Millimeter-Wave Frequency Tripling Based on Four-Wave Mixing in a Semiconductor Optical Amplifier

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***Abstract*—An approach to generating a frequency-tripled millimeter-wave (mm-wave) signal based on four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) is experimentally demonstrated. In the proposed system, two phase-correlated optical wavelengths generated by an optical phase-locked loop (OPLL) are used as two pumps to generate the FWM process in the SOA. Two idlers with a wavelength spacing three times that of the two pump wavelengths are obtained. The two pump wavelengths are then removed by two cascaded fiber Bragg gratings serving as an optical notch filter. By beating the two idlers at a photodetector, an mm-wave with a frequency that is three times that of the OPLL reference source is generated.**

***Index Terms*—Fiber Bragg grating (FBG), four-wave mixing (FWM), microwave photonics, microwave signal source, optical phase-locked loop (OPLL), semiconductor optical amplifier (SOA).**

I. Introduction

IN MANY microwave systems such as broadband wireless access networks, software-defined radio, and radar systems, a high-quality millimeter-wave (mm-wave) source is essential [1]–[3]. So far, the generation of mm-wave signal with a frequency of tens of gigahertz is still a challenge for conventional electronics. Thanks to the high potential of mm-wave generation using optics, many research activities have been directed to the generation of mm-wave signal optically. Until now, the most common way to generate an mm-wave signal is to use the optical heterodyne technique [4]–[8]. The key problem associated with this technique is that the two wavelengths applied to a photodetector (PD) for heterodyne must be phase-correlated. To obtain two phase-correlated laser wavelengths, one may use the approaches such as optical injection locking [4], optical mode locking [5], or external modulation [6]. Two phase-correlated wavelengths can also be generated by using an optical phase-locked loop (OPLL) [7], [8]. In an OPLL, a high-quality microwave signal source is needed to provide a reference frequency. To generate a high-frequency microwave signal, the reference frequency should also be high. In [9], Hyodo and Watanabe proposed a technique to generate a high-frequency mm-wave signal using low-frequency reference sources. The system was composed of three laser diodes (LDs) and two OPLLs. The first OPLL was used to phase lock the first two LDs with a beat frequency of 110 GHz. The third LD was then phase locked by a second OPLL using a low-frequency degenerated four-wave-mixing (FWM) pair obtained from a semiconductor optical amplifier (SOA), to ensure the frequency separations of the three LDs at a ratio of 1 : 2. A high-frequency mm-wave signal was thus obtained by beating the wavelengths of two of the LDs. The proposed system was able to generate an mm-wave signal up to 330 GHz, but it needs three LDs and two OPLLs, which makes the system complicated and costly.

On the other hand, mm-wave signals can also be generated based on frequency multiplication. Recently, an mm-wave generation system based on frequency multiplication using fiber-based FWM was proposed [10]. This system uses the carrier-suppressed intensity modulation to generate two phase-correlated wavelengths, and then use these two wavelengths as two pumps to produce two idlers through the FWM process in a highly nonlinear fiber (HNLF). By beating the two idlers at a PD, a microwave signal with a frequency six times that of the electrical drive signal is obtained. However, the use of a fiber-based FWM scheme has some limitations. First, to generate the two idlers with a high power, the pump power should be very high and the HNLF length should be long, which makes the system bulky and costly. Second, the effect of simulated Brillouin scattering (SBS) in the HNLF impose a limit on the input pump power level, thus limiting the FWM efficiency.

In this letter, we propose an approach to generating a frequency-tripled mm-wave signal based on FWM in an SOA. The SOA-based FWM has the advantages of simple configuration, small package, easy to integrate, and more importantly, will not suffer from the SBS problem. In the proposed system, two phase-correlated wavelengths are generated by an OPLL, which are employed as two pumps to stimulate the FWM process in the SOA. The two generated idlers have a wavelength spacing three times that of the two pump wavelengths. The two pumps at the output of the SOA are then suppressed by an optical notch filter consisting of two cascaded fiber Bragg gratings (FBGs). By beating the two idlers at a PD, a frequency-tripled mm-wave is generated.

