Tunable frequency upconversion based on a directly modulated DFB-LD and FP-LD injection

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We show a simple, convenient, and cost-effective scheme for tunable frequency upconversion at millimeter-wave band without a local oscillator. By launching a 2.5-Gb/s directly modulated baseband signal into a Fabry–Pérot laser diode (FP-LD), the mode of the FP-LD is locked by the high-order sideband of the injected signal. The beating frequency of the injection-locked mode and the injected signal can generate upconversion subcarriers. In our experiment, tunable frequency subcarriers of 28.4, 29.3, and 30.5 GHz are obtained without any radio-frequency local oscillator. The single sideband phase noises of −83.88, −76.36, and −78.54 dBc/Hz @ 10 kHz (at 28.4-, 29.3-, and 30.5-GHz subcarriers, respectively) are shown. The proposed scheme has potential to generate much higher frequency carriers.

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With the development of broadband services (e.g., video on demand, high-definition TV, and 3D-TV), the demands of broader bandwidth, especially wireless bandwidth, increase dramatically. The recent wireless access networks need to connect these services with the fixed and mobile end users[1,2]. Radio over fiber (RoF) technology provides ultra-broadband and can generate microwave signals at millimeter-wave band. The RoF architecture, an integration of wireless and fiber optic networks, is an essential technology for the provision of untethered access to broadband wireless communications in a range of applications, offering advantages such as increasing capacity and mobility as well as reducing complexity of data processing in the access network. These earlier-mentioned systems need to offer data transmission capacities well standard to the present wireless network. Nowadays main wireless standards such as IEEE 802.16 mobile and fixed WiMAX offer 2- to 66-GHz carrier frequencies[3].

A key problem of the RoF is how to upconvert a relative low bit-rate data signals to stable and cost-saving millimeter-wave band carriers using optical means. In recent years, several frequency upconversion techniques have been reported using Mach–Zehnder modulator (MZM)[4], semiconductor optical amplifier[5], gain-switched laser[6], and injection-locked semiconductor laser[7]. However, most of them need high-frequency local oscillators, which are not only complex but also costly.

In our early studies[8,9], all-optical frequency upconversion are reported by injecting a low bit-rate signal into a Fabry–Pérot laser diode (FP-LD) without any radio-frequency (RF) local oscillator. The baseband signals are generated in an external MZM. Moreover, the carrier density of a directly modulated distributed feedback (DFB) LD varies with the driver current[10], which result in the frequency modulation of the emitting light. Hence, if a directly modulated DFB-LD is used in a frequency upconversion scheme, it can provide one baseband signal with potentially much broader optical spectrum, which means a higher frequency upconversion. In this letter, we show a simple and cost-effective way to upconvert a 2.5-Gb/s nonreturn-to-zero (NRZ) on–off keying (OOK) signal to millimeter-wave band based on a directly modulated DFB-LD and an FP-LD. Tunable frequency subcarriers of 28.4, 29.3, and 30.5 GHz are obtained without any RF local oscillator. The single sideband phase noises of −83.88, −76.36, and −78.54 dBc/Hz @ 10 kHz (at 28.4-, 29.3-, and 30.5-GHz subcarriers, respectively) are shown.

The schematic of the operation principle is shown in Fig. 1(a). In FP-LD injection experiments, the stable locking area is often in the negative frequency detuning range ($\omega_s - \omega_0 < 0$)[9,11]. One optical data signal at the center wavelength of λ_s, which is generated by a directly modulated laser, has many high-order sidebands. The external injection data signal is launched into a free-running FP-LD. When one high-order sideband of the injected data signal is located in the locking area of one longitudinal mode (λ_0) of the free-running FP-LD, it can lock the wavelength and phase of λ_0 easily. The stable microwave subcarrier is achieved and $f_{RF} = f_s - f_0$.

One optical data signal at the center wavelength of λ_s has many high-order sidebands. Assuming the data signal is launched into a free-running FP-LD, when one high-order sideband at λ_0 of the injected data signal is close to one of the longitudinal modes of the free-running FP-LD, that mode will be locked to λ_0. The other free oscillating longitudinal modes will be suppressed[12]. At the same time, the phase of the locked longitudinal mode is also synchronized with λ_s due to the fixed phase relationships between the sidebands. The upconversion subcarrier is generated by the beating of injection-locking mode λ_0 and λ_s. When adjusting the wavelength of the FP-LD to make it aligned with different high-order sidebands of the data signals, subcarriers of different frequencies can be generated as long as the FP-LD is locked.

