Frequency-Quadrupling Optoelectronic Oscillator for Multichannel Upconversion

Dan Zhu, *Member, IEEE*, Shifeng Liu, De Ben, and Shilong Pan, *Member, IEEE*

***Abstract*— A frequency-quadrupling dual-loop optoelectronic oscillator (OEO) is proposed and demonstrated by two cascaded polarization modulators. The introduction of frequency quadrupling to the proposed OEO requires no optical filtering, which not only increases the maximal achievable frequency by four times, but also enables powerful optical signal processing functions. An experiment is carried out. A high-quality millimeter-wave signal at 39.75 GHz is generated using low-frequency devices. Photonic microwave upconversion at two wavelength channels is also demonstrated on the basis of the proposed frequency-quadrupling OEO.**

***Index Terms*— Frequency-quadrupling, microwave photonics, optoelectronic oscillator, upconversion.**

I. INTRODUCTION

OPTOELECTRONIC oscillator (OEO) has been investigated intensively for applications including very low phase noise microwave or millimeter-wave signal generation, RF up- and down-conversion in radar and electronic warfare systems [1], [2], optical signal processing for optical and wireless communications [3]–[5], high sensitivity sensors [6] and modern instruments [7]. A conventional OEO is an optoelectronic loop based on an analog photonic link, consisting of an intensity modulator, an optical delay line (ODL) or an electrical phase shifter, a photodetector (PD), an electrical amplifier (EA), and an electrical bandpass filter (EBPF) [1]. Due to the electronic bottleneck of the electrical and electro-optical devices used in the OEO loop, the performance of a high frequency OEO is always limited [8]. To extend the operational frequency range, frequency multiplying OEOs were reported [9]–[15]. Among which, the frequency-doubling OEO has been widely investigated [9]–[14], because it not only generates a microwave signal with a frequency that is two times the bandwidth of the electrical and electro-optical devices, but also enables many optical signal processing functions which are not possible to be implemented by a conventional OEO [3], [12]. To obtain the high-quality microwave signal with higher frequency, and to achieve more powerful optical signal processing functions, OEOs with even higher frequency multiplication factor are highly desirable. We have recently reported a frequency-quadrupling OEO based on a polarization modulator (PolM) and a notch filter [15], but an optical filter was incorporated to remove the optical carrier. The inevitable optical filtering would increase greatly the difficulty for implementation of optical signal processing in wavelength-division-multiplexer (WDM) systems [16]. In addition, the tuning range of the OEO is limited by the bandwidth of the notch area of the optical filter [15].

In this letter, a frequency-quadrupling dual-loop OEO with no optical filtering is proposed and demonstrated based on two cascaded PolMs. With no optical filtering in the OEO, the novel scheme can produce optical microwave signals at multiple wavelengths. Signal processing with no restriction on the wavelength of the injected signal is also realized. In addition, multi-channel signal processing based on WDM technology is enabled. An experiment is performed. Stable microwave signal with a frequency of 39.75 GHz is generated using low-frequency components. The OEO is applied for multichannel photonic microwave up-conversion. A 1-Gb/s pseudorandom-bit-sequence (PRBS) signal is also successfully up-converted at two wavelengths, demonstrating the potential of the OEO being applied in multi-channel signal processing.

II. PRINCIPLE

The schematic diagram of the proposed frequency-quadrupling OEO is shown in Fig. 1. A lightwave from a laser diode (LD) is introduced to a PolM (PolM1) via a polarization controller (PC; PC1). A 30%:70% optical coupler is connected to the PolM, to split the polarization-modulated signal into two branches. In the lower branch, a polarization beam splitter (PBS; PBS1) together with a PC (PC2) converts the polarization-modulated signal to an intensity-modulated signal. By carefully adjusting PC2, the equivalent intensity modulation is biased at the quadrature transmission point (QTP) [3]. PBS1 also serves as a power splitter, which divides