II. System Configuration

The configuration of the proposed mm-wave generation system is shown in Fig. 1(a). Two phase-correlated laser wavelengths are generated in an OPLL. The configuration of the OPLL is shown in Fig. 1(b), in which two external cavity semiconductor lasers with a very narrow linewidth (~50 kHz) are employed as the two optical sources and their phases are

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Color versions of Figs. 2–5 are available online at http://ieeexplore.ieee.org.

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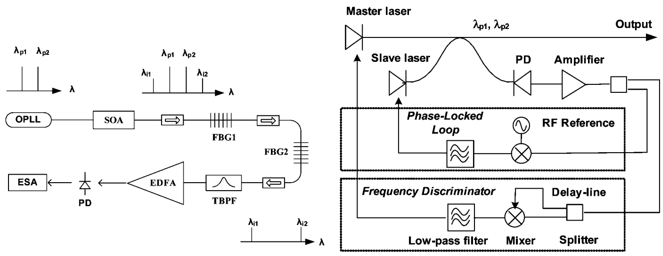
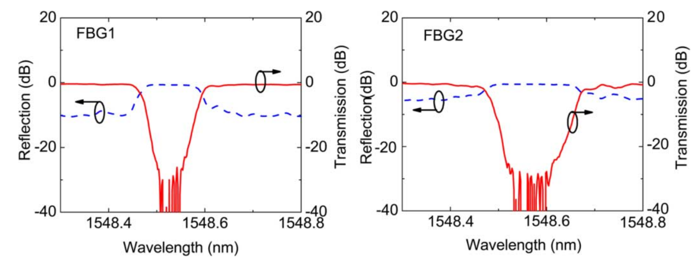


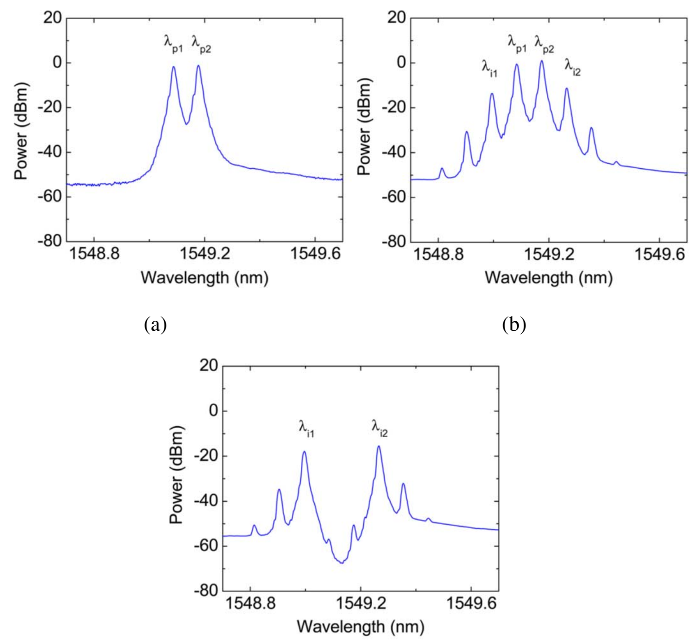
(a) (b)

Fig. 1. (a) Proposed mm-wave generation system. (b) Configuration of the OPLL.



(a) (b)

Fig. 2. Reflection and transmission spectra of (a) FBG1 and (b) FBG2.