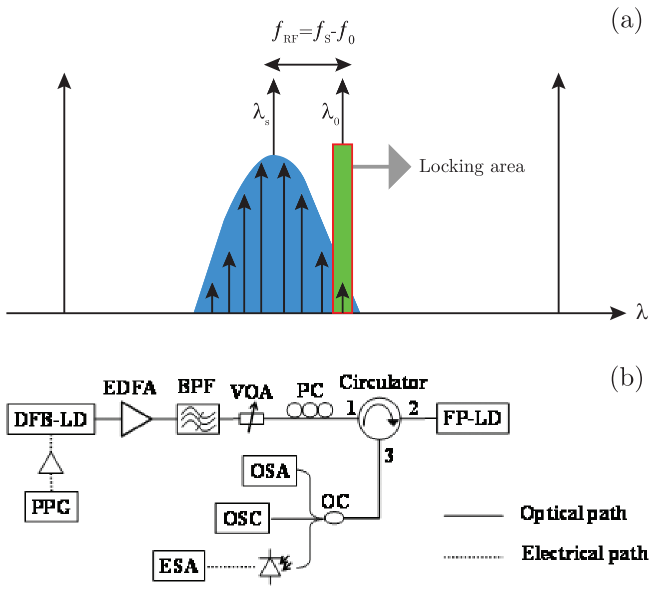


Fig. 1. (a) Schematic of the operation principle. (b) Experimental setup of the tunable frequency upconversion based on a directly modulated DFB-LD and FP-LD injection.

The experimental setup of the tunable frequency upconversion based on a directly modulated DFB-LD and FP-LD injection is shown in Fig. 1(b). A DFB-LD generates light at the wavelength of 1544.95 nm. It is directly modulated by a 2.5-Gb/s pseudorandom bit sequence (2^7-1) signal, which is generated from the pseudorandom pattern generator (PPG) and is driven by an amplifier. The bias current of the DFB laser is 40 mA. The 2.5-Gb/s optical data signal with NRZ-OOK modulation format is amplified by an erbium-doped fiber amplifier (EDFA). An optical bandpass filter (BPF) is placed after the EDFA to block the amplified spontaneous emission noise. A variable optical attenuator (VOA) is used to adjust the injection power. The polarization state of the 2.5-Gb/s signal is optimized by a polarization controller (PC) to enhance the effective power on the transverse-electric mode polarization[9]. Then the 2.5-Gb/s optical baseband signal goes into port 1 of a circulator (the isolation from port 1 to port 3 is about 40–50 dB). At port 2 of the circulator, the baseband signal is launched into a multi-quantum-well FP-LD with 171-GHz free spectrum range when at the bias of 70 mA (the threshold current of the FP-LD is 10 mA). Figures 2(a) and (b) depict the spectra of the input baseband optical data signal (λ_s at 1544.95 nm) and that of the free-running FP-LD. The power of the injected signal is 2.4 dBm. As shown in Fig. 2(c), the mode at 1545.178 nm (λ_0) of the FP-LD is locked by the high-order sideband of the input signal. The side-mode suppression ratio of injection locking is measured to be 19.37 dB. The frequency upconverted signal is obtained at port 3 of the circulator. The frequency of the subcarrier is determined by the beat of λ_0 and λ_s (28.4 GHz in Fig. 2(c)). The beating of the two lights (λ_0 and λ_s) also leads to the carrier density variation in FP-LD, which results in the four-wave mixing effect[9]. Thus, idlers are generated and there exist some small peaks on the spectrum of generated upconverted optical signal, as shown in Fig. 2(c). The frequency upconverted signal can be observed using the oscilloscope under the same synchronous trigger. It is also analyzed by an optical spectrum analyzer (OSA) and by an electrical spectrum analyzer (ESA) after being detected by a photodetector.

