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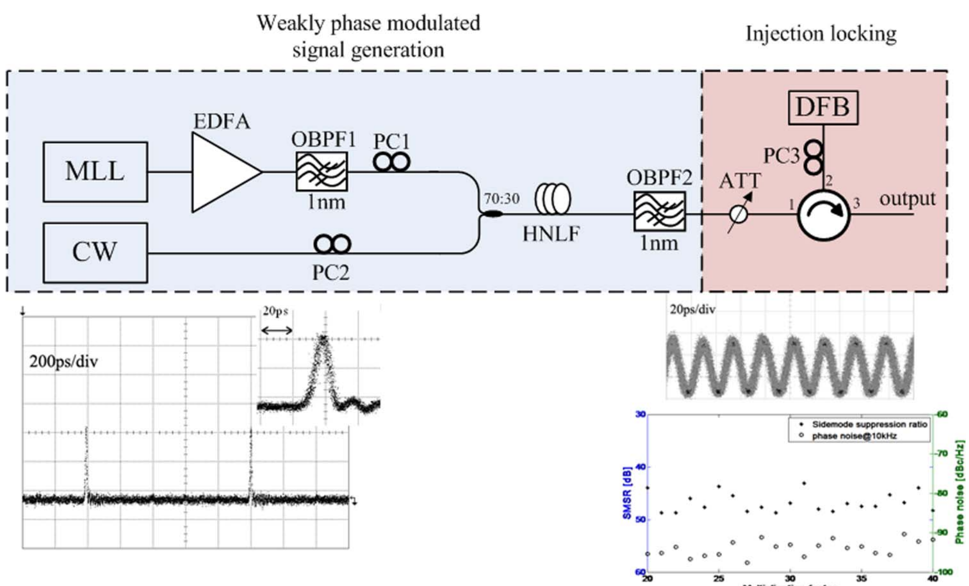

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Tunable Microwave Frequency Multiplication by Injection Locking of DFB Laser With a Weakly Phase Modulated Signal

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Abstract: We have demonstrated in this paper a novel tunable microwave frequency multiplication by injecting a weakly phase-modulated optical signal into a DFB laser diode. Signals with multiple weak sidebands are generated by cross-phase modulation of a continuous wave (CW) with short pulses from mode-locked fiber laser. Then, frequency multiplication is achieved by injection and phase locking a commercially available DFB laser to one of the harmonics of the phase modulated signal. The multiplication factor can be tuned by changing the frequency difference between the CW and the free oscillating wavelength of the DFB laser. The experimental results show that, with an original signal at a repetition rate of 1 GHz, a microwave signal with high spectral purity and stability is generated with a multiplication factor up to 60. The side-mode suppression ratio over 40 dB and phase noise lower than −90 dBc/Hz at 10 kHz are demonstrated over a continuous tuning range from 20 to 40.

Index Terms: Microwave photonics, frequency multiplication, injection locking.

1. Introduction

Microwave photonics becomes a more and more attractive topic as it can find many applications such as in radar, communications, and microwave tomography [1], [2]. One of the key techniques is to generate microwave signals in the optical domain in order to reduce infrastructure cost and to overcome the frequency bottleneck in electrical devices [3], [4]. Several techniques have been proposed to generate microwave signals using photonic methods, including optical phase-locking [5], optical beating [6] and so on. These techniques have no fundamental bandwidth limitation on the generated microwave frequency. However, it is still challenging to achieve a stable reference source comparable with a state-of-the-art electrical microwave oscillator. An alternate technique is generating high frequency microwave signals based on photonic frequency multiplication. Several kinds of photonic frequency multiplication have been demonstrated using cascaded Mach–Zehnder

