Tunable Frequency-Quadrupling Dual-Loop Optoelectronic Oscillator

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***Abstract*— A tunable frequency-quadrupling dual-loop optoelectronic oscillator (OEO) based on a polarization modulator is proposed and demonstrated. The introduce of frequency quadrupling in the proposed OEO not only increases the maximal achievable frequency by four times, extends the tuning range by four times, but also enables powerful optical signal processing functions. By incorporating an electrical-tunable yttrium-iron-garnet bandpass filter in the proposed OEO and employing a fiber Bragg grating as a wavelength-fixed optical notch filter, a high-quality microwave signal with a frequency tunable from 32 to 42.7 GHz is generated. The phase noise of the generated frequency-quadrupling signal is also studied.**

***Index Terms*— Frequency-quadrupling, optoelectronic oscillator, tunable, yttrium-iron-garnet.**

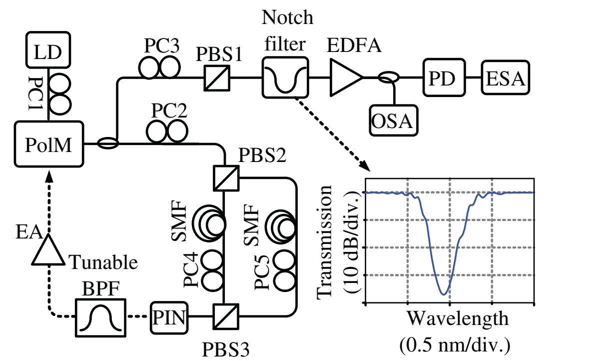

Fig. 1. Schematic diagram of the proposed tunable frequency-quadrupling dual-loop optoelectronic oscillator. Inset: transmission response of the optical notch filter. LD: laser diode; PC: polarization controller; PolM: polarization modulator; PBS: polarization beam splitter; SMF: single-mode fiber; PIN: positive-intrinsic-negative photodetector; BPF: bandpass filter; EA: electrical amplifier; EDFA: erbium-doped fiber amplifier; PD: photodetector; ESA: electrical spectrum analyzer; OSA: optical spectrum analyzer.

I. Introduction

Optoelectronic oscillator (OEO) has attracted great interests over the last two decades [1]–[6] due to its high potential for numerous applications, such as optical and wireless communications, optical signal processing, and modern instrumentation. A conventional OEO is a feedback loop consisting of an intensity modulator, an optical fiber delay line (or an electrical phase shifter), a photodetector (PD), an electrical amplifier (EA), and an electrical bandpass filter (BPF) [1]. Because lots of electrical and electro-optical devices are used, the maximal achievable frequency of the OEO is limited due to the electronic bottleneck. To extend the operational frequency range, frequency doubling OEOs were proposed [7]–[10]. The frequency doubling OEO 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 advanced optical signal processing functions which can not be implemented by a conventional OEO, such as optical non-return-to-zero (NRZ) to carrier-suppressed-return-to-zero (CSRZ) format conversion, and serial-to-parallel conversion. However, the frequency multiplication factor of the frequency doubling OEO is only two. To obtain high-quality microwave signal with higher frequency, and to achieve more powerful optical signal processing functions, OEOs with higher frequency multiplication factor are highly desirable.

In this letter, a frequency-quadrupling dual-loop OEO is proposed and demonstrated for the first time, to the best of our knowledge, based on a polarization modulator (PolM) and a wavelength-fixed optical notch filter. By incorporating a tunable Yttrium-iron-garnet (YIG) BPF in the OEO loop, the frequency tunability is realized by simply adjusting the current applied to the YIG BPF, and keeping other components in the configuration unaltered. The frequency quadrupling in the OEO also increases the tuning range by four times. An experiment is performed. Stable microwave signals with a frequency tunable from 32 to 42.7 GHz are generated using low-frequency components. The phase noise of the generated frequency-quadrupling signal is −90.69 dBc/Hz at 10 kHz offset.