(a) (b) (c)

Fig. 3. (a) Output optical spectrum of the OPLL; (b) spectrum at the output of the SOA, FWM-induced idlers are observed; (c) spectrum at the output of the cascaded FBGs, the two pump wavelengths are suppressed. The measurement resolution is 0.01 nm.

locked via the phase-locked loop, in which a feedback current is sent to the slave laser to adjust the phase of its output wavelength. To improve the frequency acquisition capability, a frequency discriminator is incorporated in the OPLL with a feedback current to adjust the frequency of the master laser. A detailed discussion on the OPLL can be found in [13]. The two output wavelengths of the OPLL, λ_{p1} and λ_{p2}, are 1549.084 and 1549.174 nm, which have a frequency difference of about 11.2 GHz. The use of the OPLL instead of using a system based on carrier-suppressed intensity modulation as the two pumps is that the output power of the OPLL is much higher than that at the output of the intensity modulator. Therefore, no optical amplifier is required between the OPLL and the SOA. In addition, in the carrier-suppressed intensity modulation system, the bias drift would result in an incomplete suppression of the optical carrier, which would lead to the generation of unwanted microwave frequency components. The two wavelengths are then fed to the SOA as two pumps. Thanks to the nonlinearity of the SOA, FWM occurs, leading to the generation of two idlers, λ_{i1} and λ_{i2}, as shown in Fig. 1(a). According to the characteristics of the FWM, the two idler wavelengths should satisfy: $\lambda_{i1} = 2\lambda_{p1} - \lambda_{p2}$ and $\lambda_{i2} = 2\lambda_{p2} - \lambda_{p1}$. The wavelength spacing between λ_{i1} and λ_{i2} is $|\lambda_{i2} - \lambda_{i1}| = 3|\lambda_{p2} - \lambda_{p1}|$. The SOA (JDS-U, CQF 872) used in the system has a peak small signal gain of 26.9 dB (at 1532 nm) and a 3-dB saturation power of 10.1 dBm at 300-mA driving current. In order to suppress the two pump wavelengths, two cascaded FBGs (FBG1 and FBG2) with a very high reflectivity $(R > 99.9\%)$ serving as an optical notch filter are used. The peak reflection wavelengths of FBG1 and FBG2 are 1548.532 and 1548.573 nm, respectively. The transmission and reflection spectra of the two FBGs are shown in Fig. 2(a) and (b). The bandwidths of FBG1 and FBG2 are 0.165 and 0.213 nm, which are wide enough to cover the two pumps but narrower than $|\lambda_{i2} - \lambda_{i1}|$; therefore, the two pump wavelengths could be sufficiently suppressed without causing much loss to the two idlers. It is noticed in the experiment that the amplified spontaneous noise (ASE) level at the output of the SOA is high, which will increase the noise level at the output of the PD. To suppress the ASE, a Fabry–Pérot tunable bandpass filter (TBPF) with a 3-dB bandwidth of about 0.5 nm is connected after the two FBGs. The isolator inserted between the SOA and FBG1 is to prevent light back-reflecting to the SOA. Two other isolators connected after FBG1 and FBG2 are to eliminate the Fabry–Pérot effect, which would lead to the instability of the system. An erbium-doped fiber amplifier (EDFA) is used after the TBPF to amplify the light to a satisfactory level before it enters the PD.

In the experiment, the power levels of the two wavelengths applied to the SOA are $P_{p1} = -1.5$ dBm and $P_{p2} = -1.0$ dBm. The optical spectrum shown in Fig. 3(a) is measured with an optical spectrum analyzer. The FWM with two idlers are observed at the output of the SOA when the driving current of the SOA is increased to 300 mA, as shown in Fig. 3(b). The wavelengths of the two idlers are 1548.994 and 1549.264 nm, which have a wavelength spacing three times that of the two pumps. The power levels of the two idlers are $P_{i1} = -13.6$ dBm and $P_{i2} = -11.1$ dBm, respectively. The two pumps at the output of the SOA are then filtered out by FBG1 and FBG2. In order to make the reflection wavelengths of the two FBGs be well aligned with the two pump wavelengths, the wavelengths of the two FBGs are slightly tuned by stretching the fiber. The optical spectrum at the output of the two FBGs is shown in Fig. 3(c). Comparing Fig. 3(b) and (c), it can be seen that the power level of the two pumps is suppressed by at least 50 dB, which is about 30 dB lower than that of the two idlers. Therefore, the