---

Manuscript received November 18, 2012; revised January 3, 2013; accepted January 10, 2013. Date of publication January 16, 2013; date of current version February 4, 2013. This work was supported in part by the National Basic Research Program of China (973 Program) under Grant 2012CB315705, in part by the National Natural Science Foundation of China under Grant 61201048 and Grant 61107063, in part by the Natural Science Foundation of Jiangsu Province under Grant BK2012381 and Grant BK2012031, in part by the Program for New Century Excellent Talents in University under Grant NCET-10-0072, in part by the Ph.D. Programs Foundation of the Ministry of Education of China under Grant 20113218120018, in part by the Post-Doctoral Science Foundation of China under Grant 2012M521078, in part by the Jiangsu Planned Projects for Postdoctoral Research Funds under Grant 1102054C, in part by the Fundamental Research Funds for the Central Universities under Grant NS2012046 and Grant NE2012002, and in part by a Priority Academic Program Development of Jiangsu Higher Education Institutions.

The authors are with the Microwave Photonics Research Laboratory, College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China. They are also with the State Key Laboratory of Millimeter Waves, Nanjing 210096, China (e-mail: pans@ieee.org).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2013.2240293

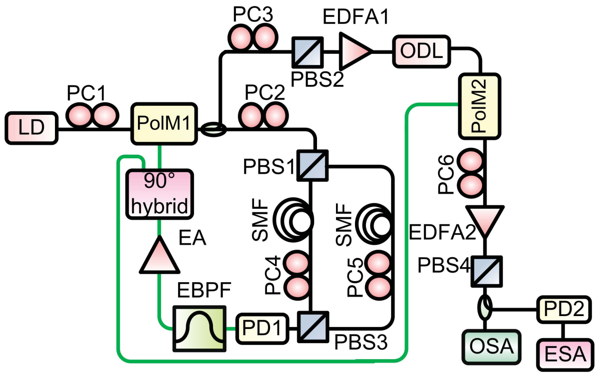

Fig. 1. Schematic diagram of the proposed frequency-quadrupling dual-loop OEO without optical filtering. LD: laser diode. PC: polarization controller. PolM: polarization modulator. PBS: polarization beam splitter. SMF: single-mode fiber. EBPF: electrical bandpass filter. EA: electrical amplifier. EDFA: erbium-doped fiber amplifier. ODL: optical delay line. PD: photodetector. ESA: electrical spectrum analyzer. OSA: optical spectrum analyzer.

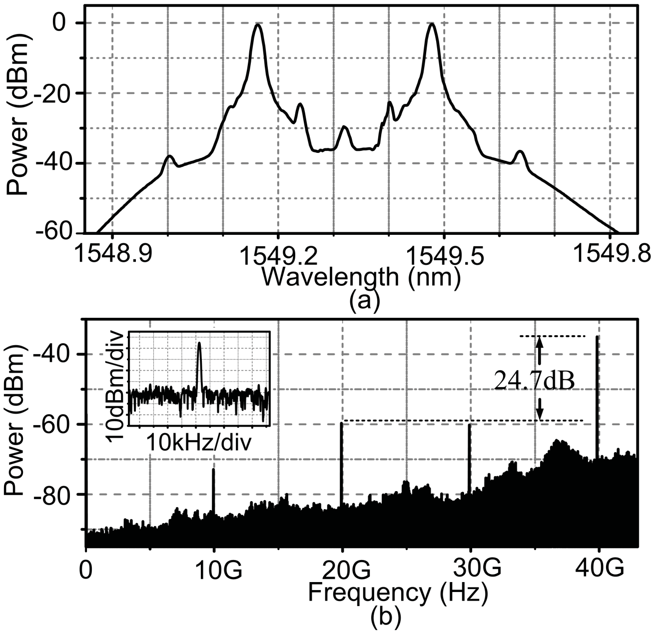

Fig. 2. (a) Optical and (b) electrical spectra of the frequency-quadrupled signal at the output of the OEO. Inset: the zoomed-in view of the 39.75-GHz signal at a span of 100 kHz and a RBW of 9.1 kHz.

