Optically Tunable Frequency-Multiplying Optoelectronic Oscillator

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***Abstract*— An optically tunable frequency-multiplying optoelectronic oscillator (OEO) incorporating a tunable microwave photonic bandpass filter is proposed and experimentally demonstrated. The microwave photonic filter is implemented employing a phase-shifted fiber Bragg grating, a polarization modulator, and a phase modulator. The frequency tuning is realized by changing the wavelength of the light wave to the OEO loop. The frequency-doubling and frequency-quadrupling operations with large frequency tunability are experimentally demonstrated. The phase noise performance of the generated microwave signals is also investigated.**

***Index Terms*— Frequency multiplication, microwave generation, microwave photonics, optoelectronic oscillator, phase-shifted fiber Bragg grating, polarization modulation.**

I. INTRODUCTION

MICROWAVE signal generation using an optoelectronic oscillator (OEO) has been considered a promising solution for producing high frequency and ultra-low phase noise microwave signals [1], and can find various applications such as radar, imaging, communications, and modern instrumentation [2]. The major limitations of a conventional OEO are the low generated frequency and the limited frequency tunability due to the fact that an electrical bandpass filter (BPF) is usually employed for single-frequency operation, which has a low and fixed central frequency. To solve these problems, many solutions have been proposed to either increase the frequency of the generated signal by frequency doubling [3], [4], or improve the frequency-tunable range by employing a slow light element [5] or a tunable microwave photonic filter [6]–[9]. However, no methods have been proposed to solve both problems simultaneously.

In this letter, we proposed a new technique to simultaneously realize high frequency generation and wideband frequency tuning based on a tunable and frequency-multiplying OEO. In the proposed OEO, a tunable microwave photonic BPF implemented based on phase modulation and phase-modulation to intensity-modulation (PM-IM) conversion using a polarization modulator (PolM), a phase modulator (PM), and a phase-shifted fiber Bragg grating (PS-FBG) is incorporated in the OEO. The frequency tuning is simply done by tuning the wavelength of the light wave to the OEO. The frequency multiplying operation is achieved by taping part of the output from the PolM and sending it to an optical polarization analyzer (PolA). The joint operation of the PolM and the PolA corresponds to an intensity modulator (IM). Depending on the biasing point at the quadrature, the minimum transmission point (MITP) or the maximum transmission point (MATP), the OEO will generate a fundamental, a frequency-doubled or a frequency-quadrupled microwave signal. An experiment is performed. A frequency-doubled microwave signal with a frequency tunable from 16 to 28 GHz and a frequency-quadrupled signal with a frequency tunable from 30 to 42 GHz are generated. To the best of our knowledge, this is the widest frequency tunable range ever achieved. The phase noise performance of the OEO is also studied.

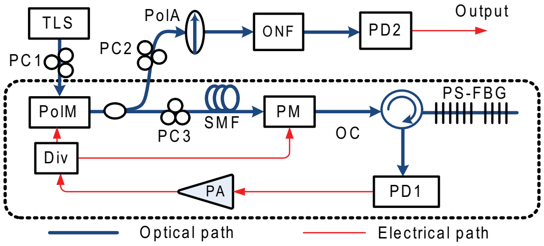

Fig. 1. Schematic of the optically tunable frequency-multiplying OEO.

II. PRINCIPLE OF OPERATION

The schematic of the proposed optically tunable frequency-multiplying OEO is shown in Fig. 1. A light wave from a tunable laser source (TLS) is sent to a PolM via a polarization controller (PC1) which makes the polarization direction of the incident light wave have an angle of 45° with respect to one principal axis of the PolM. The PolM is a special PM that supports both the transverse-electric and transverse-magnetic modes with opposite phase modulation indices [10]. The light wave at the output of the PolM is then split into two paths:

1) One is sent to the PM through a polarization controller (PC3) and a length of single-mode fiber (SMF). Since one polarization axis of the PolM is aligned with the polarization axis of the PM by adjusting PC3, the PolM also functions as a PM that supports only one polarization direction. The phase-modulated light wave from the PM is then routed to a PS-FBG via an optical circulator (OC). The PS-FBG has an ultra-narrow notch in the reflection spectrum, which will remove one sideband of the phase-modulated light wave. The reflected light wave from the PS-FBG is detected by a