II. Principle

The schematic diagram of the proposed tunable frequency-quadrupling dual-loop OEO is shown in Fig. 1. A lightwave from a laser diode (LD) passes through a PolM via a polarization controller (PC: PC1), followed by two polarization beam splitters (PBS: PBS1 and PBS2) via two PCs (PC2 and PC3). PC2 is adjusted to let the output of PBS2 equivalent to intensity modulation biased at the quadrature

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transmission point (QTP) [9]. PBS2 simultaneously serves as a polarization-modulation-to-intensity-modulation converter and a power splitter, which divides one portion of the PolM output into two optical paths with complementary intensity modulation. In each path, a section of single mode fiber (SMF) and a PC (PC4 or PC5) are inserted. The two optical paths are combined by another PBS (PBS3). Because the polarization of the optical lightwaves from the two paths is orthogonal after multiplexing in the PBS3, they would not interfere with each other when introduced to a positive-intrinsic-negative (PIN) photo detector. The converted electrical signal from the PIN is filtered by a tunable YIG BPF, amplified by a low noise amplifier, and then fed back to the RF port of the PolM, to form an oscillation at one of its eigenmodes determined by the center frequency of the YIG BPF [11]. It should be noted that the combination of polarization modulation and polarization multiplexing introduces two loops, which can be used to efficiently increase the side mode suppression ratio (SMSR) in the OEO [12], [13].

On the other hand, PC3 is adjusted to let the output of PBS1 equivalent to intensity modulation biased at the maximum transmission point (MTP), which generates an optical signal with an optical carrier and two second-order sidebands. A wavelength-fixed optical notch filter is connected to remove the optical carrier. Two phase-correlated optical wavelengths with a wavelength spacing corresponding to four times the frequency of the oscillation signal in the OEO loop are then obtained. By beating the two wavelengths at a PD, a high-quality frequency-quadrupled microwave signal is generated [14]. Since the notch filter is used to remove the optical carrier, and the adjustment of the OEO oscillating frequency only changes the locations of the sidebands, frequency tuning of the proposed frequency quadrupling OEO requires no modification of the components except for the current applied to the YIG filter. The bandwidth of the optical notch filter should be selected to keep the two second-order sidebands outside the notch area, so the minimum frequency that can be generated by the OEO is f_T, where f_T is the bandwidth of the notch.

III. Experiment Result and Discussion

An experiment based on the setup shown in Fig. 1 is carried out. The OEO consists of a LD, a PolM, three PBSs, a PIN, a high-bandwidth PD, two sections of SMF, an erbium-doped fiber amplifier (EDFA), a tunable YIG BPF, an optical notch filter and an EA. The major parameters are as follows: the LD used in our experiments is Agilent N7714A tunable laser source with a wavelength stability of 2.5 pm; the wavelength is 1550.280 nm, which is located at the notch center of the optical notch filter; the optical notch filter is implemented by a fiber Bragg grating (FBG) with a transmission response shown as an inset in Fig. 1; the PolM (Versawave Technologies) has a bandwidth of 40 GHz and a half-wave voltage of 3.5 V; the lengths of the SMFs are 4.4 km and 0.6 km, respectively; the PIN has a bandwidth of 10 GHz and a responsivity of 0.88A/W; the YIG BPF with a bandwidth of 50 MHz has a tunable frequency from 8 to 12 GHz with a tuning rate of

