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# Tunable optoelectronic oscillator incorporating a carrier phase-shifted double sideband modulation system

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ABSTRACT

A tunable optoelectronic oscillator (OEO) implemented by using a carrier phase-shifted double sideband modulation (CPS-DSB) system consisting of an optical coupler (OC), a Mach–Zehnder modulator (MZM) biased at the minimum transmission point, a polarization beam splitter (PBS), and a tunable optical delay line (TODL) is proposed and experimentally demonstrated. The key device in the system is the CPS-DSB system, which functions in conjunction with a chirped fiber Bragg grating (CFBG) in the loop form a high-*Q* microwave photonic filter (MPF). Through simply adjusting the TODL, the central frequency of the MPF is shifted and the frequency tunability of the OEO can be realized. A detailed theoretical analysis is provided and the results are confirmed by an experiment. A microwave signal with a frequency-tuning range from 7.24 to 14.05 GHz is generated. The phase noise, the long-term stability and the side-mode suppression performance of the generated microwave signal are also investigated.

## 1. Introduction

Optoelectronic oscillators (OEOs) with the unique ability to generate high spectral purity and low phase noise microwave signals [1] can be applicated in the fields of radar, radio-over-fiber system, sensor, optical signal processing, and modern instrumentation [2–4]. In a conventional OEO structure, an electrical bandpass filter (EBPF) is employed to perform selection of the oscillation mode, but the frequency-tuning range is limited due to the narrow bandwidth and fixed central frequency of the EBPF [5]. To overcome the problem, microwave photonic filters (MPFs) are considered as a reasonable candidates for replacing the EBPF, which can bring the advantages of immunity to electromagnetic interference (EMI), high bandwidth, wideband tunability [6]. In [7], a tunable OEO was obtained by using an injection-locked Fabry–Perot laser diode (FP-LD) as a MPF, a frequency-tuning range from 6.14 to 10.85 GHz was realized by adjusting the wavelength of the incident light wave or the longitudinal modes of the FP-LD. However, the scheme has a poor stability because the instability of the FP-LD may cause a fluctuation in frequency. In [8], a MPF consisting of a two-port phase modulator (PM) and a linear chirped fiber Bragg grating (LCFBG) was incorporated into an OEO, which realizes a frequency-tuning range from 6.5 to 11.5 GHz by tuning the dispersion of the LCFBG. However, the dispersion is difficult to realize a large tunable range in practice. In [9], a joint operation of a polarization modulator, a CFBG, and a polarization beam splitter (PBS) form a MPF. By incorporating the MPF into an OEO, a frequency-tuning range from 5.8 to 11.8 GHz was generated by tuning the polarization state of the polarization controller (PC) placed before the PBS, but the PC is susceptible to ambient condition, which have an effect on the system stability. In [10], a MPF was implemented with cascaded infinite impulse response filter. The MPF can be reconfigured by adjusting the lengths of the cascaded recirculating delay lines (RDLs), and then the oscillation frequency is tuned. However, mutual interference is found between the two RDLs. In [11], using a directly modulated DFB semiconductor laser in an OEO, a frequency-tuning range from 3.77 to 8.75 GHz was generated by changing the bias current and the operation temperature of the DFB laser. However, the modulation bandwidth is limited by directly modulated distributed feedback (DFB) semiconductor laser, and the stability of the oscillation signal is impressionable to ambient condition.

In this paper, we propose and demonstrate a novel wideband tunable OEO based on a carrier phase-shifted double sideband modulation (CPS-DSB) system, which is implemented using an optical coupler (OC), a Mach–Zehnder modulator (MZM) biased at the minimum transmission point (MITP), a PBS, and a tunable optical delay line (TODL). By the joint operation of the CPS-DSB system and a CFBG forming a MPF with the central frequency can be shifted by simply tuning the TODL. Therefore, the frequency tunability and the coarse mode selection of the OEO are realized.

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In addition, the dual-loops system is constructed between two PBS, which performs fine selection of the oscillation mode by means of the Vernier principle [12]. A detailed theoretical analysis was carried out and a proof of concept experiment has been done. The performance of the generated microwave signal is verified by measuring tunability, single-sideband (SSB) phase noise, spectral purity, and long-term stability.

## 2. Principle

Fig.1(a) shows the schematic of the proposed tunable OEO. A linearly polarized light wave from a laser diode (LD) is split into two branches via an OC. In the upper branch, a TODL is used to implement the phase shift of the optical carrier. In the lower branch, the MZM biased at the MITP is used to modulate the feedback signal, which realizes the carrier suppression double sideband modulation. After combination by a $PBS_1$, the CPS-DSB signal is formed, the formation process of which is explicated in Fig. 1(b). Here, we use small-signal modulation condition where only the optical carrier and 1st-order sidebands are considered. The CPS-DSB signal is then launched to a CFBG through an optical circulator, where the function of the CFBG is as a dispersive element. Subsequently, an optical domain dual-loop composite cavity is introduced to perform fine selection of the oscillation mode [12]. After that, the optical signal is converted to a microwave signal by a photodetector (PD) and then fed back to the MZM to form an oscillation loop. An erbium-doped fiber amplifier (EDFA) and an electrical amplifier (EA) are used in the oscillation loop to provide sufficient gain.