The waveform of the data signal at 28.4-GHz microwave subcarrier and that of the zoomed subcarrier are shown in Fig. 3(a). The original 2.5-Gb/s baseband data signal is depicted together (red line) and the codes "111100101100" are selected for comparison. It can be concluded that the frequency upconverted signal matches the baseband data well. The electrical spectrum of the upconverted signal, 28.4 GHz, is shown in Fig. 3(b). Subsequently, the single sideband phase noise of the subcarrier is −83.88 dBc/Hz @ 10 kHz, as shown in Fig. 3(c).

By changing the wavelength of the FP-LD slightly, the generated subcarriers at 29.3 and 30.5 GHz are obtained, and the results are shown in Figs. 4 and 5, respectively. The injection power is optimized to be 7.4 dBm (for 29.3 GHz) and 7.6 dBm (for 30.5 GHz) to make sure the FP-LD is in the locked state. The single sideband phase noises of the 29.3 and 30.5 GHz subcarriers are measured to be −76.36 and −78.54 dBc/Hz @ 10 kHz, respectively. We believe that the upconversion frequency can go up to be even higher if the performance of the directly modulated DFB-LD is optimized to get much broader optical spectrum.

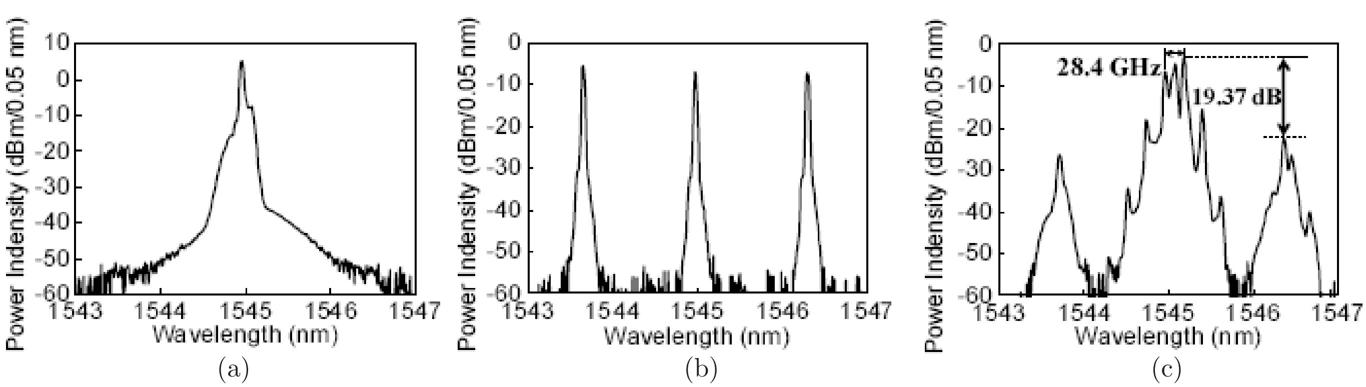
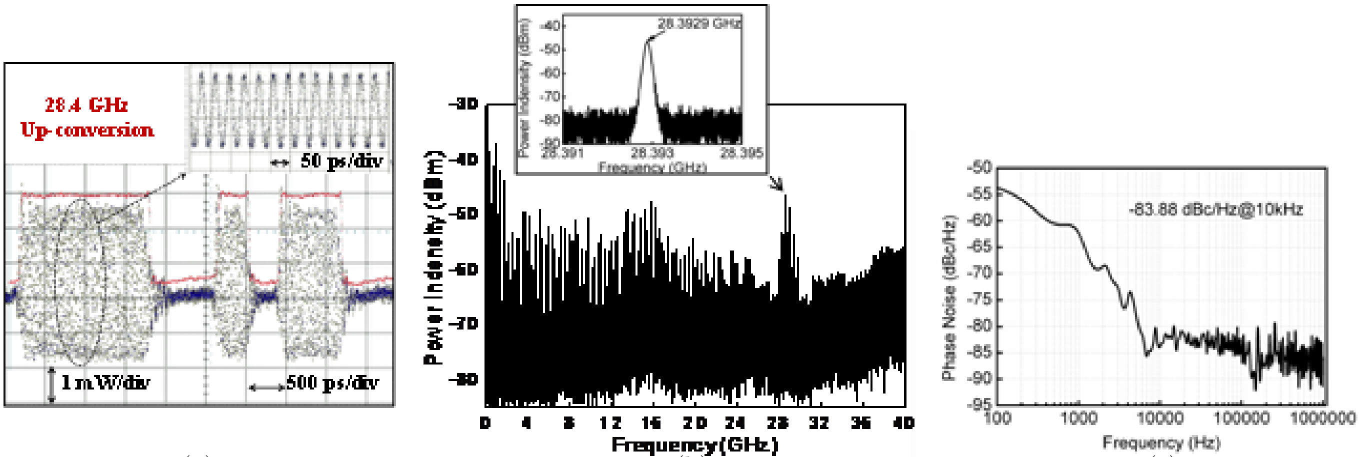
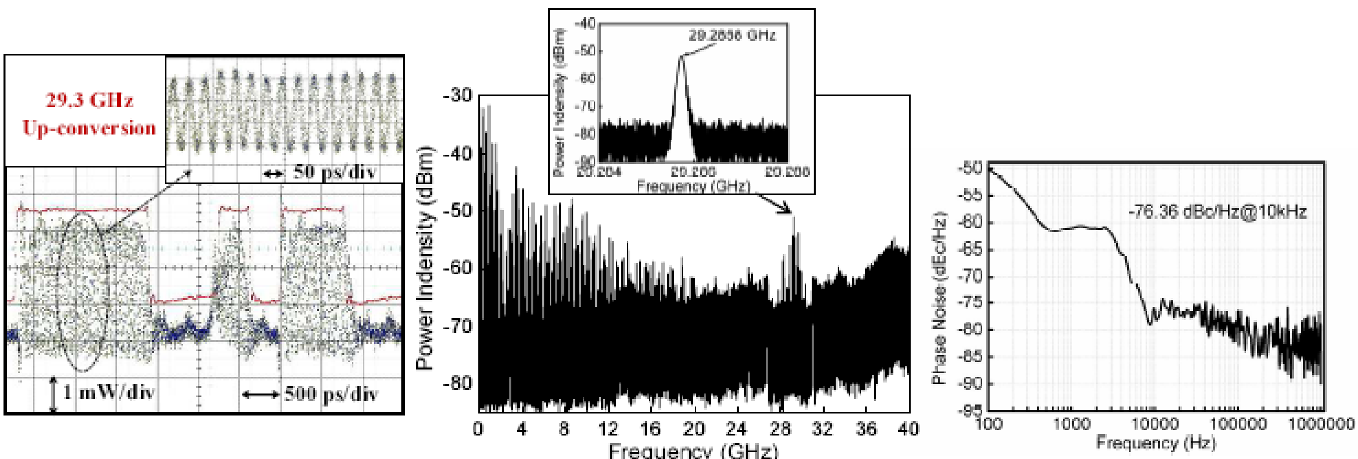