one portion of the PolM1 output into two optical paths with complementary intensity modulation. In each path, a length of single mode fiber (SMF) and a PC are inserted. The two optical paths are combined by another PBS (PBS3), to perform polarization multiplexing [17], [18]. As indicated in the previous works [15], [17], the combination of the polarization modulation and polarization multiplexing to introduce two loops can efficiently increase the side mode suppression ratio in the OEO. A PD (PD1) is used to perform optical-to-electrical conversion. The electrical signal is filtered by an EBPF, amplified by a low noise EA, and then fed back to the RF placeport of PolM1 to form an oscillation. In the upper branch, photonic microwave frequency quadrupling is performed. Another set of PC (PC3) and PBS (PBS2) is used to convert the polarization-modulated signal to a carrier-suppressed intensity-modulated signal, i.e., only -1^{st}- and $+1^{\text{st}}$-order sidebands are kept in the output signal. Then, a second carrier-suppressed intensity-modulation is performed by another PolM (PolM2) together with a PC (PC6) and a PBS (PBS4). After the modulation, the -1^{st}-order sideband generates a -2^{nd}-order sideband and an optical carrier, and the $+1^{\text{st}}$ order sideband generates a $+2^{\text{nd}}$-order sideband and another optical carrier. By incorporating a hybrid coupler to introduce a 90-degree phase shift between the RF signals to the two PolMs, the optical carriers generated by the two first-order sidebands counteract with each other. As a result, two phase-correlated optical wavelengths with a wavelength spacing corresponding to four times the frequency of the oscillation signal in the OEO loop are obtained [19], [20]. It should be noted that the time delay difference between the optical signal and the electrical signal to PolM2 would make the frequency quadrupling wavelength dependent, therefore, an ODL is inserted to eliminate this time delay difference.

To perform photonic microwave up-conversion using the OEO, the CW signal injected to Pol01 can be replaced by optical baseband signals. In the lower branch, the oscillation of the OEO will not be affected since the baseband signal would be effectively eliminated by the high-Q EBPF in the OEO loop. On the other hand, the upper branch would output an up-converted signal at four times the fundamental frequency because of the optical mixing in the PolMs. Since the PolM has a large operational wavelength range and there is no wavelength selective device in the scheme, photonic microwave up-conversion based on the proposed OEO is wavelength independent [22] and can support multi-channel operation.

III. EXPERIMENT RESULTS AND DISCUSSIONS

An experiment based on the setup shown in Fig. 1 is performed. The OEO constists of a LD, two PolMs, four PBSs, six PCs, two PDs, two sections of SMF, two erbium-doped fiber amplifiers (EDFAs), a 90° hybrid coupler, an EBPF, an EA and an ODL. The major parameters are as follows: the LD has a wavelength stability of 2.5 pm; the PolM (Versawave Technologies) has a bandwidth of 40 GHz and a half-wave voltage of 3.5 V; the lengths of the SMFs in the dual loops are 0.5 and 0.6 km, respectively; the EBPF has a bandwidth of 11.34 MHz centered at 9.953 GHz; the 90° hybrid coupler has a phase variation within ±12° in 1.7–36 GHz; the gain of the EA is about 40 dB, which generates a phase modulation index of around 0.4π in the PolM; PD1 has a bandwidth of 10 GHz and a responsivity of 0.88 A/W; PD2 has a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The optical spectra are monitored using an optical spectrum analyzer (OSA; Yokogawa AQ6370C) with a resolution of 0.02-nm. The electrical spectrum and the phase noise are measured by an electrical spectrum analyzer (ESA) with a phase noise measurement module (Agilent E4447A, 3 Hz–43 GHz).

In order to investigate the performance of the frequency-quadrupling OEO, the wavelength of the LD is set at

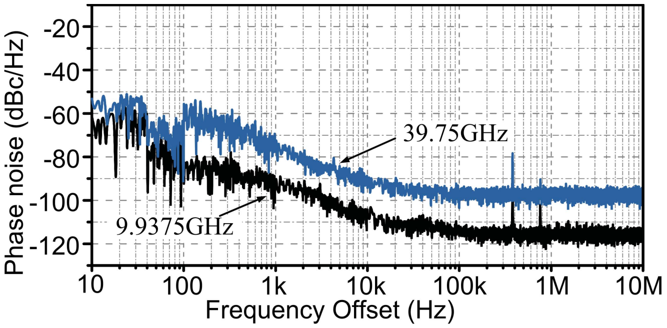

Fig. 3. Phase-noise spectra of the 39.75-GHz frequency-quadrupled signal and the 9.9375-GHz fundamental signal.