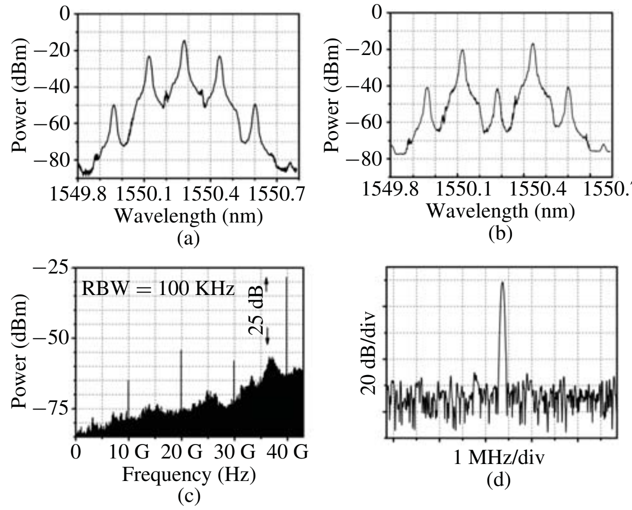

Fig. 2. Optical spectra (a) before the optical notch filter, (b) after the optical notch filter and the EDFA, (c) electrical spectrum of the generated microwave signal, and (d) zoom-in view of the 39.75-GHz signal at SPAN 10 MHz and RBW 91 kHz.

20 MHz/mA; the gain of the EA is about 40 dB, which generates a phase modulation index of around 0.4π in the PolM; the PD has a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The electrical spectrum is measured by an electrical spectrum analyzer (ESA) with a phase noise measurement module (Agilent E4447A, 3 Hz-43 GHz). In addition, an optical spectrum analyzer (OSA) (Yokogawa AQ6370C) with a resolution of 0.02 nm is employed to monitor the optical spectrum.

Fig. 2 (a) shows the optical spectrum at the output of PBS1 when the center frequency of the YIG BPF is fixed at 9.94 GHz. An optical carrier, two second-order, and two small forth-order sidebands are observed. The wavelengths of the two second-order sidebands are 1550.123 nm and 1550.441 nm, indicating a wavelength spacing of 0.318nm (39.75GHz), which is four times the frequency of the fundamental oscillating signal of the OEO. With the optical carrier removed by the optical notch filter, the remaining two second-order sidebands are 21-dB higher than the residual optical carrier and the forth-order sidebands, as shown in Fig. 2(b). Fig. 2(c) shows the electrical spectrum of the generated microwave signal. As can be seen, the spectrum of the frequency-quadrupled component is 25-dB higher than that of other harmonics. A zoom-in view of the electrical spectrum of the frequency-quadrupling signal at 39.75GHz is also provided in Fig. 2(d).

To investigate the spectral quality of the generated microwave signal, the single-sideband (SSB) phase noise of the signal is measured by the ESA. Fig. 3 shows the measurement results. As a comparison, the phase noise spectrum of the 9.9375-GHz fundamental microwave signal is also shown. The phase noises of the 9.9375 and 39.75 GHz signals are -90.6 and -103.9 dBc/Hz, respectively, at a 10-kHz offset frequency. The generated 39.75 GHz signal has 13-dB phase noise degradation as compared with that of the 9.9375 GHz fundamental signal. Theoretically, the phase noise of a frequency-quadrupled signal should have a phase noise degradation of about $10\log_{10}4^2 = 12$ dB. The measurement

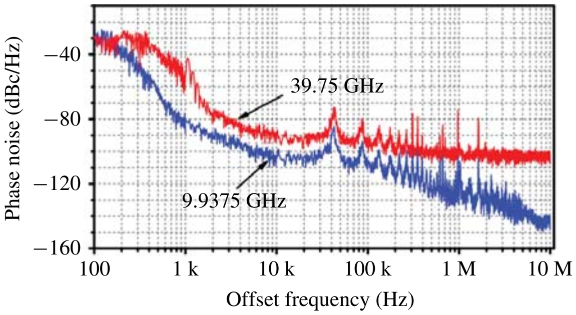

Fig. 3. Phase-noise spectra of the 39.75-GHz frequency-quadrupling signal and the 9.9375-GHz fundamental signal.

