A Compact Optoelectronic Oscillator Based on an Electroabsorption Modulated Laser

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***Abstract*— A novel method to miniaturize the optoelectronic oscillator (OEO) is proposed and demonstrated by replacing the laser source, intensity modulator, and photodetector with an electroabsorption modulated laser (EML), because the electroabsorption modulator (EAM) in the EML can perform simultaneously photodetection and intensity modulation. A 9.945-GHz microwave signal with a phase noise of −101.31 dBc/Hz at 10 kHz offset is experimentally generated. The dependence of the phase noise on the EAM bias voltage is investigated. The EML-based OEO features low cost, simple structure, and potentially high operational frequency, which can find applications in future communications, radars, navigation, and satellite systems.**

***Index Terms*— Electroabsorption modulated laser, microwave generation, microwave photonics, optoelectronic oscillator (OEO).**

I. Introduction

OPTOELECTRONIC oscillator (OEO), invented by Yao and Maleki in 1996 [1], is considered an attractive and promising way to produce microwave or millimeter-wave signals with high spectral purity and low phase noise. Conventionally, the OEO consists of a laser source, an intensity modulator (IM), a long fiber delay line, a photodetector (PD), an electrical amplifier, an electrical phase shifter (PS), an electrical bandpass filter (EBPF) and other electrical or optical devices [2–5]. The use of so many discrete electrical and optical components in the OEO not only makes it bulky, but also leads to considerable power consumption, which may not meet the strict requirement of the future communications, radars, navigation and satellite systems. Previously, a lot of efforts were devoted to minimize the size of the OEO. One of the most widely adopted ways is to replace the long fiber delay lines by high-Q optical resonators, such as whispering gallery modes (WGM) resonators [6–8] and fiber ring resonators (FRRs) [9, 10]. But higher Q value means larger coupling difficulty and higher wavelength selectivity. Sophisticated circuit must be applied to maintain the stable operation of the OEO. Another way to reduce the size of the OEO is to replace the laser source and the IM with a directly modulated laser (DML), which would save one device and its related control circuit [11, 12] . However, the DMLs under large signal modulation would broaden the linewidth of the optical carrier, leading to large phase noise in the OEO (e.g., around −75 dBc/Hz @ 10-kHz offset for a 10-GHz OEO [12]).

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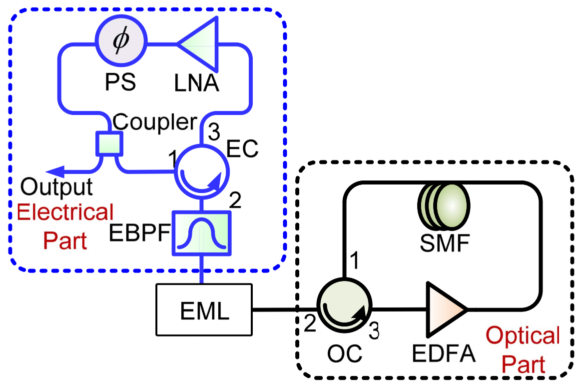

Fig. 1. Schematic diagram of optoelectronic oscillator based on the electroabsorption modulated laser. EC: electrical circulator. LNA: low noise amplifier. OC: optical circulator. EDFA: Erbium-doped optical fiber amplifier. SMF: single-mode fiber.

In this Letter, we propose a novel method to miniaturize the OEO by replacing the laser source, modulator and photodetector with an electroabsorption-modulated laser (EML), which saves two devices and the corresponding drive circuits. An EML-based OEO is experimentally constructed to demonstrate the feasibility of replacing the laser source, modulator and photodetector with the EML. A high-purity 9.945-GHz signal with a phase noise as low as −101.31 dBc/Hz (−126.2 dBc/Hz) at 10 kHz (1 MHz) offset is generated, showing that the EML-based OEO has acceptable performance.

