A novel tunable optoelectronic oscillator based on a photonic RF phase shifter

JIANG Cheng-long (江成龙)*, **CHEN Fu-shen** (陈福深), **and YI XI Kang-zhu** (益西康珠)
School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

(Received 24 July 2013)

A novel tunable optoelectronic oscillator (OEO) based on a photonic radio frequency (RF) phase shifter is proposed and analyzed, which consists of a dual-drive Mach-Zehnder modulator (DMZM), a 90° hybrid coupler and a tunable microwave amplifier (TMA). This tunable OEO has a simple configuration, and the frequency of the oscillating signal can be tuned by adjusting the amplification factor of the tunable amplifier. The simulation results show that the maximum frequency shift from the center oscillation frequency is 1.48 MHz when the amplification factor of the TMA is set at 10.
Document code: A **Article ID:** 1673-1905(2013)06-0446-3
DOI 10.1007/s11801-013-3132-1

Radio frequency (RF) oscillators with high quality and low phase noise have lots of applications in diverse fields, such as wireless communications, radar, radio-over-fiber (ROF) system and modern instrumentation[1,2]. Optoelectronic oscillators (OEOs)[3], which can generate spectrally pure microwave or even millimeter-wave signals in both optical and electrical domains simultaneously, have attracted significant interest among various RF generation technologies. As an important feature of optoelectronic oscillators, frequency tunability has been implemented by different schemes[4-10]. In Ref.[4], a tunable OEO was proposed by using dispersive fibers and a wavelength-tunable laser diode. A tunable OEO with yttrium iron garnet (YIG) filter was demonstrated in Ref.[5]. With a directly modulated laser diode in Ref.[6], a tunable OEO was realized by adjusting the driving current of the laser diode. Employing a semiconductor optical amplifier (SOA)-based slow light element, another tunable OEO was reported in Ref.[7]. Using a wavelength-dependent resonant component like an injection-locked Fabry-Perot laser diode (LD) in Ref.[8] or a narrow-band phase-shifted fiber Bragg grating (FBG) in Ref.[9], the oscillation frequency was tuned. In Ref.[10], by tuning the dispersion of a linearly chirped FBG, the frequency tuning of OEO was realized. Several improved structures[11-14] based on Ref.[10] were demonstrated recently, but the complexity was increased.

In this paper, we introduce a novel tunable OEO with a photonic RF phase shifter[15,16] consisting of a dual-drive Mach-Zehnder modulator (DMZM), a 90° hybrid coupler and a tunable microwave amplifier (TMA). When tuning the RF ratio between two electrodes of the DMZM by TMA, a variable phase shift is generated. As the phase is a part of the total loop delay, the oscillation frequency is tuned when the phase condition is changed. The structure and the performance of this tunable OEO are discussed.

Fig.1 shows the schematic diagram of the configuration of the proposed tunable OEO. The key component is the photonic RF phase shifter formed by a DMZM, a TA and a 90° hybrid coupler. The light wave from LD is sent to the DMZM, and is split equally into two arms. Two RF signals with the same frequency but different amplitudes drive the electrodes of arm 1 and arm 2, respectively. The two RF signals are given by

$$V_{RF1}=V_1\sin\omega t, \quad (1)$$
$$V_{RF2}=V_2\cos\omega t, \quad (2)$$

where ω is the RF frequency, and V_1 and V_2 are the two RF amplitudes. V_1 and V_2 are given by $V_1=V$ and $V_2=gV$, where g is the amplification factor of TA. Arm 2 uses an additional direct current (DC) bias of $-V_\pi/2$, and V_π is the half-wave voltage of the DMZM. The optical signals in arm 1 and arm 2 can be expressed as

$$E_1=\frac{E}{\sqrt{2}}\sin(\omega_0 t+\frac{\pi V_{RF1}}{V_\pi})=\frac{E}{\sqrt{2}}\sin(\omega_0 t+\frac{\pi V_1\sin\omega t}{V_\pi}), \quad (3)$$

$$E_2=\frac{E}{\sqrt{2}}\sin(\omega_0 t-\frac{\pi V_{RF2}}{V_\pi}+\frac{\pi}{2})=\frac{E}{\sqrt{2}}\cos(\omega_0 t-\frac{\pi V_2\cos\omega t}{V_\pi}), \quad (4)$$

where E is the amplitude of electric field, and ω_0 is the frequency of the incident light. The output of the DMZM