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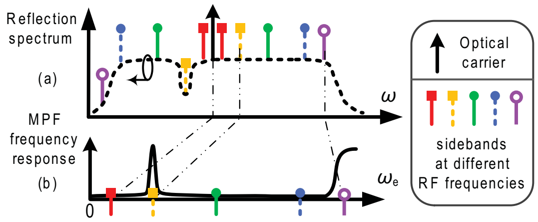

Fig. 2. Illustration of the operation of the microwave photonic filter (MPF). (a) Reflection spectrum of the PS-FBG. (b) Frequency response of the MPF.

photodetector (PD1), which leads to the implementation of a high-Q frequency-tunable microwave photonic BPF due to PM-IM conversion. The operation of the microwave photonic filter is shown in Fig. 2. A detailed theoretical analysis can be found in [11]. The signal at the output of PD1 is amplified by a RF power amplifier (PA) and applied to the PolM and the PM via a power divider (Div) to form a frequency-tunable OEO which would generate a fundamental frequency. Since the central frequency of the microwave photonic BPF can be tuned by tuning the wavelength of the TLS, the frequency of the generated fundamental signal can also be tuned.

2) The other is sent to a PolA followed by an optical notch filter (ONF) through a second PC (PC2) for achieving frequency multiplying. The principal axis of the PolA is also oriented with an angle of 45° to the same principle axis of the PolM, the PolM functions in junction with the PolA as an IM. By adjusting a static phase introduced by PC2, the PolM-based IM can be biased to operate at the quadrature, the MITP or the MATP. When biased at the quadrature point, two $\pm 1^{\text{st}}$-order sidebands with the optical carrier are generated [12]. By applying the optical signal at PD2, a microwave signal at the fundamental frequency is generated. When biased at the MITP, only two $\pm 1^{\text{st}}$-order sidebands are generated. By beating the two sidebands at PD2, a frequency-doubled microwave signal is generated [12]. When biased at the MATP, two $\pm 2^{\text{nd}}$-order sidebands with the optical carrier are generated. By using the ONF to remove the optical carrier and beating the two $\pm 2^{\text{nd}}$-order sidebands at PD2, a frequency-quadrupled microwave is generated [12]. The frequency of the frequency-multiplied signal can also be tuned by tuning the wavelength of the incident light wave with the tuning step determined by the wavelength tuning step of the TLS.

III. RESULTS AND DISCUSSION

An experiment based on the setup shown in Fig. 1 is performed. The length of the SMF is about 500 m, the length between the PM and the power divider is about 10 m. The reflection response of the PS-FBG and the frequency response of the microwave photonic BPF are measured and shown in Fig. 3. To measure the frequency response, the loop is opened at the output port of PD1, and only the PM is used. The 3-dB bandwidth of the microwave photonic BPF is about 40 MHz. It was shown that the use of two cascaded PMs would further decrease the bandwidth of the microwave photonic BPF [11]. By tuning the wavelength of the optical carrier, the center frequency of the microwave photonic BPF is accordingly tuned.

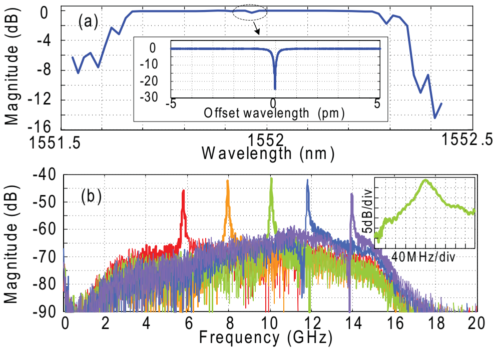

Fig. 3. (a) Measured reflection response of the PS-FBG. The inset gives a zoomed-in view of the notch. (b) Measured frequency response of the tunable microwave photonic BPF at five different frequencies. The inset gives a zoomed-in view of the frequency response when the center frequency is 10 GHz.

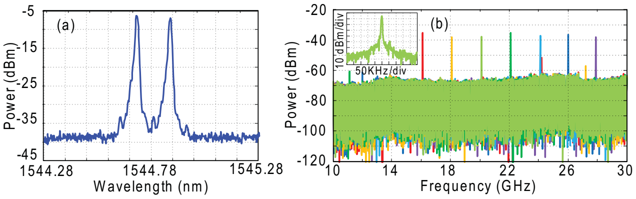

Fig. 4. (a) Optical spectrum at the output of the PolA. The PolM functions as an IM biased at the MITP. (b) Electrical spectra of the generated frequency-doubled microwave signal with the frequency tuned from 16 to 28 GHz. The resolution bandwidth (RBW) is 3 MHz. The inset gives a zoomed-in view of the 20-GHz signal with a frequency span of 500 KHz and an RBW of 4.7 KHz.