II. Principle

Fig. 1 shows the schematic diagram of the proof-of-concept experiment for demonstrating the feasibility of replacing the laser source, modulator and PD in a conventional OEO with an EML. The 13-GHz EML (Apogee Photonics LIM 100) is a laser diode and EAM monolithically integrated device, in which the laser diode generates an optical carrier and the EAM obtains simultaneously efficient RF modulation and photodetection because of the Franz-Keldysh effect and the p-i-n structure [13–15]. Since the intensity modulation and photodetection is realized by the single device, the optoelectronic feedback loop in the conventional OEO [1–5] can be divided into two parts, i.e. optical part and electrical part. The output of the EML is fed back to the EML to perform photodetection after passing through the optical part. Then the detected signal is fed back to the RF port of the EML via the electrical part. The electrical part consists of an EBPF, a circulator, a low noise amplifier (LNA), a phase shifter and an electrical coupler. The bandwidth of the EBPF is 11.34 MHz centered at 9.95 GHz. The small-signal gain of the LNA is 40 dB. The optical part consists of an optical circulator (OC), an Erbium-doped fiber amplifier (EDFA) and a 3-km single-mode fiber (SMF). It should be noted that the optical part can be realized by a reflective structure, in which a fiber Bragg grating, a fiber mirror or a reflective resonator can be used to reflect the optical signal back to the EML. With this reflective optical structure, the requirement of the length of the optical delay line can be reduced to a half, or a reflective resonator can be directly incorporated, which further simplifies the OEO. Taking into account that the EAM in the EML has many other features such as low-voltage operation, and high bandwidth over 60 GHz, the EML-based OEO can have advantages in terms of low cost and high operational frequency.

III. Experiment Results and Discussion

In the EML-based OEO, the photodetection performance of the EML is of great importance, which is tested by introducing an optical microwave signal to the EML. The optical microwave signal is generated by modulating a lightwave at a Mach-Zehnder modulator (MZM) biased at the quadrature point (QTP) by a 9.95-GHz sinusoidal signal with a power of 7 dBm. Fig. 2(a) shows the power of the detected microwave signal as a function of the EAM bias voltage. The input optical power to the EML is fixed at 4 dBm during the measurement of Fig. 2(a). As can be seen, larger EAM bias voltage results in higher photodetection efficiency. For instance, when the voltage is increased from −0.7 to −1.8 V, the measured power of the 9.95-GHz signal is increased from −41.95 dBm to −30.59 dBm if the drive current of the laser diode is 40 mA. In addition, when the drive current of the laser diode is increased which means that the CW optical power to the EAM is increased, the photodetection efficiency would be decreased because the CW lightwave would consume considerable carriers in the EAM. Fig. 2(b) shows the measured electrical power as a function of the injected optical power to the EML when the bias voltage of the EAM is −1.4 V and the drive current of the laser diode is 40 mA. The electrical power increases almost linearly with the injected power. No saturation effect is observed for an optical power up to 10 dBm. The slope of the curve is 2, showing that the photodetection in the EML fits the square law, comparable with an ordinary PD.

An experiment based on the setup in Fig. 1 is performed. The generated microwave signal is monitored by an electrical

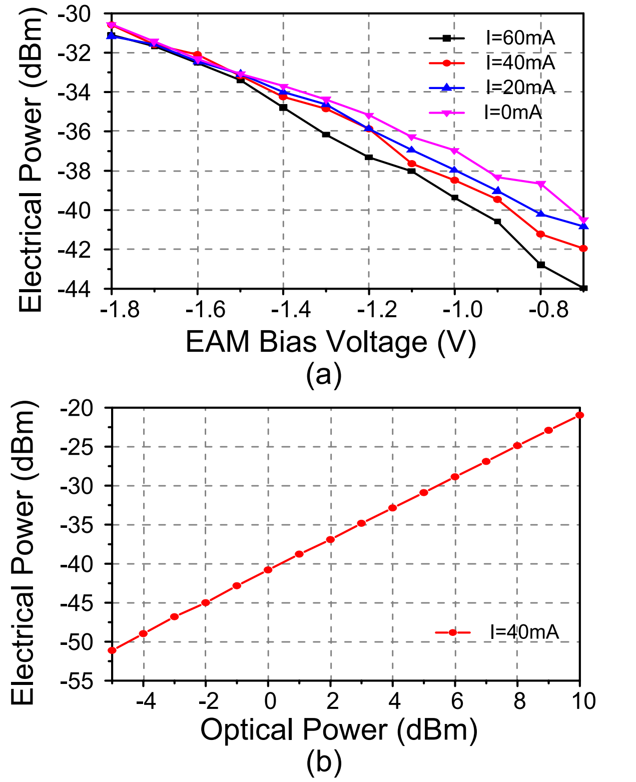

Fig. 2. Photodetection performance of the EML. (a) Detected microwave power as a function of the EAM bias voltage. (b) Detected microwave power as a function of the injected optical power when the EAM is biased at −1.4 V and the drive current of the laser diode is 40 mA.