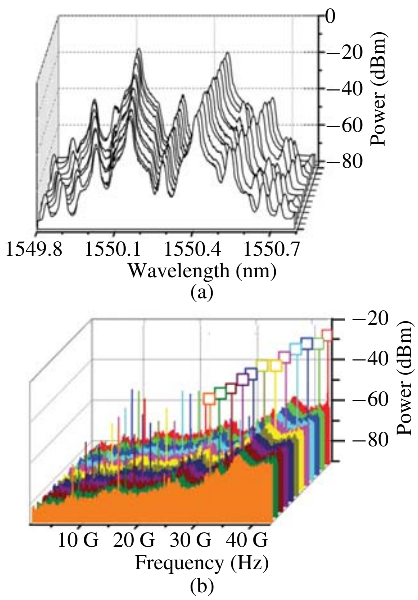

Fig. 4. (a) Optical spectra after the optical notch filter and (b) electrical spectra of the generated electrical signals (RBW = 100 kHz) when the current applied to the YIG BPF is tuned from 0.464 to 0.625 A.

is consistent with the theoretical prediction. It should be noted that the frequency-quadrupling signal is measured after an EDFA in the upper branch in Fig. 1 while the fundamental signal is measured in the lower branch. The introduction of EDFA would introduce significant amplitude noise and phase noise, forming a relatively high floor in the phase noise spectrum of the 39.75 GHz signal when the offset frequency is greater than 200 kHz. In addition, the phase noise measurement based on the ESA would be seriously affected by intensity noise, so the actual phase noise performance should be better than that shown in Fig. 3.

The tunability of the OEO is realized by changing the drive current to the YIG BPF. When the current varies from 0.464 to 0.625 A, the center frequency of the BPF varies from 8 to 10.675 GHz. Fig. 4(a) shows the optical spectra of the filtered optical signals when the BPF is driven by 12 typical current values. For all the cases, the second-order sidebands are more than 20-dB higher than the optical carrier and other sidebands. The electrical spectra of the generated electrical signals are shown in Fig. 4(b). A frequency tuning range from 32 to 42.7 GHz is achieved. During the frequency tuning, only the drive current to the YIG BPF is changed, and all other parameters are kept unaltered. It should be noted that microwave signals with a frequency higher than 43 GHz can also be achieved by our system. However, they can not be observed due to the limited measurement range of the ESA.

IV. Conclusion

We proposed and demonstrated a frequency-quadrupling OEO based on polarization modulation and polarization multiplexing, to generate high-frequency microwave signal using only low-frequency devices. The tunability of the OEO was introduced by incorporating a YIG BPF driven by a current source. By adjusting the current to the YIG BPF from 0.464 to 0.625 A, microwave signals from 32 to 42.7 GHz were achieved. The SSB phase noise of the generated frequency-quadrupling signal at 39.75 GHz was measured to be −90.69 dBc/Hz @10 kHz. The proposed system can find applications in secure wireless communication, radars, electronic warfare, optical signal processing and modern instrumentation.

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

[3] D. Lu, X. F. Zhao, C. Y. Lou, and L. Huo, "Synchronized clock multiplication through optical subharmonic injection locking of an optoelectronic oscillator," *Opt. Commun.*, vol. 284, no. 12, pp. 2742–2746, Jun. 2011.

[4] 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.

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

[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. 15, 2010.

[7] T. Sakamoto, T. Kawanishi, and M. Izutsu, "Optoelectronic oscillator using push-pull Mach-Zehnder modulator biased at null point for optical two-tone signal generation," in *Proc. CLEO 2005*, vols. 1–3. pp. 877–879.

[8] M. Shin, V. S. Grigoryan, and P. Kumar, "Frequency-doubling optoelectronic oscillator for generating high-frequency microwave signals with low phase noise," *Electron. Lett.*, vol. 43, no. 4, pp. 242–244, Feb. 15, 2007.

[9] 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.

[10] 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.

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

[12] 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.*, to be published.

[13] 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.

[14] S. L. Pan, C. Wang, and J. P. Yao, "Generation of a stable and frequency-tunable microwave signal using a polarization modulator and a wavelength-fixed notch filter," in *Proc. OFC 2009*, vols. 1–5. pp. 402–404.