* E-mail: Jchenglong_uestc@163.com

can be described as

$$E_{out} = E_1 + E_2 = \frac{E}{\sqrt{2}}\sin(\omega_0 t + \frac{\pi V_1 \sin\omega t}{V_\pi}) + \frac{E}{\sqrt{2}}\cos(\omega_0 t - \frac{\pi V_2 \cos\omega t}{V_\pi}) . \quad (5)$$

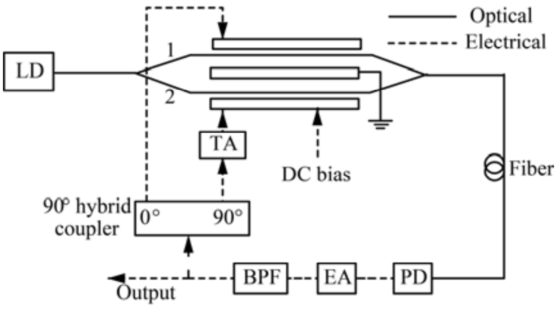


Fig.1 Schematic diagram of the proposed tunable OEO

After transmission over a fiber and recovered by a photodetector (PD), the RF output after the electrical amplifier (EA) is given by

$$V = C\sin\{\delta \sin[\omega(t+\tau)+\varphi]\} , \quad (6)$$

where C is a constant including the input optical power, the responsivity and the load impedance of the PD, and the amplification factor of EA, τ is the optical delay of the fiber, and δ and φ can be expressed as

$$\delta = \frac{\pi}{V_\pi}\sqrt{V_1^2 + V_2^2} = \frac{\pi V}{V_\pi}\sqrt{1+g^2} , \quad (7)$$

$$\varphi = \arctan\frac{V_2}{V_1} = \arctan g . \quad (8)$$

Expanding the right side of Eq.(6) with Bessel functions, an RF band-pass filter (BPF) in the loop is used to block all harmonic components, so Eq.(6) becomes

$$V = CJ_1(\delta)\sin[\omega(t+\tau)+\varphi] . \quad (9)$$

Comparing Eqs.(1) and (9), it can be seen that a phase shift φ of RF signal 1 is achieved.

Then the signal is split into two parts by the 90° hybrid coupler, and sent back to the electrodes of the DMZM. If the EA can supply sufficient gain to the loss in the loop, the OEO will start to oscillate when the loop is closed. Similar to Ref.[8], the total output after PD at any instant is the summation of all circulating fields. When the oscillation is stable, the effective open-loop gain $CJ_1(\delta)$ is a little less than unity, which is given as

$$V' = \exp(\mathrm{j}\omega t)\times\sum_{m=0}^{\infty}[CJ_1(\delta)]^m \exp(\mathrm{j}m\omega\tau + \mathrm{j}m\varphi) = \frac{\exp(\mathrm{j}\omega t)}{1 - CJ_1(\delta)\exp(\mathrm{j}\omega\tau + \mathrm{j}\varphi)} . \quad (10)$$

The corresponding RF power is then given as

$$P \propto V'^2 = \frac{1}{1+[CJ_1(\delta)]^2 - 2CJ_1(\delta)\cos(\omega\tau+\varphi)} . \quad (11)$$