A. Frequency Doubling

The frequency doubling is achieved when the PolM functions as an IM that is biased at the MITP. The carrier wavelength is tuned to generate a fundamental frequency at 10 GHz. The optical spectrum at the output of the PolA is shown in Fig. 4(a). As can be seen the optical carrier is suppressed and only two $\pm 1^{\text{st}}$-order sidebands are observed. By beating the two $\pm 1^{\text{st}}$-order sidebands at PD2, a frequency-doubled signal at 20 GHz is generated. Fig. 4(b) shows the superimposed spectra of the generated microwave signal with the microwave frequency tuned over a frequency range from 16 to 28 GHz.

B. Frequency Quadrupling

When the PolM-based IM is biased at the MATP, frequency quadrupling is realized. The optical spectra at the outputs of the PolA and the ONF are shown in Fig. 5(a) and (b) when the fundamental frequency is 10 GHz. We can see that the $\pm 1^{\text{st}}$-order sidebands are suppressed, and the two $\pm 2^{\text{nd}}$-order sidebands become dominant after the optical carrier is removed by the NOF. Fig. 5(c) shows the superimposed spectra of the generated microwave signals with the frequency tuned over a frequency range from 30 to 42 GHz with a tuning step of about 2 GHz. Fig. 5(d) gives a zoom-in view of the 40-GHz microwave signal with a span of 500 KHz.

For both cases, the frequency tuning range could be further increased by using a PolM, PM, PD and PA with wider bandwidths, and a PS-FBG with a wider reflection bandwidth.

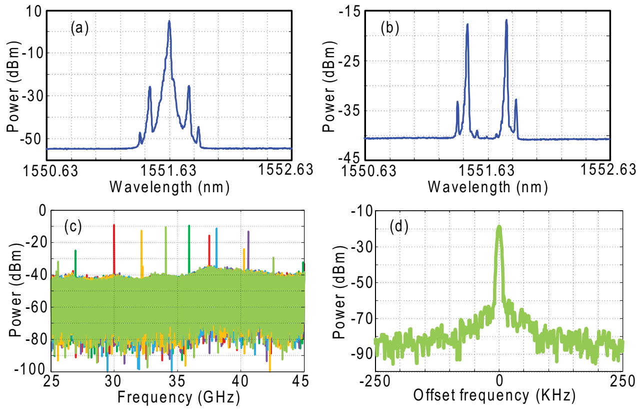

Fig. 5. (a) Optical spectrum at the output of the PolA. (b) Optical spectrum at the output of the ONF. The PolM functions as an IM biased at the MATP. (c) Electrical spectra of the generated frequency-quadrupled microwave signal with the frequency tuned from 30 to 42 GHz. The RBW is 3 MHz. (d) Zoomed-in view of the 40-GHz signal. The RBW is 4.7 KHz.

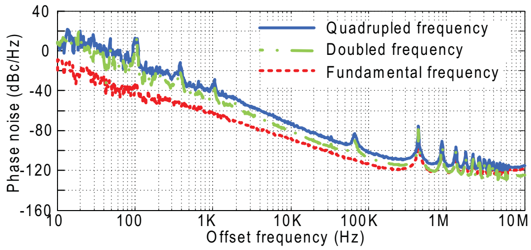

Fig. 6. Phase noise measurements for the fundamental (6-GHz), frequency-doubled (12-GHz), and frequency-quadrupled (24-GHz) signals.

C. Stability and Phase Noise

The stability of the proposed OEO is also evaluated. To do so, the system is allowed to operate in a room environment for a period of 20 minutes. No significant changes in the spectrum of the generated microwave signal are observed. The long term stability is also evaluated. Due to the wavelength drifts of the TLS and the unpackaged PS-FBG, a frequency shift of a few MHz can be observed after a few hours of operation.