Fig. 2. Spectra of (a) the 2.5-Gb/s optical baseband signal, (b) free-running FP-LD, and (c) frequency upconverted signal at port 3 of the circulator.



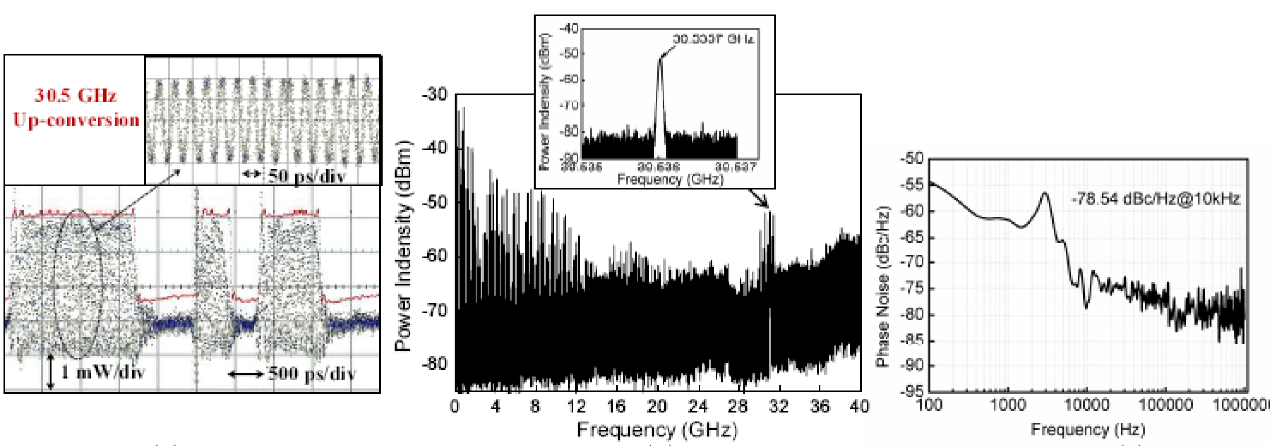
(a) (b) (c)