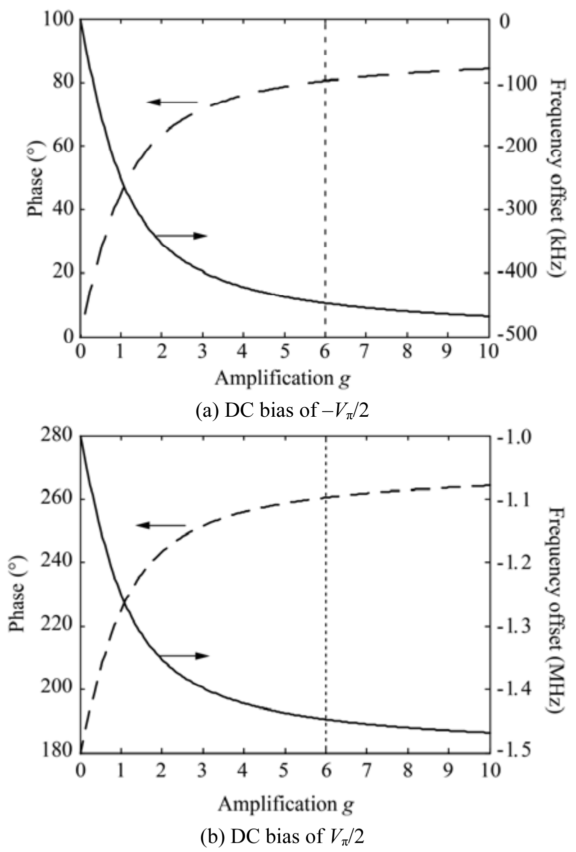
Only the frequencies which meet the condition of $\omega\tau+\varphi=2k\pi$ (k=0,1,2⋯) can oscillate. It can be got from Eq.(11) that the oscillation frequency will change with a variation of φ obtained by g. The relationship between φ and the oscillation frequency is given by

$$\Delta f = -\frac{1}{2\pi\tau}\Delta\varphi . \quad (12)$$

Then a tunable OEO obtained by the phase shift φ is realized.

We suppose the fiber length is 100 m which is equivalent to an optical delay τ of 0.5 μs, and then a BPF with a 3 dB bandwidth of 2 MHz can obtain a single-mode oscillation. From Eqs.(8) and (12), the relations of the phase shift and the frequency tunability with the amplification factor of TA are shown in Fig.2(a).

When the DC bias $-V_\pi/2$ is altered to $V_\pi/2$, the phase shift φ becomes $\varphi+\pi$, and a similar result is shown in Fig.2(b). A larger offset frequency from 1 MHz to 1.48 MHz is achieved. Fig.3 shows the calculated frequency spectra of the tunable OEO with three different oscillation frequencies.



(a) DC bias of $-V_\pi/2$

(b) DC bias of $V_\pi/2$

Fig.2 The influence of different amplification factors on phase and frequency offset

In order to oscillate, the effective open-loop gain $CJ_1(\delta)$ must be larger than unity. However, as a function of g as shown in Eq.(7), δ changes at the same time while tuning the oscillation frequency. Though EA in the loop can be tuned to compensate the fluctuation, it is difficult to realize since $J_1(\delta)$ is nonlinear. As shown in Fig.4, $J_1(\delta)$ varies within a relative narrow range when $g\leq6$, and decrease drastically when $g\geq6$.

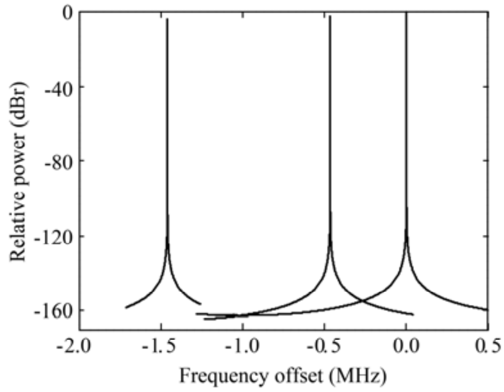


Fig.3 Calculated frequency spectra of the tunable OEO with three different oscillation frequencies