The phase noise performance (PNP) of the proposed OEO is also evaluated, which is done by using an Agilent E5052B signal source analyzer with an Agilent E5053A microwave downconverter. The phase noises of the fundamental, frequency-doubled and frequency-quadrupled signals at a 100-kHz offset frequency are respectively -113.4 dBc/Hz, -107.1 dBc/Hz and -101.7 dBc/Hz, as shown in Fig. 6. The frequency-doubled and quadrupled signals have a 6-dB and 12-dB phase noise degradation compared with the fundamental frequency signal, which are consistent with the theoretical degradation given by $20\log_{10}2 \approx 6.0$ dB, and $20\log_{10}4 \approx 12.0$ dB. However, the phase noises of the frequency-multiplied signals at lower offset frequencies are a little poorer than the theoretical values, which could be contributed from an additional phase noise introduced by polarization fluctuations. The peaks at the 400-KHz offset frequency and its integer multiples correspond to the sidemodes of the OEO. In the experiment, when the OEO is tuned, the PNP is not changed, so the phase noise is frequency independent. Note that the phase noise performance can be improved if a highly wavelength-stable laser source is employed [13], [14] since the frequency noise of the laser source will be converted to the phase noise of the OEO [8], [9] due to the use of the MPF.

IV. CONCLUSION

A simple and novel wideband tunable frequency-multiplying OEO incorporating a microwave photonic BPF based on PM-IM conversion using a PolM, a PM and a PS-FBG has been proposed and demonstrated. The key features of the proposed OEO include: 1) the generation of a high frequency microwave signal can be achieved by using low-frequency components in the OEO; 2) wideband microwave frequency tuning can be realized by simply tuning the wavelength of the incident light wave. A frequency-doubled and quadrupled microwave signals with a frequency tunable from 16 to 28 GHz and from 30 to 42 GHz were, respectively, demonstrated. This is, to the best of our knowledge, the widest frequency-tunable range ever achieved. The PNP of the generated signals was also evaluated.

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REFERENCES

[1] X. S. Yao and L. Maleki, “Optoelectronic microwave oscillator,” *J. Opt. Soc. Amer. B*, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.

[2] X. S. Yao and L. Maleki, “Opto-electronic oscillator and its applications,” in *Proc. Microw. Photon. Tech. Dig. Int. Topical Meeting*, Kyoto, Japan, Dec. 1996, pp. 265–268.

[3] M. Shin, V. Grigoryan, and P. Kumar, “Frequency-doubling optoelectronic oscillator for generating high-frequency microwave signals with lowphase noise,” *Electron. Lett.*, vol. 43, no. 4, pp. 242–244, Feb. 2007.

[4] S. 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.

[5] E. Shumakher, S. Ó. Dúill, and G. Eisenstein, “Optoelectronic oscillator tunable by an SOA based slow light element,” *J. Lightw. Technol.*, vol. 27, no. 18, pp. 4063–4068, Sep. 15, 2009.

[6] S. Pan and J. P. Yao, “Wideband and frequency-tunable microwave generation using an optoelectronic oscillator incorporating a Fabry–Perot laser diode with external optical injection,” *Opt. Lett.*, vol. 35, no. 11, pp. 1911–1913, Jun. 2010.

[7] W. Li and J. P. Yao, “An optically tunable optoelectronic oscillator,” *J. Lightw. Technol.*, vol. 28, no. 18, pp. 2640–2645, Sep. 15, 2010.

[8] X. S. Yao, “High-quality microwave signal generation by use of Brillouin scattering in optical fibers,” *Opt. Lett.*, vol. 22, no. 17, pp. 1329–1331, Sep. 1997.

[9] X. S. Yao, “Phase-to-amplitude modulation conversion using Brillouin selective sideband amplification,” *IEEE Photon. Technol. Lett.*, vol. 10, no. 2, pp. 264–266, Feb. 1998.

[10] J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, “40 GHz electro-optic polarization modulator for fiber optic communications systems,” *Proc. SPIE*, vol. 5577, pp. 133–143, Dec. 2004.

[11] W. Li and J. P. Yao, “Wideband frequency-tunable optoelectronic oscillator incorporating a tunable microwave-photonic filter based on phase-modulation to intensity-modulation conversion using a phase-shifted fiber-Bragg grating,” *IEEE Trans. Microw. Theory Tech.*, to be published.

[12] W. Li and J. P. 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.

[13] D. Eliyahu, D. Seidel, and L. Maleki, “RF amplitude and phase-noise reduction of an optical link and an optoelectronic oscillator,” *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 2, pp. 449–456, Feb. 2008.

[14] K. Volyanskiy, Y. K. Chembo, L. Larger, and E. Rubiola, “Contribution of laser frequency and power fluctuations to the microwave phase noise of optoelectronic oscillators,” *J. Lightw. Technol.*, vol. 28, no. 18, pp. 2730–2735, Sep. 15, 2010.