and unwanted high-order idlers. Optional wavelength suppression (one or more wavelengths) or spectral line-by-line operation is also available if the filter was replaced by a proper one in the BFL cavity.

4 Conclusion

Though creating harmonic frequencies by FWM effect in the SOA and suppressing two original modulation sidebands, millimeter-wave subcarrier at 60 GHz (six times of modulation frequency) is generated. Unlike conventional techniques, this scheme can realize multiwavelength filtering at the same time with no need of wavelength matching. Furthermore, this technique shows simple implementation and flexibility in the future millimeter-wave signal generation and distribution.

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