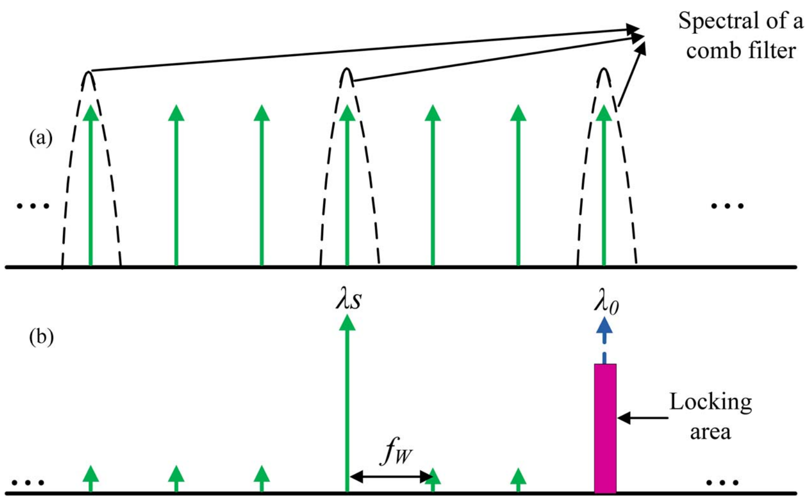

Fig. 1. Schematic of the principle of operation. (a) Frequency multiplication by comb filters. (b) Frequency multiplication by injection locking of DFB laser.

modulator (MZM) [7], [8] or phase modulator (PM) [9], polarization-dependent properties of a PM [10], [11], four-wave mixing [12], [13] and so on. However, the multiplication factor is limited because of the difficulty in efficient generation of high-order harmonics. On the other hand, mode-locked laser (MLL) with high order harmonics can be useful in generation of microwave with large multiplication factor. However, by employing a passive comb filters [14], such as Fabry-Pérot (F-P) filter, to suppress the undesired harmonics, the free space range (FSR) and passband of the filter should be adjusted carefully and the wavelength drifting of the MLL will result in the amplitude fluctuation of the generated microwave.

In this paper, we demonstrate tunable frequency multiplication by injecting a weakly phase modulated optical signal into a commercially available distributed feedback (DFB) laser diode. A continuous wave (CW) is first weekly phase modulated by mode-locked pulses based on cross phase modulation (XPM) in order to generate harmonics, and then launched into a DFB laser. When the DFB laser is locked to one of the harmonics of the injected light, the desired frequency will be greatly enhanced while the others are suppressed. The phase modulated signal instead of the intensity modulated signal is employed to avoid the rapid charge carrier change in DFB laser in order to make the frequency multiplication stable. In this experiment, a microwave signal with high spectral purity and stability is generated with a tunable frequency from 20 GHz to 60 GHz, corresponding to a tunable multiplication factor from 20 up to 60.

2. Operation Principle

The basic idea of the photonic microwave generation is simple: beating of two phase-correlated lights with desired frequency difference. First of all, to achieve large multiplication factor, high order harmonics should be generated. Thus, in our scheme, mode-locked laser is used as it has broad spectra and high order harmonic frequencies.

One idea to select two desired frequency components is the use of a comb filter, such as passive F-P filter, a F-P laser, multisection DFB laser [15] or the dispersion character of fiber [16]. The frequency components which match the passband of the comb filter will be remained and the others will be suppressed. Taking F-P filter as an example [as shown in Fig. 1(a)], the FSR of the filters should be designed to match the desired microwave frequency. In addition, the passband of the comb filter should be adjusted carefully to match the wavelength of the MLL. Besides, it is hard to achieve a wide tuning range of the multiplication factor as it is determined by the FSR of the comb filter.

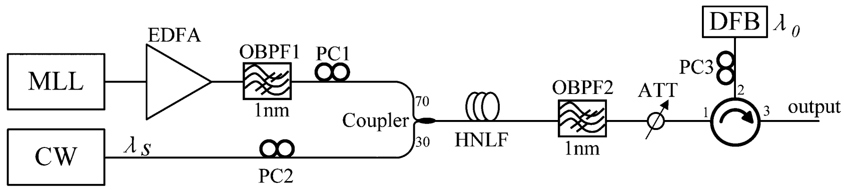

Fig. 2. Experimental setup of tunable microwave frequency multiplication. (MLL: Mode-Locked Laser; EDFA: Erbium Doped Fiber; OBPF: Optical Band-Pass Filter; PC: Polarization Controller; HNLF: High Nonlinear Fiber; ATT: Attenuator).

