Local Oscillator Free Frequency Up-Conversion at Millimeter-Wave Band

Wang Wenrui, Yu Jinlong, Wu Bo, Han Bingchen, Wang Ju, Ye Lingyun, and Yang Enze

***Abstract*— We have demonstrated all-optical frequency up-conversion at millimeter-wave band without using local oscillators. By launching a low bit rate signal into a Fabry–Pérot laser diode (FP-LD), a microwave subcarrier is generated based on the four wavelength mixing and injection mode locking. Due to the dynamic charge carrier density response during the injection locking, the wavelength of the leading part of the subcarrier will be red-shifted while that of the falling part will be blue-shifted. By compensating the generated chirp with a suitable negative dispersion device, the time-domain pulses will be compressed and the second harmonic of the subcarrier will be generated. A polarization interferometer is used to further suppress the foundational frequency. In our experiment, a subcarrier of 30.8 and 34.8 GHz is obtained by launching a 2.5-Gb/s NRZ signal into the FP-LD. We also show that the photonic frequency up-conversion can go up to ∼60 GHz with the proposed scheme.**

***Index Terms*— Microwave photonics, all-optical up-conversion, injection locking, Fabry–Pérot laser diode.**

I. Introduction

THE capacity of the data traffic grows dynamically in recent years because of the emerging demands in video-based applications and multimedia services. As a result, optical fibers are deployed more and more in access networks due to their much larger bandwidth–distance product than those of twisted-pair copper cables. On the other hand, broadband wireless access, especially at millimeter (mm) waveband, is another trend in next generation access networks, because it offers end user greater flexibility and convenience. Therefore, the integration of wireless and optical networks, namely hybrid optical and wireless access networks (HOWAN) [1]–[3], becomes a promising solution for next generation access network.

In the HOWAN, it is interesting to extend the subcarrier frequency of the wireless signal to mm waveband as it offers both mobility and large bandwidth at the same time. However, the implementation cost of mm-wave systems based on high-frequency electrical devices is still very high. From the economic perspective, it is desirable to generate the mm-wave subcarrier and also up-convert the intermediate frequency to the mm-wave band using optical means. Over the past few years, several approaches have been proposed, such as using Mach-Zehnder modulator [4], electro-absorption modulator [5], [6], semiconductor optical amplifier [7] and so on. However, most of them still need high-frequency local oscillators, which is not cost-effective.

In our previous works, we have reported a local oscillator free optical frequency up-conversion based on injection locking of Febry-Perot laser diode (FP-LD) [8]. However, it is hard to directly achieve mm-wave subcarrier using the method, since the FP-LD will not be mode-locked if the wavelength of the injected signal is too far from the lasing mode of the FP-LD. In this letter, we propose a novel and simple way to up-convert a 2.5 Gb/s NRZ signal to mm-wave band and the subcarriers of 30.8 GHz and 34.8 GHz are obtained. The proposed scheme can easily scale to higher-frequency subcarrier up-conversion and we show the photonic frequency up-conversion to ∼60 GHz can be achieved.

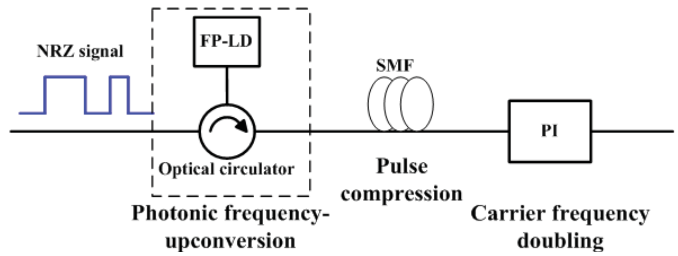

Fig. 1. Block diagram of frequency up-conversion in mm-wave band.

II. Operation Principal

Fig.1 shows the block diagram of the local oscillator free optical frequency up-conversion to mm-wave band based on injection locking of a FP-LD, which mainly consists of photonic frequency up-conversion, pulse compression and carrier frequency doubling.