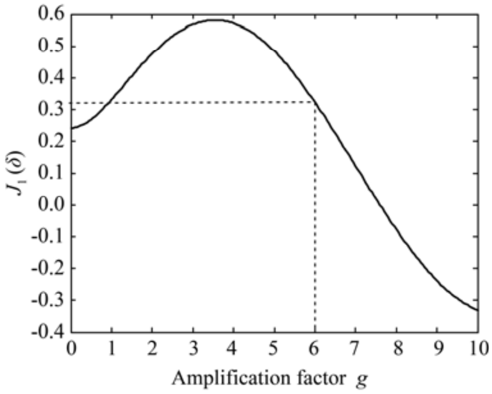


Fig.4 Variation of $J_1(\delta)$ with amplification factor g

Meanwhile, compared with those when g ranging from 6 to 10, it can be noticed in Fig.2 that the phase shift and the oscillation frequency change more significantly when g ranging from 0 to 6. Consequently, we can conclude that this tunable OEO performs preferably when the amplification factor of TA ranging from 0 to 6.

A novel approach to achieve a frequency-tunable OEO using a photonic RF phase shifter is proposed and simulated in this paper. In the proposed system, the oscillation frequency can be easily tuned by changing the amplification factor of TA. An obvious variation of the oscillation frequency is obtained by adjusting g from 0 to 6, and a maximum frequency shift of 1.48 MHz from the center oscillation frequency is achieved when g is set at 10. This technique is insusceptible to environment conditions, and it can be applied in the areas of radars and fiber wireless communications.

References

[1] Capmany J. and Novak D., Nature Photonics **1**, 319 (2007).

[2] Yao X. S. and Maleki L., IEEE Journal of Quantum Electronics **32**, 1141 (1996).

[3] Yao X. S. and Maleki L., JOSA B **13**, 1725 (1996).

[4] Poinsot S., Porte H., Goedgebuer J. P., Rhodes W. T. and Boussert B., Optics Letters **27**, 1300 (2002).

[5] Eliyahu D. and Maleki L., Tunable, Ultra-low Phase Noise YIG based Optoelectronic Oscillator, 2003 IEEE MTT-S International Microwave Symposium Digest **3**, 2185 (2003).

[6] Kotb H. E., Safwat A. E., Boghdady H. and Khalil D., Tuning of an RF Optoelectronic Oscillator, IEEE MWP'06 International Topical Meeting on Microwave Photonics, 1 (2006).

[7] Shumakher E., Dúill S. Ó. and Eisenstein G., Journal of Lightwave Technology **27**, 4063 (2009).

[8] Pan S. and Yao J., Optics Letters **35**, 1911 (2010).

[9] Li W. and Yao J., IEEE Transactions on Microwave Theory and Techniques **60**, 1735 (2012).

[10] Li W. and Yao J., Journal of Lightwave Technology **28**, 2640 (2010).

[11] WEI Zhi-hu, WANG Rong, FANG Tao, PU Tao, SUN Guo-dan, XIONG Jin-tian and ZHEN Fei, Journal of Optoelectronics·Laser **23**, 1649 (2012). (in Chinese)

[12] Wei Z., Wang R., Pu T., Sun G., Fang T. and Zheng J., Optical Fiber Technology **19**, 383 (2013).

[13] Yang B., Jin X., Chen Y., Zhou J., Zhang X., Zheng S. and Chi H., IEEE Photonics Technology Letters **25**, 921 (2013).

[14] Wei Z., Pan S., Wang R., Pu T., Sun G., Fang T. and Zheng J., Optical Engineering **52**, 055005 (2013).

[15] Lee S. S., Udupa A. H., Erlig H., Zhang H., Yian C., Zhang C., Chang Y., Bhattacharya D., Tsap B., Steier W. H., Dalton L. R. and Fetterman H. R., IEEE Microwave and Guided Wave Letters **9**, 357 (1999).

[16] LI Hai-bin, CHEN Wei-you, QU Peng-fei, XIAO Yong-chuan and DONG Wei, Journal of Optoelectronics·Laser **22**, 1624 (2011). (in Chinese)