Our idea to achieve frequency multiplication is injection locking a DFB laser with generated harmonics. As illustrated in Fig. 1(b), The injected light at λ_s, has harmonics with a frequency interval of f_w. If one of the harmonics is located in the stable locking area (close or with slightly negative frequency detuning) to the lasing frequency of DFB laser (donated as λ_0), the DFB laser will be phase locked to the harmonic. Therefore, the stable microwave multiplication will be achieved through the beating of λ_s and λ_0. The multiplication factor can be easily tuned either by changing λ_s or λ_0. Note that the locking bandwidth will be narrower as the injection power goes lower [17], weakly phase modulated signal is used for injection locking in our scheme to ensure that there will be only one harmonic in the locking area at a time.

In principle, the harmonics of the injected light can be generated either by intensity modulation or phase modulation. In our scheme, the injected light is phase modulated by short pulses from a MLL based on the XPM in a high nonlinear fiber (HNLF). Therefore, there is no intensity fluctuation on the injected light and the amplitude vibration in the generated microwave can be eliminated. The detuning frequency range for stable injection locking is dependent on the ratio of the amplitude of injected light (that on transverse-electric (TE) mode polarization) to amplitude of the DFB laser [18]. When the DFB laser is locked to the harmonic of the injected light, stable microwave frequency multiplication can be achieved even if there are still some small wavelength drifting or amplitude fluctuation, which greatly reduces the stability requirement of both the MLL and the DFB laser.

3. Experimental Setup

Fig. 2 shows a schematic diagram of the experimental setup of tunable microwave frequency multiplication by optical injection locking of DFB laser, which mainly consists of two parts: the XPM based phase modulation on a CW light and injection locking of DFB laser. The short pulses with 1 GHz repetition rate are generated by an actively mode-locked fiber laser (MLL) with a central wavelength of 1533.32 nm, and then amplified using an erbium doped fiber amplifier followed by a 1-nm optical bandpass filter to suppress the ASE noise. The amplified 1-GHz pulses are then launched into a 500 meter long HNLF together with a CW light emitted from a tunable external-cavity laser (Agilent 81980a) through a 70:30 optical coupler. The polarizations of short pulses and CW light are adjusted by polarization controllers (PCs) to achieve the maximum efficiency of the XPM. The HNLF has a nonlinear coefficient of 11 $W^{-1}km^{-1}$, a zero dispersion wavelength at 1545 nm and a dispersion slope of 0.03 ps/nm · km. Another optical tunable bandpass filter (OBPF2) with a 3 dB bandwidth of 1 nm is employed to separate the phase modulated light from the short pulses. The phase modulated light is injected into the DFB laser through an optical circulator (OC). Another polarization controller (PC3) is used to align the polarization of the inject light with the TE polarization of the DFB laser. A commercially available DFB laser without optical isolator at the output is used for generation of microwaves with tunable multiplication factor. The DFB laser is biased at 40 mA while the threshold current of which is 10 mA.

4. Experimental Results

The optical spectrum of the MLL is shown in Fig. 3(a), with a 3 dB bandwidth of 1.9 nm. Although the OBPF with a 3 dB bandwidth of 1 nm will broaden the short pulses, the spectrum after the filter is still broad enough for microwave frequency generation up to 60 GHz ($\sim$0.48 nm), which is the

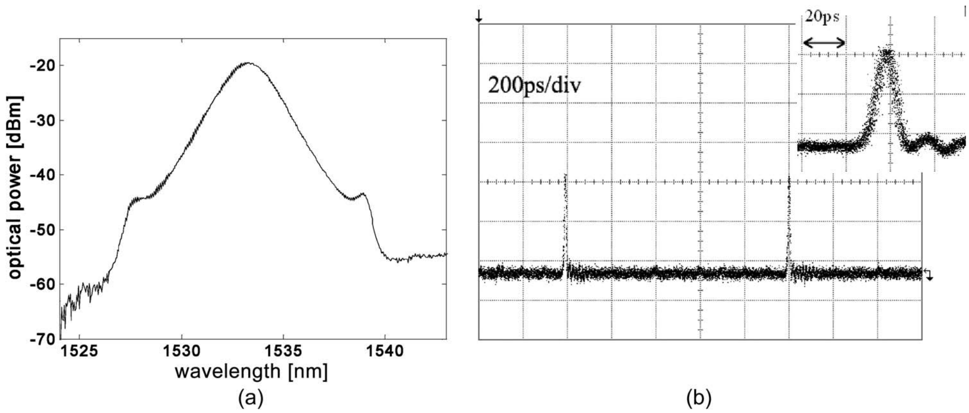

Fig. 3. (a) Spectrum and (b) waveform of short pulses generated form mode-locked laser.