1549.326 nm. Fig. 2(a) shows the optical spectrum at the output of PBS4. As can be seen, a small optical carrier, two small first-order sidebands, two second-order sidebands and two small fourth-order sidebands are observed. The optical carrier and the first-order sidebands are 29- and 22-dB less than the second-order sidebands, respectively. The two second-order sidebands have a wavelength spacing of 0.316 nm (39.75 GHz), which is four times the frequency of the fundamental oscillating signal of the OEO. Fig. 2(b) shows the electrical spectrum of the generated microwave signal. The frequency-quadrupled component is 24.7-dB higher than other undesired harmonics. A zoom-in view of the electrical spectrum of the 39.75 GHz component is also provided in Fig. 2(b), showing the quality of the generated signal is very high. The single-sideband (SSB) phase noises of the fundamental oscillation signal in the loop and the frequency-quadrupled signal are measured by the ESA. As can be seen in Fig. 3, the phase noises of the 9.9375 and 39.75 GHz signals are -108.05 and -92 dBc/Hz, respectively, at a 10-kHz offset frequency. Theoretically, the phase noise of a frequency-quadrupled signal should have a phase noise degradation of $10\log_{10}4^2 = 12$ dB. However, in the experiment the phase noise degradation is 16 dB, which is partly because of the amplified spontaneous emission (ASE) noises introduced by the two EDFAs in the upper branch. It should be noted that the phase noise measurement based on the ESA would be seriously affected by the intensity noise, so the actual phase noise performance should be better than those shown in Fig. 3. The electrical spectrum of the 39.75-GHz signal is observed for more than 15 minutes in the laboratory environment. No significant variation is observed.

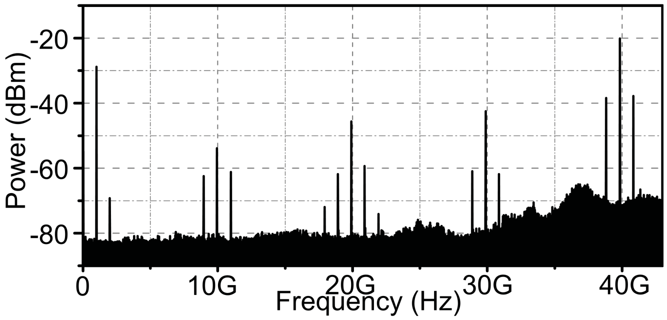

Fig. 4. Electrical spectrum of the 1-GHz upconverted signal (RBW = 100 kHz).

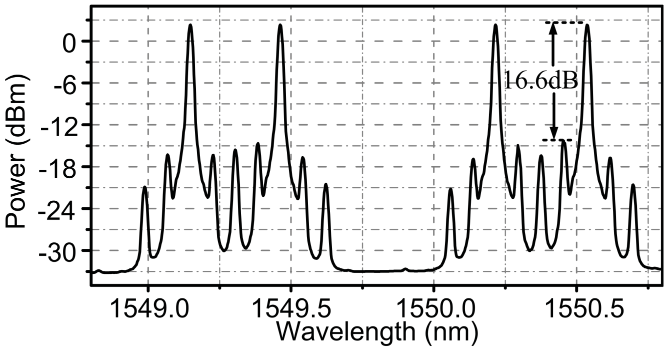

Fig. 5. Optical spectrum at the output of PBS4 when upconverting 1-Gb/s PRBS signal in two channels.

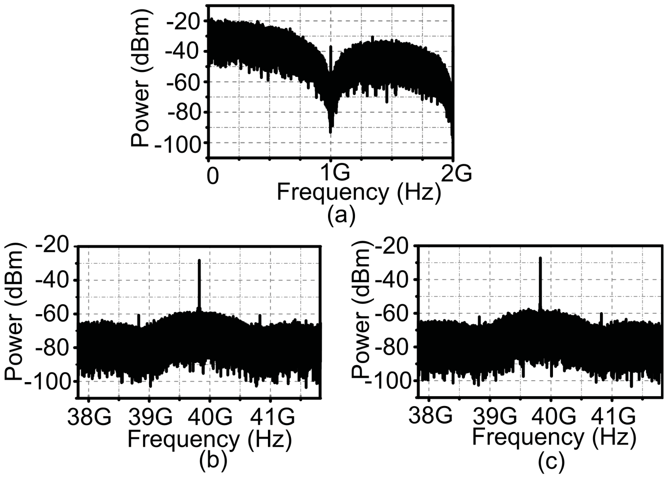

Fig. 6. Electrical spectra. (a) 1-Gb/s PRBS signal and the corresponding upconverted PRBS signal at 39.75 GHz for the (b) 1549.326-nm and (c) 1550.400-nm channels.