The operation principal of the photonic frequency up-conversion based on FP-LD has been explained in detail in [8]. Based on a combination of four wavelength mixing (FWM) and injection mode locking [9], [10], one of FP-LD's lasing mode λ_0 is mode locked to the harmonic frequency of the data-modulated external injection light centered at λ_s. The frequency of the generated microwave subcarrier equals to the frequency difference of λ_0 and λ_s. However, the efficiency of

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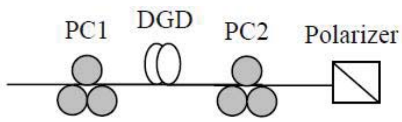

Fig. 2. Setup of polarization dependent delay interferometer.

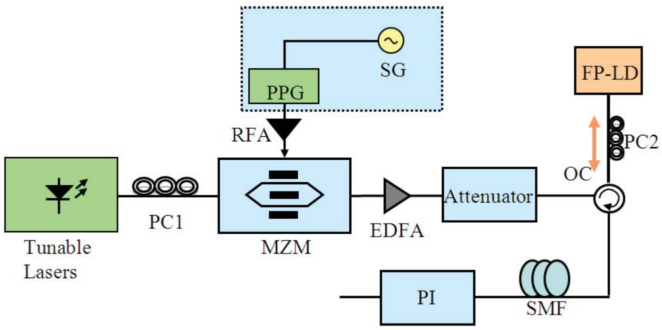

Fig. 3. Experimental setup. (PC: polarization controller; MZM: Mach-Zehnder modulator; SG: Signal generator; PPG: pseudorandom pattern generation; RFA: radio-frequency amplifier; EDFA: Erbium doped fiber amplifier; OC: optical circulator; SMF: single mode fiber; PI: polarization interferometer.)

FWM deceases when λ_0 and λ_s are away from each other and the FP-LD will not be mode locked if the frequency difference of λ_0 and λ_s is too much. Photonic frequency doubling is a simple and low-cost method to further extend the frequency of subcarriers to mm-wave band. Here, we achieve frequency doubling using pulse compression and polarization interferometer (PI).

Due to the dynamic charge carrier density response during the injection locking of FP-LD, the wavelength of the leading part of subcarrier will be red-shifted while that of falling part will be blue-shifted. With a suitable negative dispersion device, the time-domain pulses will be compressed and the 2nd harmonic of the subcarrier will be generated. The amount of the dispersion should be optimized to achieve a pulse duty cycle of ∼19% for Gaussian pulses and the compressed pulses should not be too short, otherwise the power will be transferred to higher harmonics.

However, the fundamental frequency still remains after the pulse compression. Therefore, a PI is used to suppress the fundamental frequency while keeping the 2nd harmonic. The PI is consists of two polarization controllers (PC), a programmable differential-group-delay (DGD) module (or polarization maintaining fiber) in between, and a polarizer, as shown in Fig.2. The PI has a sinusoidal transfer function, with a free spectrum range (FSR) inversely proportional to the DGD and extinction ratio determined by the polarization state of the polarizer with respect to the main polarization axis of the DGD [11], [12]. If the subcarrier frequency and its 2nd harmonic are aligned with the stopband and passband of the PI respectively, the fundamental frequency can be suppressed.

III. Experiment Setup and Results

The experimental setup is depicted in Fig.3, which mainly consists of a tunable laser source (TLS), a Mach–Zehnder $LiNbO_3$ intensity modulator, an erbium-doped fiber amplifier (EDFA), an optical attenuator, an optical circulator, a FP-LD, a 10km long single mode fiber (SMF), and a PI with tunable DGD module. A continuous-wave light generated from a TLS is modulated to a 2.5 Gb/s NRZ-OOK signal (PRBS of 2^7-1) in the $LiNbO_3$ intensity modulator. An EDFA together with a variable attenuator is employed to control the injection power. The NRZ signal is injected into the FP-LD through the port two of the optical circulator (OC). Another polarization controller (PC2) is used to align the signal polarization to the transverse-electric (TE) polarization mode of FP-LD in order to enhance the FWM effects. The effective injected power is about 10dBm when the attenuation is 0dB and the polarization of the lightwave perfectly matches the TE mode of FP-LD. A commercially available FP-LD with a FSR of about 171 GHz is biased at 40 mA (the threshold current is 10 mA).