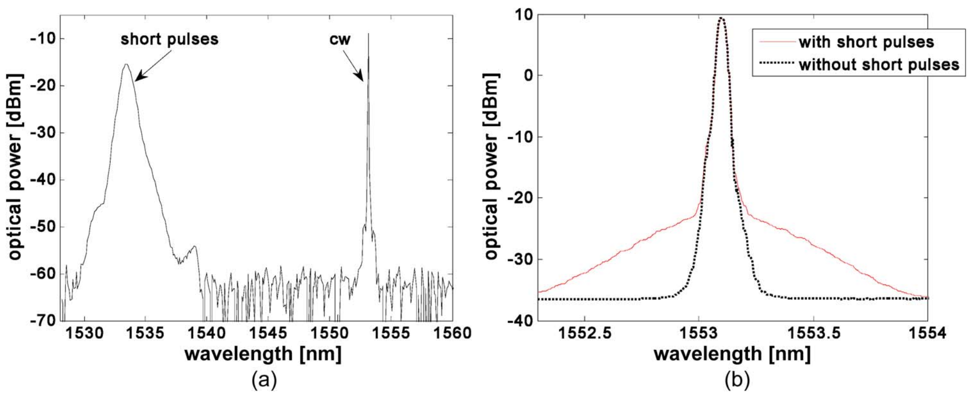

Fig. 4. (a) Spectrum of the short pulses and CW light wave at the input of HNLF. (b) Comparison of the optical spectra with and without phase modulation.

highest frequency we can observe due to the bandwidth limitation of oscilloscope and electrical spectrum analyzer. It has already been demonstrated that with proper setting, the MLL can generate several fs short pulses with tens of nanometers bandwidth [19]. That makes it possible to generate microwave signal with larger multiplication factor. Fig. 3(b) shows the waveform of short pulses generated by MLL with a repetition rate of 1 GHz (inset is the zoom-in eye diagram).

In the experiment, a HNLF is used for weakly phase modulation. The average output power of the MLL is 13.6 dBm. The optical spectrum of the signals at the input of the HNLF can be seen in Fig. 4(a). The short pulses and CW light are at 1533.32 and 1553.11 nm, respectively. At the output of the HNLF, the phase-modulated CW light is filtered out. Fig. 4(b) shows the CW light with and without phase modulation. Although, the repetition frequency cannot be observed because of the limited resolution of the spectrum analyzer (0.05 nm), the spectrum broadening after XPM effect can be clearly seen. The optical power is about -23.5 dBm and -26.7 dBm at 0.16 nm (20 GHz) and 0.32 nm (40 GHz) offset from the central wavelength, respectively. The power ratio of the sidebands and the carrier is -32.3 dB (20 GHz sideband) and -35.5 dB (40 GHz sideband). The phase modulation depth is quite low in our experiment and can be certainly increased by increasing the optical power of short pulses into the HNLF. However, it is already enough for injection locking the DFB laser, as we will show below.

Then the phase modulated signal is injected into the DFB laser. The central wavelength of the DFB laser is set to be 1553.43 nm, approximately 40 GHz away from the center wavelength of the phase modulated signal. The power of the injected light is adjusted to be 1.3 dBm. After the injection, the

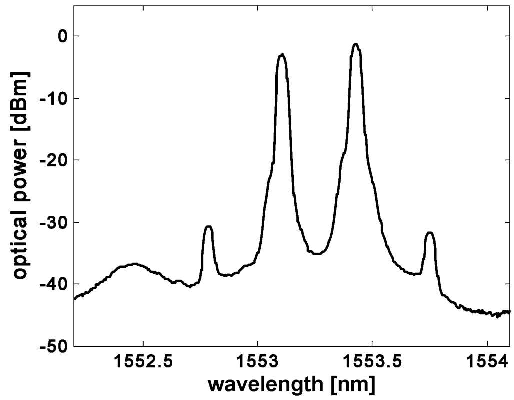

Fig. 5. Spectrum of DBF laser injection locked by a weakly phase modulated signal.