To validate the feasibility of the photonic microwave upconversion based on the proposed OEO, a 1-GHz sinusoidal signal generated by a microwave source (Agilent E8257D) with a power of 1.5 dBm is applied to a MZM placed after the LD in Fig. 1. Fig. 4 shows the electrical spectrum of the up-converted signal, which includes the harmonic components of 0–4 orders. Thanks to the frequency quadrupling, the power of the fourth-order harmonic is more than 20-dB higher than other undesired harmonics. To evaluate the multichannel photonic microwave up-conversion using the OEO, the LD in the OEO is replaced by two LDs followed by a MZM. The wavelengths are set to be 1549.326 nm and 1550.400 nm, respectively. The MZM has a bandwidth of 10 GHz and a half-wave voltage of 4 V, which is driven by a 1-Gbit/s PRBS signal with a word length of 2^{31}-1. Fig. 5 shows the optical spectrum of the dual-wavelength up-converted signal at the output of PBS4. A similar performance at the two channels is observed. Fig. 6 shows the electrical spectra of the 1-Gbit/s PRBS signal before and after the photonic up-conversion system. The baseband signal in Fig. 6(a) is successfully up-converted to the 39.75-GHz carrier, as shown in Fig. 6(b) and (c) in both channels. Because of the wavelength independent feature of the scheme, it should be able to perform clock recovery for arbitrary input wavelength, multiwavelength format conversion and other signal processing functions in digital optical communication systems [3]. It should be noted that the power variation of the optical signals to the OEO would affect the power of the oscillation signal, which further degrades the performance of the photonic microwave up-conversion based on the OEO. One possible solution to this problem is to place an EDFA with constant output power before the OEO.

IV. CONCLUSION

We proposed and demonstrated a novel frequency-quadrupling OEO with no optical filtering, to generate a high-frequency microwave signal and to up-convert multi-channel baseband signals to the millimeter-wave band using only low-frequency devices. A frequency-quadrupling signal at 39.75 GHz with a SSB phase noise of −92 dBc/Hz @ 10 kHz offset was generated, and simultaneous photonic microwave up-conversion at two channels was confirmed. The system is wavelength independent, which can be potentially applied in distributed antenna systems for wireless communication, sensing, and electronic warfare.

REFERENCES

[1] X. S. Yao and L. Maleki, "Optoelectronic oscillator for photonic systems," *IEEE J. Quantum Electron.*, vol. 32, no. 7, pp. 1141–1149, Jul. 1996.

[2] I. Ozdur, D. Mandridis, N. Hoghooghi, and P. J. Delfyett, "Low noise optically tunable opto-electronic oscillator with Fabry–Pérot Etalon," *J. Lightw. Technol.*, vol. 28, no. 21, pp. 3100–3106, Nov. 1, 2010.

[3] S. L. Pan and J. P. Yao, "Multichannel optical signal processing in NRZ systems based on a frequency-doubling optoelectronic oscillator," *IEEE J. Sel. Topic Quantum Electron.*, vol. 16, no. 5, pp. 1460–1468, Oct. 2010.

[4] L. Huo, Y. Dong, C. Lou, and Y. Gao, "Clock extraction using an opto-electronic oscillator from high-speed NRZ signal and NRZ-to-RZ format transformation," *IEEE Photon. Technol. Lett.*, vol. 15, no. 7, pp. 981–983, Jul. 2003.

[5] Y. C. Chi, P. C. Peng, and G. R. Lin, "Clock-free RZ-BPSK data generation using self-starting optoelectronic oscillator," *J. Lightw. Technol.*, vol. 29, no. 11, pp. 1702–1707, Jun. 1, 2011.

[6] L. D. Nguyen, K. Nakatani, and B. Journet, "Refractive index measurement by using an optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 12, pp. 857–859, Jun. 1, 2010.