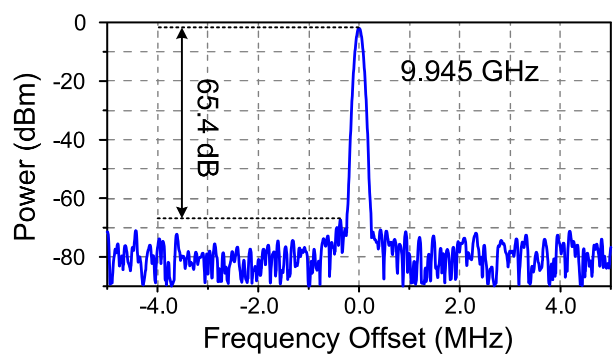

Fig. 3. Electrical spectrum of the microwave signal generated by the EML-based OEO. RBW = 91 kHz.

spectrum analyzer (ESA, Agilent E4447AU) with a phase noise measurement module. In addition, an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02-nm is used to observe the optical spectrum. Fig. 3 shows the electrical spectrum of the generated microwave signal. The EML is biased at −1.3 V and the drive current is 50 mA. To avoid self-excited oscillation in the electrical part due to the limited isolation of the electrical circulator and the reflection from the RF port of the EML, the gain of the LNA is controlled to let no signal output from the electrical coupler when the optical part is disconnected. By closing the OEO loop, a pure 9.945-GHz microwave signal with no significant side mode is observed, as shown in Fig. 3. The side-mode suppression ratio

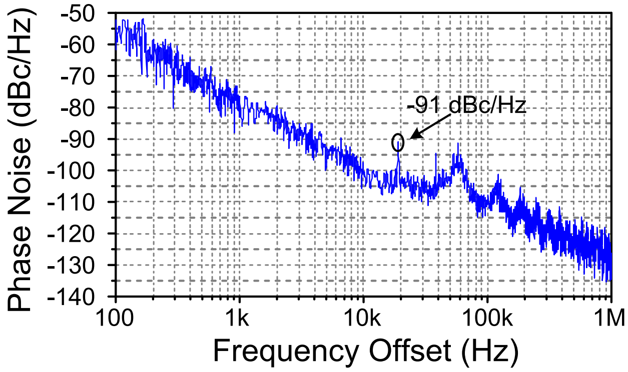

Fig. 4. Phase noise spectrum of the microwave signal generated by the EML-based OEO.

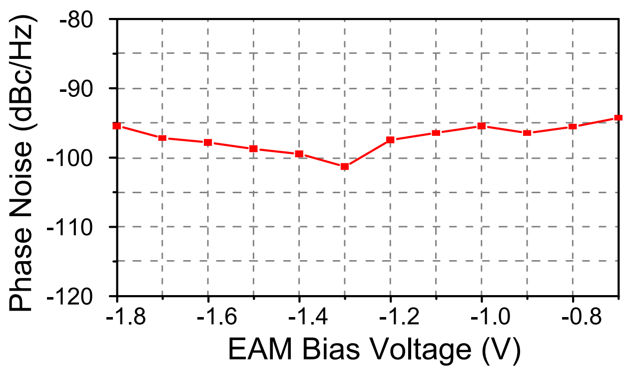

Fig. 5. Phase noise as a function of the EAM bias voltage.

(SMSR) is 65.4 dB. As compared with the conventional OEO with a single 3-km SMF loop configuration, the side modes in the electrical spectrum are very small. One possible reason is that the cross-absorption modulation (XAM) between the forward and backward lights in the EAM of the EML would help suppressing the undesirable side modes in the generated microwave signal.

Fig. 4 shows the single-sideband (SSB) phase noise performance of the microwave signal generated by the EML-based OEO. As can be seen, the phase noise of the 9.945-GHz signal is −101.31 dBc/Hz at 10 kHz offset and −126.2 dBc/Hz at 1 MHz offset. In addition, the maximal phase noise of the side modes is about −91 dBc/Hz. It should be noted that the phase noise performance has been deteriorated owing to the amplified spontaneous emission (ASE) noise in the EDFA. If an EML with higher output power is used, the EDFA can be removed or a suitable optical bandpass filter (OBPF) is available to suppress the ASE noise, the phase noise performance would be further improved. The dependence of the phase noise on the EAM bias voltage is also investigated. Fig. 5 shows the phase noises when the bias voltage of the EML is adjusted from −1.8 V to −0.7 V. For all the cases, the phase noise of the generated signal is lower than −94 dBc/Hz @ 10 kHz offset and the variation is less than 7 dB.