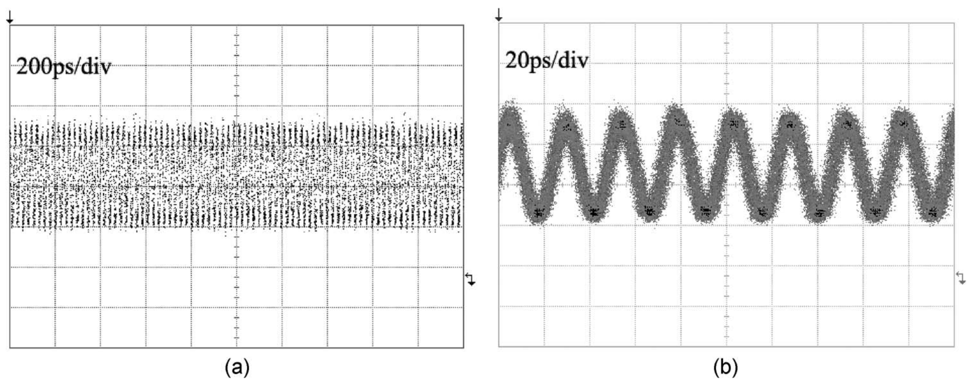

Fig. 6. (a) Overall view and (b) zoom-in waveform of generated microwave at the output of DFB laser.

spectrum of the output signal of the DFB laser is shown in Fig. 5. Compared to Fig. 4(b), one of the harmonic sidebands, which is located in the locking area of DFB laser, is greatly enhanced after injection locking. Thus, two frequency components, apart by 40 GHz, can be clearly seen in Fig. 5. The side modes in the Figure are generated due to the four-wave-mixing in the DFB laser.

The waveform of the generated microwave with multiplied frequency in depicted in Fig. 6. Fig. 6(a) provide an overall view of the signal output from the DFB laser, which shows the signal keeps mode locking and there is no obvious amplitude fluctuation during the whole period. Eye diagram accumulated for two minutes [Fig. 6(b)] demonstrates the long-term stability of generated microwave.

To further evaluate the performance of generated photonic microwave, the signal is converted into electrical domain using a 50 GHz PIN detector, amplified and observed by a microwave spectrum analyzer (Agilent 8564EC). Fig. 7(a) and (b) show the electrical spectra of the 40 GHz microwave signal without and with injection locking. When the DFB laser is not locked to the harmonic of the injected signal, we can only see the beating noise around 40.08 GHz, which is the frequency difference of the CW light and free-running DFB laser. By aligning the polarization of the injected signal with TE polarization of the DFB laser, the DFB laser is then locked to the harmonic of the injected signal and a clean 40 GHz radio frequency (RF) signal is generated [Fig. 7(b)]. Note that the frequency difference between the injected light and the free-running DFB laser ($\sim$40.08 GHz in the experiment) is not necessarily be adjusted very accurately. The DFB laser can be locked to the inject light as long as the harmonic of the injected light is within the locking area of the DFB laser, which shows the frequency tolerance of the proposed scheme.

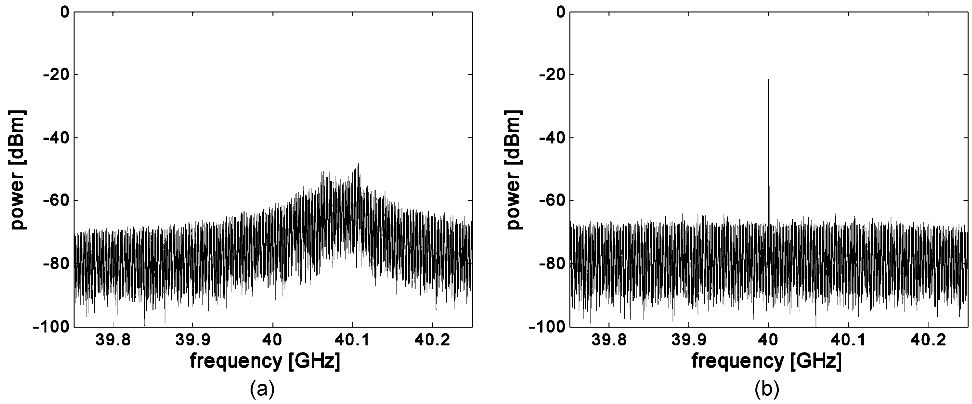

Fig. 7. Spectrum of the signal at the output of DFB laser, (a) without and (b) with injection locking.