Firstly, the TSL is set to be centered at 1551.142 nm and the injection power is adjusted to 5.2dBm. When the sideband of the injected signal is locked to one of the lasing mode of the FP-LD, a side mode suppression ratio (SMSR) of 37 dB can be achieved, as shown in Fig.4(a) and the generated microwave subcarrier is synchronized to the injected 2.5Gb/s NRZ data signal. As shown in Fig.4(b)-(d), the up-converted signal is clearly seen on the oscilloscope using the same trigger as the original data. The temporal waveform of injection 2.5Gb/s data signal with a pattern of "0110110101101" is shown in Fig.4(b). As shown in Fig.4(c)-(d), the injected data is up-converted to a generated 15.4 GHz microwave subcarrier. The output power of up-converted signals is 5dBm, achieving a RF signal conversion efficiency of about −0.2dB. The RF spectrum of the up-converted signal is measured, as shown in Fig.5(a). Microwave subcarrier of 15.4 GHz is clearly seen in the spectrum and there are no frequency components at harmonics.

Subsequently, the up-converted signal generated from the FP-LD passes through a 10-km long SMF for pulse compression, which is just a rough compensation and could be better optimized. Nevertheless, the pulse width is compressed from 32.5ps to 21ps, as shown in Fig.4(e). The RF spectrum of the compressed signal is depicted in Fig.5(b), in which more than 20dB enhancement in 2nd harmonic of the subcarrier can be clearly seen. Note that a compact dispersion media, such as chirped fiber bragg grating with suitable dispersion could be used for future integration.

Finally, a PI is used to suppress fundamental frequency and keep the 2nd harmonic. The DGD of the PI is set to be 32.5ps, which is equal to 1/30.8GHz. By properly adjust the polarization, the frequency of the subcarrier is doubled, as shown in Fig4(f). Fig.5(c) provides the spectrum of the signal after PI. The fundamental frequency at 15.4GHz is suppressed by ∼18dB and the 2nd harmonic at 30.8GHz is kept. The single-sideband (SSB) phase noise before and after the frequency doubling is −88.67dBc/Hz@10kHz and −83.33 dBc/Hz@10kHz away from the subcarriers respectively, which are shown in Fig. 5(d). The slightly degradation of phase noise performance after the frequency doubling is mainly due to the losses of the SMF and the PI.

The frequency of the up-converted subcarrier can be tuned by adjusting the injection wavelength and power. Keeping the

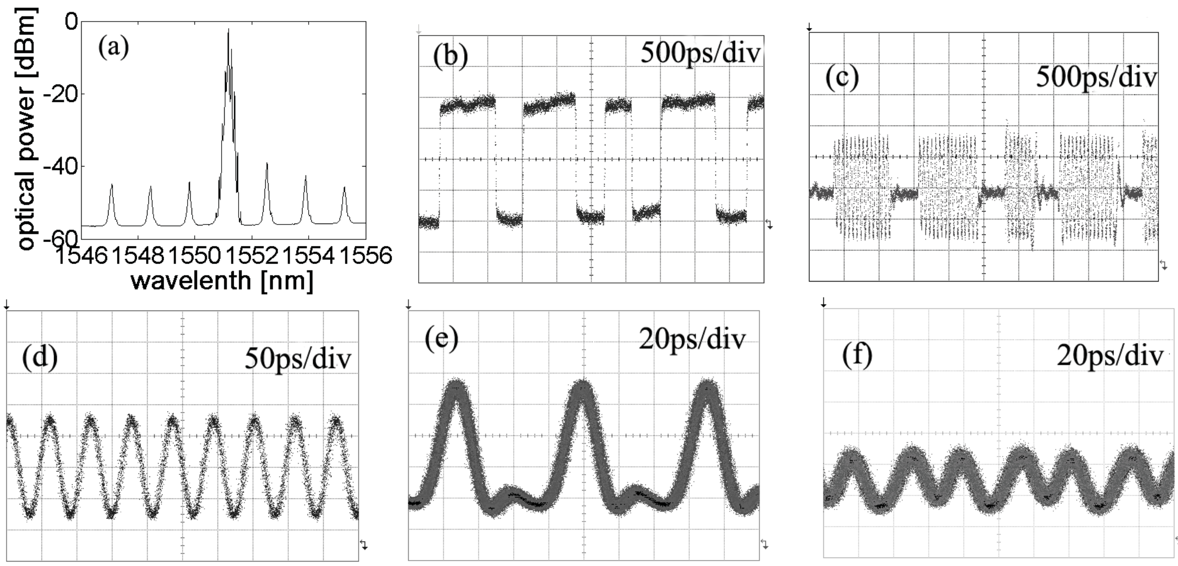

Fig. 4. (a) Optical spectrum of the injection locking of F-P laser, (b) waveform of injected NRZ signal, (c) waveform of up-converted signal output from F-P laser, (d) zoomed waveform of the subcarrier of the up-converted signal, (e) subcarrier after pulse compression, and (f) frequency doubling signal after PI.