IV. Conclusion

A simple way to reduce the size of the OEO using an EML was proposed and experimentally demonstrated. The EAM in the EML has dual functionalities of photodetection and intensity modulation, so the laser source, modulator and photodetector in a conventional OEO can be replaced with a single EML. A 9.945-GHz microwave signal with a phase noise as low as −101.31 dBc/Hz at 10-kHz offset was obtained. The SMSR is less than 65 dB and the phase noises of the side modes were suppressed to be lower than −91 dBc/Hz with a single-loop configuration. The EML-based OEO can also reduce the required length of the optical delay line if a reflective optical path is used. In addition, if a reflective resonator is applied to replace the long fiber delay [7], an ultra-compact OEO would be realized.

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, "Multiloop optoelectronic oscillator," *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[3] W. Zhou and G. Blasche, "Injection-locked dual opto-electronic oscillator with ultra-low phase noise and ultra-low spurious level," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, pp. 929–933, Mar. 2005.

[4] J. Lasri, P. Devgan, R. Tang, and P. Kumar, "Self-starting optoelectronic oscillator for generating ultra-low-jitter high-rate (10 GHz or higher) optical pulses," *Opt. Express*, vol. 11, no. 12, pp. 1430–1435, Jun. 2003.

[5] 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, Oct. 2010.

[6] A. Matsko, L. Maleki, A. Savchenkov, and V. Ilchenko, "Whispering gallery mode based optoelectronic microwave oscillator," *J. Modern Opt.*, vol. 50, nos. 15–17, pp. 2523–2542, Mar. 2003.

[7] K. Volyanskiy, P. Salzenstein, H. Tavernier, M. Pogurmirskiy, Y. K. Chembo, and L. Larger, "Compact optoelectronic microwave oscillators using ultra-high Q whispering gallery mode disk-resonators and phase modulation," *Opt. Express*, vol. 18, no. 21, pp. 22358–22363, Oct. 2010.

[8] L. Maleki, "Sources: The optoelectronic oscillator," *Nature Photon.*, vol. 5, pp. 728–730, Dec. 2011.

[9] P.-H. Merrer, O. Llopis, and G. Cibiel, "Laser stabilization on a fiber ring resonator and application to RF filtering," *IEEE Photon. Technol. Lett.*, vol. 20, no. 16, pp. 1399–1401, Aug. 15, 2008.

[10] K. Saleh, P.-H. Merrer, O. Llopis, and G. Cibiel, "Optical scattering noise in high Q fiber ring resonators and its effect on optoelectronic oscillator phase noise," *Opt. Lett.*, vol. 37, no. 4, pp. 518–520, Feb. 2012.

[11] J. Kitching, E. Ferre-Pikal, L. Hollberg, and F. Walls, "Optoelectronic microwave oscillators using diode lasers," in *Proc. IEEE Adv. Semicond. Laser Conf.*, Aug. 1997, pp. 21–22.

[12] K. Koizumi, M. Yoshida, and M. Nakazawa, "A 10-GHz optoelectronic oscillator at 1.1 μm using a single-mode VCSEL and a photonic crystal fiber," *IEEE Photon. Technol. Lett.*, vol. 22, no. 5, pp. 293–295, Mar. 1, 2010.

[13] R. Welstand, S. Pappert, C. Sun, J. Zhu, Y. Liu, and P. Yu, "Dual-function electroabsorption waveguide modulator/detector for optoelectronic transceiver applications," *IEEE Photon. Technol. Lett.*, vol. 8, no. 11, pp. 1540–1542, Nov. 1996.

[14] T. H. Wood, E. Carr, B. Kasper, R. Linke, C. Burrus, and K. Walker, "Bidirectional fibre-optical transmission using a multiple-quantum-well (MQW) modulator/detector," *Electron. Lett.*, vol. 22, pp. 528–529, May 1986.

[15] L. Westbrook and D. Moodie, "Simultaneous bi-directional analogue fibre-optic transmission using an electroabsorption modulator," *Electron. Lett.*, vol. 32, pp. 1806–1807, Sep. 1996.