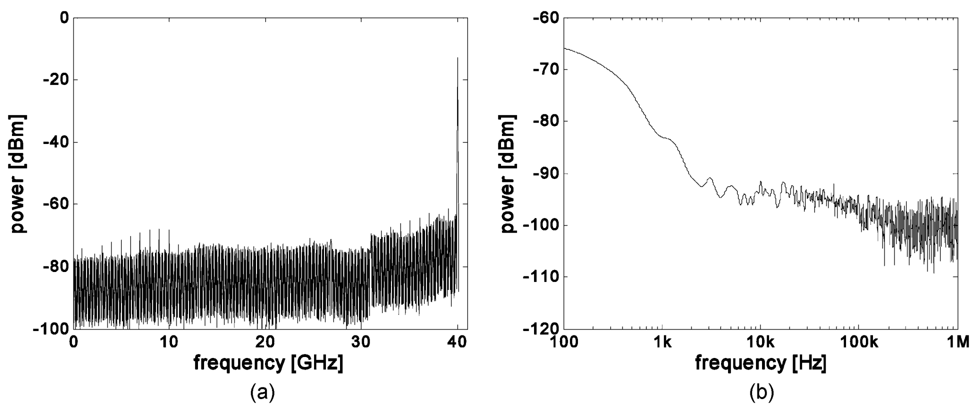

Fig. 8. (a) Electrical spectrum and (b) phase noise of the generated microwave.

Fig. 8(a) gives the full span of the generated microwave with a side mode suppression ratio of 48.3 dB. Furthermore, the single-sideband phase noise of the 40 GHz signal is measured from 100 Hz to 1 MHz offset frequencies. The phase noise is -91.8 dBc/Hz at the 10 kHz offset from the carrier, which shows a good quality of the generated microwave signal. The root-mean-square (RMS) timing jitters of the 40 GHz signal is 76.8 fs, calculated by integrating the spectral noise-power density measured above using the following equation [20]:

$$\sigma = \sqrt{2\int_{f_{\min}}^{f_{\max}} L(f)df} \Big/ 2\pi f_{osc}$$

where the f_{osc} is the oscillation frequency.

Then, we characterized the tunability of the proposed scheme. The multiplication factor can be tuned by changing the wavelength of either the injected CW light or the DFB laser. In this experiment, we change the wavelength CW light emitted from an ECL. Alternately, the free-running wavelength of DFB laser can also be tuned through temperature controlling. In the experiment, multiplication factor is tuned continuously from 40 down to 20. The SMSR and the SBB phase noise under different multiplication factor is provided in Fig. 9. It is shown that the SMSR is higher than 43 dB and the phase noise at the 10 kHz offset is lower than -90 dBc/Hz in the whole tuning range. The maximum multiplication factor is limited to 40 because of the bandwidth limitation of the microwave spectrum analyzer, which is 40 GHz.

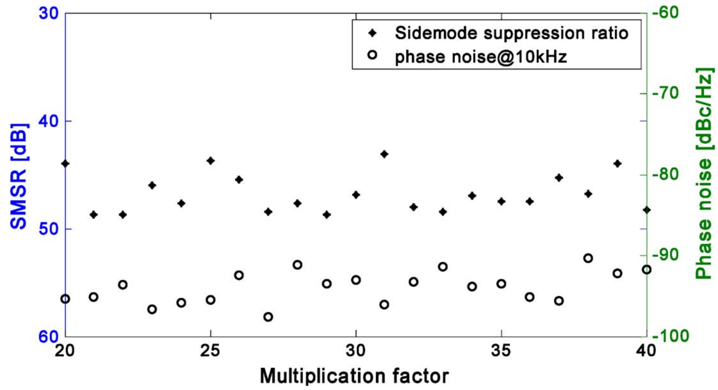

Fig. 9. Sidemode suppression ratio and phase noise under different multiplication factor.