Following that, the operation of the OEO is discussed. Firstly, we analyze the open-loop response of the OEO. An optical carrier from a laser diode (LD) is split into two branches via an OC. For the upper branch, the electrical field at the output of the TODL is given by $E_1(t) = \sqrt{2}E_0 \exp(j\omega_c t + j\Phi)/2$, where $E_0$ is the electrical amplitude of the LD and $\Phi = \beta \cdot \Delta l$ ($\beta$ is the wave-number, $\Delta l$ is the length delay of the TODL) is the phase shift of the optical carrier. For the lower branch, suppose the input modulation microwave signal $V_{in} = V_e \cos(\omega_e t)$, where $V_e$ and $\omega_e$ are the amplitude and angular frequency of the microwave signal. Under small-signal modulation condition, the electrical field at the output of the MZM (biased at the MITP) is given by $E_2(t) \approx \sqrt{2}E_0 jJ_1(m)\{\exp[j(\omega_c + \omega_e)t] + \exp[j(\omega_c - \omega_e)t]\}/4$, where $m = \pi V_e/V_\pi$, $V_\pi$ is the half-wave voltage of the MZM, $J_n(\cdot)$ is the $n$th-order Bessel function of the first kind. $E_1(t)$ and $E_2(t)$ are then combined by the $PBS_1$, the CPS-DSB signal is formed, and its electrical field can be expressed as

$$E_3(t) = E_1(t) + E_2(t) \approx E_0\{2exp(j\omega_c t + j\Phi) \\ + jJ_1(m)(exp[j(\omega_c + \omega_e)t] + exp[j(\omega_c - \omega_e)t])\}/4$$

When the CPS-DSB signal is sent to a CFBG via an optical circulator, which functions as a dispersive element. The dispersion-induced phase shift introduced into the optical carrier and the 1st-order sidebands in Eq. (1), respectively. Thus, we have [13]

$$E_{CFBG}(t) = F^{-1}\{E_3(\omega)exp(j\theta)\} \\ = E_0\{2exp(j\omega_c t + j\Phi) + jJ_1(m)(exp[j(\omega_c + \omega_e)t \\ -\lambda^2\omega_e^2\chi/4\pi c] + exp[j(\omega_c - \omega_e)t - \lambda^2\omega_e^2\chi/4\pi c])\}/4$$

where $\theta = -\lambda^2(\omega - \omega_c)^2\chi/4\pi c$, $\lambda$ is the wavelength of the LD, $\chi$ is the accumulated dispersion of the CFBG. $F^{-1}(\cdot)$ is inverse Fourier transform. $c$ is the velocity of light in vacuum. After square-law detection by a PD, ignoring the DC current and the higher order harmonics, the recovered microwave signal can be written as

$$V(\omega_e, t) = \rho E_0^2 R J_1(m)\sin(\omega_e t)\cos(\lambda^2\omega_e^2\chi/4\pi c - \Phi)/2 \tag{3}$$

where $\rho$ is a constant which is determined by the optical link loss, the EDFA, and the responsivity of the PD. $R$ is the load impedance of the PD. Therefore, the frequency response can be expressed as

$$H(\omega_e) = \pi\rho E_0^2 R\cos(\lambda^2\omega_e^2\chi/4\pi c - \Phi)/8V_\pi \tag{4}$$

As can be seen from Eq. (3), the term $F_1(\omega_e) = \cos(\lambda^2\omega_e^2\chi/4\pi c - \Phi)$ corresponds to a MPF, which resulted from that $F_1(\omega_e)$ is a frequency-dependent function. Accordingly, the transmission peak is demonstrated when $\lambda^2\omega_e^2\chi/4\pi c - \Phi = k\pi$, $k = 0, 1, 2, \ldots$, the frequency of the transmission peak is then obtained as

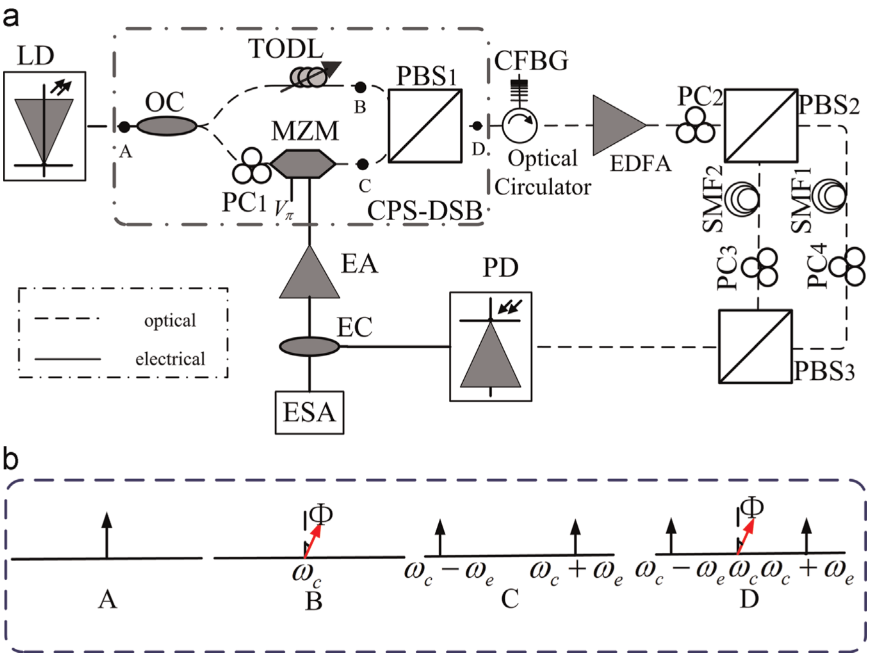

**Fig. 1.** (a) Schematic of the proposed tunable OEO. LD: laser diode. TODL: tunable optical delay line. OC: optical coupler MZM: Mach–Zehnder modulator. CFBG: chirped fiber bragg grating. PC: polarization controller. PBS: polarization beam splitter. SMF: single-mode fiber. PD: photodetector. EC: electrical coupler. EA: electrical amplifier. ESA: electrical spectrum analyzer. (b) The formation process of the CPS-DSB system.