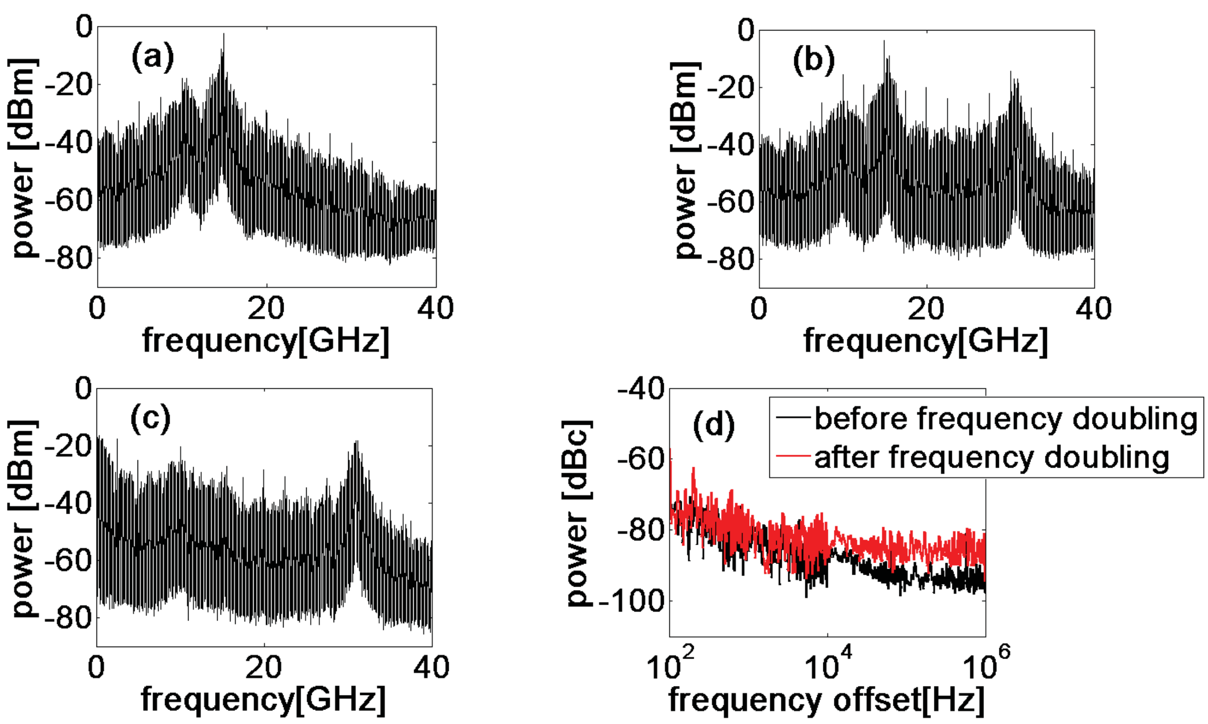

Fig. 5. Electrical spectra of (a) signal output from injection locking F-P laser, (b) after pulse compression by 10km SMF, (c) after frequency doubling by PI, and (d) single-sideband phase noise of the subcarrier.

injection wavelength at 1551.142nm and increasing the injection power to 9.2dBm, the subcarrier frequency generated by FP-LD is increased to 17.4GHz. Fig.6(a) shows the electrical spectrum of the up-converted signal and the inset of Fig.6(a) shows the waveform of subcarrier. The frequency of the subcarrier can still be doubled by pulse compression and the PI. Fig.6 (b) and (c) show the electrical spectra and waveforms of the signal after 10-km SMF and after PI with a DGD of 28.7 ps, respectively. A 23 dB enhancement of the 2nd harmonic and a 19 dB suppression of the fundamental frequency are achieved by pulse compression and PI, respectively.