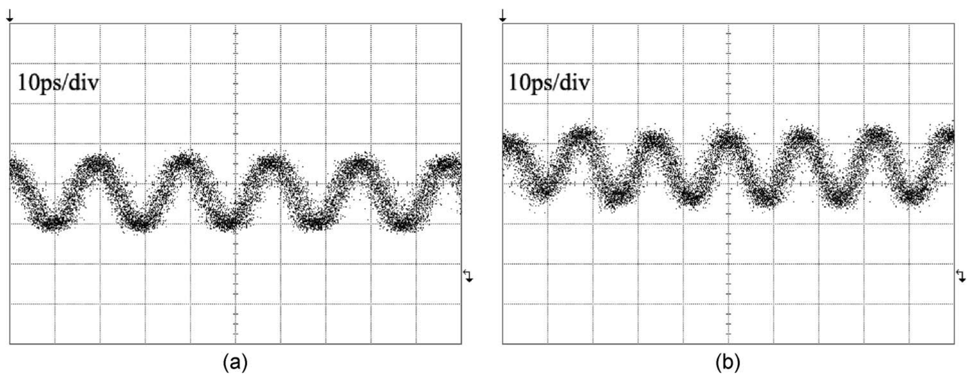

Fig. 10. Waveform of (a) 51 GHz and (b) 60 GHz microwave generated.

Actually, the multiplication factor can go even higher with the increase of the injection power. We get ~50 GHz microwave at the injection power of 5.6 dBm and ~60 GHz microwave at the injection power of 8.7 dBm. Note that the phase modulation depth is about −39 dB@50 GHz and −42 dB@ 60 GHz, the minimum injection power of the harmonic for stable phase locking is around −34 dBm. The SMSR and the SBB phase noise cannot be measured because of the bandwidth limitation of Agilent8564EC. However, the waveform of the signal is observed and measured by optical oscilloscope, as shown in Fig. 10(a) and (b). The measured frequency is 51 GHz and 60 GHz, respectively. Since the optical oscilloscope (Agilent86100A) has an optical bandwidth of 40 GHz and electrical bandwidth of 50 GHz, an amplitude reduction in the waveforms is observed and the signal seems a bit noisy. The injection locking of the DFB laser is mainly determined by the power of the harmonic, the multiplication frequency can exceed hundreds of GHz using proposed scheme with enough phase modulation depth as well as the injection power.

5. Conclusion

We have demonstrated a microwave frequency multiplication with a continuous tunable multiplication factor. By injection locking a DFB laser with the harmonic of a weakly phase modulated signal, microwave signal with high spectral purity and stability is generated. In the experiment, the multiplication factor varies from 20 up to 60 by adjusting the central wavelength of injected light. SMSR over 43 dB and phase noise lower than −90 dBc/Hz@10 kHz is achieved over the tuning range from 20 to 40 GHz.

References

[1] Z. Jia, J. Yu, G. Ellinas, and G. Chang, "Key enabling technologies for optical-wireless networks: Optical millimeter-wave generation, wavelength reuse, and architecture," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3452–3471, Nov. 2007.

[2] S. Sarkar, S. Dixit, and B. Mukherjee, "Hybrid wireless-optical broadband-access network (WOBAN): A review of relevant challenges," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3329–3340, Nov. 2007.

[3] M. Weiss, M. Huchard, A. Stohr, B. Charbonnier, S. Fedderwitz, and D. S. Jager, "60-GHz photonic millimeter-wave link for short- to mediumrang wireless transmission up to 12.5 Gb/s," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2424–2429, Aug. 2008.

[4] S.-H. Fan, H.-C. Chien, Y.-T. Hsueh, A. Chowdhury, J. Yu, and G.-K. Chang, "Simultaneous transmission of wireless and wireline services using a single 60-GHz radio-over-fiber channel by coherent subcarrier modulation," *IEEE Photon. Technol. Lett.*, vol. 21, no. 16, pp. 1127–1129, Aug. 2009.

[5] L. A. Johansson and A. J. Seeds, "36-GHz 140-Mb/s radio-over-fiber transmission using an optical injection phase-lock loop source," *IEEE Photon. Technol. Lett.*, vol. 13, no. 8, pp. 893–895, Aug. 2001.