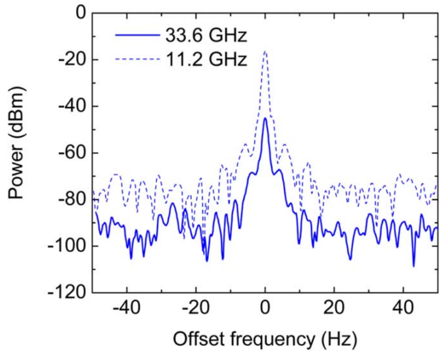


Fig. 4. RF spectra of the generated 33.6-GHz signal and the 11.2-GHz beat signal obtained directly from the OPLL.

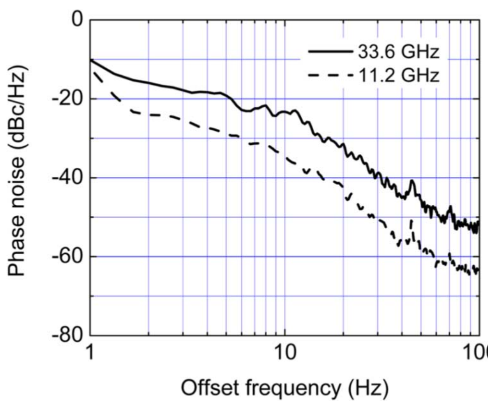


Fig. 5. Phase noise of the generated 33.6-GHz signal and the 11.2-GHz signal from the OPLL.

two residual pumps will not contribute to the mm-wave generation. Then, the output from the two FBGs is applied to the TBPF to suppress ASE of the SOA, and amplified by an EDFA. The output power of the EDFA is measured to be -0.6 dBm.

III. Result and Discussion

In the experiment, the frequency of the reference source in the OPLL is 11.2 GHz. By beating the two idlers at the PD, an mm-wave signal with a frequency of 33.6 GHz (three times the frequency of the reference source of the OPLL) is successfully obtained, as shown in Fig. 4. The phase noise performance of the generated 33.6-GHz signal and the 11.2-GHz signal from the OPLL are studied using an electrical spectrum analyzer (ESA) (HP 8565E). The noise values are obtained from the spectrum measurements with the ESA resolution set at 1 Hz, by calculating the ratio between the power at the offset frequency and the peak power, averaged over 50 measurements. As can be seen in Fig. 5, the generated 33.6-GHz signal has an about 10-dB phase noise degradation compared with the 11.2-GHz signal. Theoretically, the phase noise of a frequency-tripled signal will have a phase noise degradation of about $10\log_{10}(3^2) = 9.5$ dB. The measurement is consistent with the theoretical prediction. In the experiment, a slight fluctuation of the amplitude of the 33.6 GHz is observed, which is caused by the polarization state variations of the two wavelengths from the OPLL. It is believed that by using polarization-maintaining (PM) fibers in the OPLL, the amplitude stability can be improved.

Apart from the 33.6-GHz signal, a microwave signal at 11.2 GHz is also observed when displaying the spectrum in a larger frequency span, which is resulted from the beating between the two idlers and the higher order FWM frequencies, generated by the cascaded FWM processes in the SOA. By using a more sophisticated filtering system [9], these unwanted frequencies can be well suppressed.

IV. Conclusion

An optical system that could generate a frequency-tripled mm-wave based on FWM in an SOA was demonstrated. In this system, two phase-correlated wavelengths were generated by an OPLL, which were used as the two pumps, applied to the SOA to stimulate the FWM process. Two idlers with a wavelength spacing three times that of the two pumps were obtained. In the experiment, when the frequency of the OPLL reference source was tuned at 11.2 GHz, a frequency-tripled mm-wave signal at 33.6 GHz was generated. The phase noise performance of the generated 33.6-GHz signal was investigated. It was found that phase noise performance was about 10 dB poorer than that of the input 11.2-GHz signal, which was consistent with the theoretical prediction.

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