Actually, the frequency of up-conversed subcarrier can go even higher. We increase the bias current of FP-LD to 60mA. The injection wavelength and power is set to be 1552.649nm and 8.3dBm, respectively. Up-converted signal with subcarrier frequency of 29.3GHz is achieved. Fig.7 (a) and (b) show the waveform and the electrical spectrum of the subcarrier, respectively. Since the SMF and PI are passive devices, there

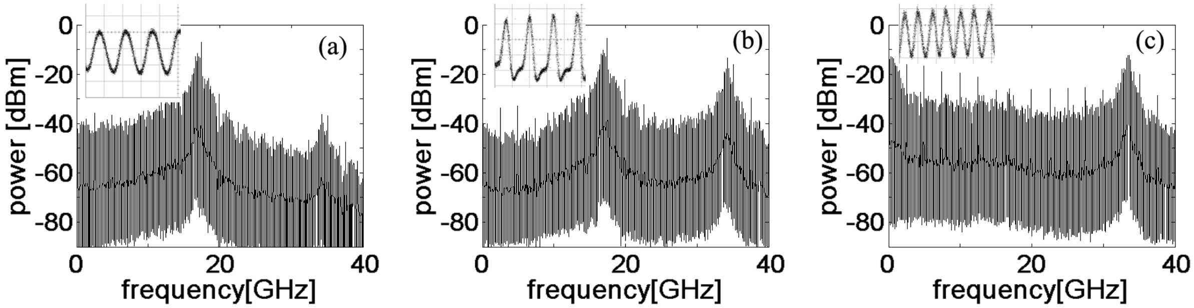

Fig. 6. Electrical spectra and waveforms of (a) signal output from injection locking F-P laser, (b) after pulse compression by 10km SMF, and (c) after frequency doubling by PI.

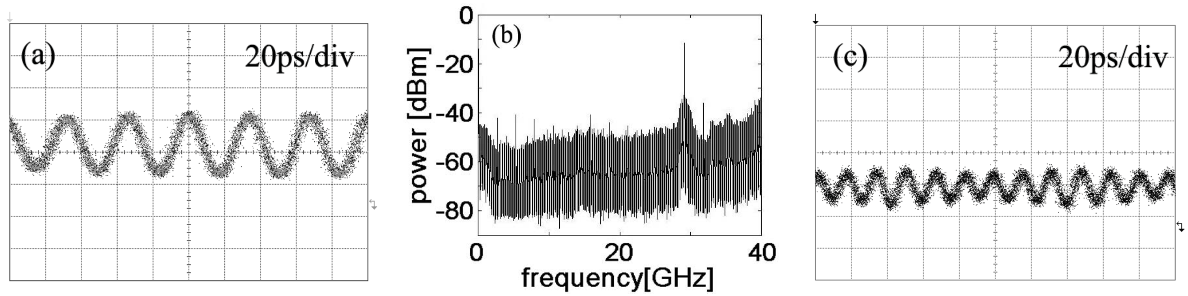

Fig. 7. (a) Waveform of up-converted signal output from FP-LD, (b) electrical spectrum of the up-converted signal, and (c) zoomed waveform of the subcarrier.

is no foundational limitation of the data rate. Although our RF spectrum analyzer with a bandwidth limitation of 40GHz cannot measure the spectrum after pulse compression and PI, the 58.6GHz frequency doubled subcarrier after dispersion and the PI can be observed by the oscilloscope, as shown in Fig.7(c). The bandwidth of the oscilloscope (Agilent 86100) is also 40GHz, so the observed signal seems to be weak, but the 58.6GHz frequency doubling can still be seen.

IV. Conclusion

We have demonstrated a local oscillator free optical frequency up-conversion at millimeter-wave band based on injection locking of a FP laser. By injection locking of a FP-LD with NRZ baseband signal, RF signals with tunable subcarrier is achieved without using local oscillators. We also generate the 2nd harmonic of the subcarrier using pulse compression in negative dispersion device and suppress the fundamental frequency using polarization interferometer. As a result, the frequency of the subcarrier is double and extended to millimeter-wave band. By adjusting the injection optical power, RF signals with subcarrier frequency of 30.8GHz and 34.8GHz are achieved. The up-conversion frequency can go up to ∼60GHz by adjusting bias current of the FP-LD, the injection power and wavelength. We believe the proposed scheme is a cost-effective solution for frequency up-conversion in HOWAN.

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