[7] D. Eliyahu and L. Maleki, "Tunable, ultra-low phase noise YIG based opto-electronic oscillator," in *IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 3. pp. 2185–2187, Jun. 2003.

[8] D. Chang, *et al.*, "39-GHz optoelectronic oscillator using broad-band polymer electrooptic modulator," *IEEE Photon. Technol. Lett.*, vol. 14, no. 2, pp. 191–193, Feb. 2002.

[9] M. Shin and P. Kumar, "1.25 Gb/s optical data channel up-conversion in 20 GHz-band via a frequency-doubling optoelectronic oscillator for radio-over-fiber systems," in *IEEE MTT-S Int. Microw. Symp., Tech. Dig.*, Jun. 2007, pp. 63–66.

[10] S. L. Pan and J. P. Yao, "A frequency-doubling optoelectronic oscillator using a polarization modulator," *IEEE Photon. Technol. Lett.*, vol. 21, no. 13, pp. 929–931, Jul. 1, 2009.

[11] H. Tsuchida, "Simultaneous prescaled clock recovery and serial-to-parallel conversion of data signals using a polarization modulator-based optoelectronic oscillator," *J. Lightw. Technol.*, vol. 27, no. 17, pp. 3777–3782, Sep. 1, 2009.

[12] D. Zhu, S. L. Pan, S. H. Cai, and D. Ben, "High-performance photonic microwave downconverter based on a frequency-doubling optoelectronic oscillator," *J. Lightw. Technol.*, vol. 30, no. 18, pp. 3036–3042, Sep. 15, 2012.

[13] L. Wang, N. Zhu, W. Li, and J. Liu, "A frequency-doubling optoelectronic oscillator based on a dual-parallel Mach-Zehnder modulator and a chirped fiber bragg grating," *IEEE Photon. Technol. Lett.*, vol. 23, no. 22, pp. 1688–1690, Nov. 15, 2011.

[14] B. Yang, *et al.*, "Optically tunable frequency-doubling brillouin optoelectronic oscillator with carrier phase-shifted double sideband modulation," *IEEE Photon. Technol. Lett.*, vol. 24, no. 12, pp. 1051–1053, Jun. 15, 2012.

[15] D. Zhu, S. Pan, and D. Ben, "Tunable frequency-quadrupling dual-loop optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 24, no. 3, pp. 194–196, Feb. 1, 2012.

[16] C. T. Lin, *et al.*, "Optical millimeter-wave up-conversion employing frequency quadrupling without optical filtering," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 8, pp. 2084–2092, Aug. 2009.

[17] S. H. Cai, S. L. Pan, D. Zhu, Z. Z. Tang P. Zhou, and X. F. Chen, "Coupled frequency-doubling optoelectronic oscillator based on polarization modulation and polarization multiplexing," *Opt. Commun.*, vol. 285, no. 6, pp. 1140–1143, Mar. 2012.

[18] Y. Jiang, J. L. Yu, Y. T. Wang, L. T. Zhang, and E. Z. Yang, "An optical domain combined dual-loop optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 19, no. 11, pp. 807–809, Jun. 1, 2007.

[19] J. Zhang, H. Chen, M. Chen, T. Wang, and S. Xie, "A photonic microwave frequency quadrupler using two cascaded intensity modulators with repetitious optical carrier suppression," *IEEE Photon. Technol. Lett.*, vol. 19, no. 14, pp. 1057–1059, Jul. 15, 2007.

[20] H. Chi and J. Yao, "Frequency quadrupling and upconversion in a radio over fiber link," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2706–2711, Aug. 1, 2008.

[21] Y. Zhao, X. Zheng, H. Wen, and H. Zhang, "Simplified optical millime-ter-wave generation configuration by frequency quadrupling using two cascaded Mach-Zehnder modulators," *Opt. Lett.*, vol. 34, no.21, pp. 3250–3252, Nov. 2009.

[22] P. Zhou, Z. Z. Tang, S. L. Pan, D. Zhu, and D. Ben, "Photonic microwave up-conversion using an optoelectronic oscillator based on a polarization modulator," *Electron. Lett.*, vol. 48, no. 5, pp. 271–272, Mar. 2012.