[6] M. Hyodo, K. S. Abedin, N. Onodera, and M. Watanabe, "Beat signal synchronization for optical generation of millimetre-wave signals," *Electron. Lett.*, vol. 39, no. 24, pp. 1740–1741, Nov. 2003.

[7] W. Li and J. Yao, "Investigation of photonically assisted microwave frequency multiplication based on external modulation," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3259–3268, Nov. 2010.

[8] G. H. Nguyen, B. Cabon, and Y. L. Guennec, "Generation of 60-GHz MB-OFDM signal-over-fiber by up-conversion using cascaded external modulators," *J. Lightw. Technol.*, vol. 27, no. 11, pp. 1496–1502, Jun. 2009.

[9] E. R. Alonso, H. Yang, J. H. Lorente, B. Huiszoon, J. V. Zantvoort, and A. M. J. Koonen, "Generation and transmission of high frequency radio signals through fiber links up to 125 km by means of the optical frequency multiplication technique," in *Proc. Int. Top. Meet. Microw. Photon.*, 2008, pp. 205–208.

[10] S. Pan and J. Yao, "Tunable subterahertz wave generation based on photonic frequency sextupling using a polarization modulator and a wavelength-fixed notch filter," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 7, pp. 1967–1975, Jul. 2010.

[11] M. G. Larrode, A. M. J. Koonen, J. J. V. Olmos, and E. J. M. Verdurmen, "Microwave signal generation and transmission based on optical frequency multiplication with a polarization interferometer," *J. Lightw. Technol.*, vol. 25, no. 6, pp. 1372–1378, Jun. 2007.

[12] A. Wiberg, P. Perez-Millan, M. V. Andres, and P.-O. Hedekvist, "Microwave-photonic frequency multiplication utilizing optical four-wave mixing and fiber Bragg gratings," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 329–334, Jan. 2006.

[13] A. Garcia, G. Pillet, L. Manager, L. Morvan, S. Babiel, S. Fedderwitz, and A. Stohr, "Low phase noise and frequency tunable 95-115 GHz photonic LO based upon DSB-SC modulation in an MZM and FWM in an UL-SOA," in *Proc. MWP*, 2012, pp. 152–155.

[14] H. Song, N. Shimizu, T. Furuta, K. Suizu, H. Ito, and T. Nagatsuma, "Broadband-frequency-tunable sub-terahertz wave generation using an optical comb, AWGs, optical switches, and a uni-traveling carrier photodiode for spectroscopic applications," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2521–2530, Aug. 2008.

[15] C. Laperle, M. Svilans, M. Poirier, and M. Tetu, "Frequency multiplication of microwave signals by sideband optical injection locking using a monolithic dual-wavelength DFB laser device," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1219–1224, Jul. 1999.

[16] W. J. Lai, P. Shum, and L. N. Binh, "Stability and transient analyses of temporal Talbot-effect-based repetition-rate multiplication mode-locked laser systems," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 437–439, Feb. 2004.

[17] S. Hwang, J. Liu, and J. K. White, "Characteristics of period-one oscillations in semiconductor lasers subject to optical injection," *IEEE J. Sel. Top. Quantum Electron.*, vol. 10, no. 5, pp. 974–981, Sep./Oct. 2004.

[18] B. Wu, J. Yu, Z. Zhang, B. Han, J. Luo, J. Guo, W. Wang, J. Wang, and E. Yang, "A novel and tunable frequency-upconversion based on FP-LD injection of one low bit-rate signal without any RF local oscillator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 14, pp. 1027–1029, Jul. 2010.

[19] J. Xu, S. Wu, J. Liu, Q. Wang, Q. Yang, and P. Wang, "Femtosecond Er-doped fiber lasers mode-locked with graphene oxide saturable absorber," in *Proc. CLEO*, May 6–11, 2012, pp. 1–2.

[20] W. Wang, J. Yu, A. Zhang, B. Han, H. Hu, L. Zhang, and E. Yang, "Investigation of a rate- selectable all-optical packet clock recovery system," *IEEE Photon. Technol. Lett.*, vol. 20, no. 7, pp. 466–468, Apr. 2008.