Fig. 3. (a) Waveform of the data signal at 28.4-GHz subcarrier compared with the original baseband signal and zoomed waveform of the subcarrier, (b) electrical spectrum of the upconverted signal at 28.4 GHz, and (c) single sideband phase noise of the subcarrier at 28.4 GHz.



(a) (b) (c)

Fig. 4. (a) Waveform of the upconverted signal at 29.3-GHz subcarrier compared with the original baseband signal and zoomed waveform of the subcarrier, (b) electrical spectrum of the upconverted signal at 29.3 GHz, and (c) single sideband phase noise of the subcarrier at 29.3 GHz.



(a) (b) (c)

Fig. 5. (a) Waveform of the upconverted signal at 30.5-GHz subcarrier compared with the original baseband signal and zoomed waveform of the subcarrier, (b) electrical spectrum of the upconverted signal at 30.5 GHz, and (c) single sideband phase noise of the subcarrier at 30.5 GHz.

In conclusion, a 2.5-Gb/s optical NRZ-OOK data signal is converted into a tunable millimeter-wave band subcarrier (potentially up to be higher than 30 GHz) based on a directly modulated DFB-LD and injection FP-LD. The scheme is simple, convenient, and cost-effective, and it can be integrated, which may find important applications in future, with the downlink in optical transmission for wireless communication systems. The temperature of the directly modulated laser and the FP-LD is controlled precisely. The wavelength (frequency) drift is less than 0.08 nm (approximate 10 GHz) in long term. However, as long as the sideband of the baseband signal is within the locking area, the FP-LD will be locked and this upconversion system can work well. How to more precisely slow the FP-LD frequency drifts needs further research in future.

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References

1. C. Tang, R. Li, Y. Shao, N. Chi, J. Yu, Z. Dong, and G. K. Chang, Chin. Opt. Lett. **11**, 020608 (2013).
2. T. M. F. Alves, M. Morant, A. V. T. Cartaxo, R. Llorente, P. Cluzeaud, and R. Sambaraju, Chin. Opt. Lett. **11**, 100605 (2013).
3. R. Karthikeyan and S. Prakasam, Int. J. Comput. Appl. **64**, 14 (2013).
4. M. Weiß, M. Huchard, A. Stöhr, B. Charbonnier, S. Fedderwitz, and D. S. Jäger, J. Lightwave Technol. **26**, 2424 (2008).
5. H.-J. Kim, S.-H. Lee, H.-J. Song, B.-M. Jung, and J.-I. Song, in *Proceedings of OptoElectronics and Communication Conference (OECC)* WJ5 (2009).
6. H. Shams, P. M. Anandarajah, P. Perry, and L. P. Barry, IEEE Trans. Microwave Theory **58**, 3372 (2010).
7. M. I. Memon, G. Mezosi, B. Li, D. Lu, Z. Wang, and S. Yu, IEEE Photon. Technol. Lett. **21,** 733 (2009).
8. W. Wang, J. Yu, B. Wu, B. Han, J. Wang, L. Ye, and E. Yang, IEEE Photon. Technol. Lett. **25**, 1377 (2013).
9. B. Wu, J. Yu, Z. Zhang, B. Han, J. Luo, J. Guo, W. Wang, J. Wang, and E. Yang, IEEE Photon. Technol. Lett. **22,** 1027 (2010).
10. J. C. Cartledge and R. C. Srinivasan, J. Lightwave Technol. **15,** 852 (1997).
11. J. M. Liu, H. F. Chen, X. J. Meng, and T. B. Simpson, IEEE Photon. Technol. Lett. **9,** 1325 (1997).
12. R. Gordon, IEEE J. Quantum Elect. **42**, 353 (2006).