A novel optoelectronic oscillator based on all optical signal processing

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A novel dual-loop optoelectronic oscillator (OEO), which is constructed based on all optical signal processing, is proposed and analyzed. By inserting an erbium-doped fiber amplifier (EDFA) and a fiber Bragg grating (FBG) on the optical domain, the amplification and filter are implemented in the OEO loop. The performance of the OEO is improved without any electronic filter or electronic amplifier. A theoretical analysis is performed, and the generated microwave signal exhibits good performance with phase noise lower than –120 dBc/Hz at 10 kHz and a high side-mode suppression ratio (SMSR).

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Recently, optoelectronic oscillators (OEOs) have attracted considerable attention for the generation of microwave signals with high frequency and ultra-low phase noise in various applications, such as radar, radio-over-fiber (RoF) system, phased array antennas, optical signal processing and modern instrumentation[1-3]. The conventional OEO is a single loop system, including an intensity modulator, an optical fiber delay line, a photodetector (PD), an electrical bandpass filter (EBPF) and an electrical amplifier (EA). When the loop gain is larger than the loss and the round-trip phase shift of signal is an integer multiple of 2π, the OEO can generate an oscillation at a certain frequency determined by the center frequency of the EBPF and oscillation modes[1]. However, the long fiber loops with a high Q oscillator lead to modes spacing too narrow to be filtered by standard EBPF. To ensure that an OEO operates at a single oscillation mode, several schemes have been reported[4-9]. The OEO signals are amplified and filtered by electrical devices to meet the requirement of oscillation. Thus, the performance of the OEO is degraded[10].

In this paper, a dual-loop OEO based on all optical signal processing is proposed and demonstrated. For the OEO, a low-biased Mach-Zehnder modulator (MZM) followed by optical amplification with an erbium-doped fiber amplifier (EDFA) is used to compensate the oscillating loop losses[11]. Also a fiber Bragg grating (FBG) is used as the mode selector instead of an EBPF[12], which can simultaneously achieve low phase noise and a high side-mode suppression ratio (SMSR). The theoretical analysis and simulation show that the phase noise of the generated microwave signals is lower than –120 dBc/Hz at frequency offset of 10 kHz. The SMSR is suppressed over 70 dB (or 50 dB) with frequency span of 4 MHz (or 20 GHz).

The schematic diagram of the proposed dual-loop OEO based on all optical signal processing is shown in Fig.1. The light wave from a laser diode (LD) is coupled into a low-biased MZM via polarization controller 1 (PC1), passing through an FBG via optical circulator, reflected by the FBG, and sent to an EDFA via the optical circulator again. After optical amplification by the EDFA, the light wave is split into two optical paths by a polarization-beam splitter (PBS) via PC2. In each path, a section of single-mode fiber (SMF) and a PC (PC3 or PC4) are inserted. The two optical paths are combined by polarization-beam combiner (PBC). The combined signal is converted to an electrical signal by a PD and fed back to the MZM to form the OEO loop.

Mathematically, the electrical field at the output of the MZM can be expressed as[13]

$$E_{\mathrm{MZM,O}}(\phi_{\mathrm{DC}},t)=\sqrt{\alpha}E_0\cos\omega_0 t\cos\{\frac{\Phi[V(t)]}{2}\}=$$
$$\sqrt{\alpha}E_0\cos\omega_0 t\cos[\frac{\phi_{\mathrm{DC}}}{2}+\frac{\gamma}{2}\cos(\Omega t+\varphi)]=$$
$$\sqrt{\alpha}E_0\cos\omega_0 t\{\cos(\frac{\phi_{\mathrm{DC}}}{2})[J_0(\frac{\gamma}{2})+$$
$$2\sum_{m=1}^{\infty}(-1)^m J_{2m}(\frac{\gamma}{2})\cos 2m\times$$

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$$(\Omega t+\varphi)]-2\sin(\frac{\phi_{DC}}{2})\sum_{m=1}^{\infty}(-1)^m J_{2m-1}(\frac{\gamma}{2})\times$$
$$\cos(2m-1)(\Omega t+\varphi)]\}, \quad (1)$$

where E_0 and ω_0 are the electric field amplitude and angular frequency of the incident light wave, respectively, $V(t)$ is the applied electrical driving voltage, φ is the initial phase of electrical input signal, Ω is the angular frequency of the electrical input signal, $\Phi[V(t)]$ is the optical phase difference between the two arms of MZM caused by $V(t)$, where $\gamma=\pi V_{AC}/V_\pi$ and $\Phi_{DC}=\pi V_{DC}/V_\pi$, $\gamma/2$ and V_π are the phase modulation index and half-wave voltage of the MZM, respectively, $J_n(\cdot)$ is the nth-order Bessel function of the first kind, and α is the optical loss of MZM.

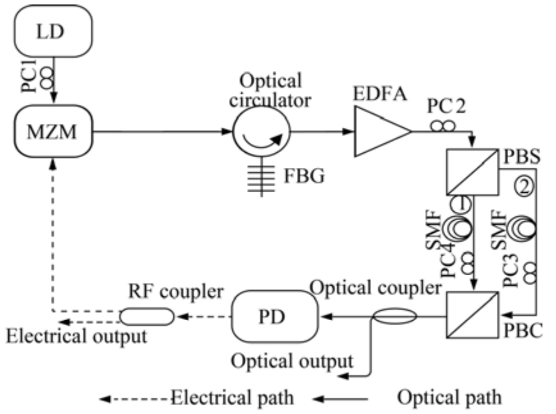


Fig.1 Schematic diagram of the proposed dual-loop OEO based on all optical signal processing

When the signal in Eq.(1) is reflected by the FBG and amplified by the EDFA, the electrical field becomes

$$E_{FBG,O}(\phi_{DC},t)=\sqrt{\alpha\beta G_0}E_0\{r(\omega_0)\times$$
$$\cos(\frac{\phi_{DC}}{2})\cos(\omega_0 t)J_0(\frac{\gamma}{2})+$$
$$\sin(\frac{\phi_{DC}}{2})J_1(\frac{\gamma}{2})[r(\omega_0+\Omega)\cos((\omega_0+\Omega)t+\varphi)+$$
$$r(\omega_0-\Omega)\cos((\omega_0-\Omega)t-\varphi)]\}, \quad (2)$$

where $r(\omega)$ is the reflection profile of the FBG, and ω is the angular frequency of the light wave to the FBG. β is the optical loss of FBG and EDFA. G_0 is the EDFA gain and $G_0=G_{0,SS}/[1+(G_{0,SS}P_{MZM,0}/P_{max,0})^{\chi}]$, where $G_{0,SS}$ is the small-signal (SS) EDFA gain, $P_{MZM,0}$ is the optical input power to the EDFA, $P_{max,0}$ is the maximum optical output power of the EDFA, and χ is an empirical constant with a typical value near unity[11].

Then the optical field is split into two optical paths by PBS via PC2, and PC2 is inserted to let the output of PBS equivalent to intensity modulation biased at π/2. Furthermore, the electrical fields of two optical paths can be expressed as

$$E_1(\phi_{DC},t)=\frac{\sqrt{2}}{2}\sqrt{\alpha\beta G_0}E_0\{r(\omega_0)\cos(\frac{\phi_{DC}}{2})\times$$
$$\cos(\omega_0 t)J_0(\frac{\gamma}{2})+\sin(\frac{\phi_{DC}}{2})J_1(\frac{\gamma}{2})[r(\omega_0+\Omega)\times$$
$$\cos((\omega_0+\Omega)t+\varphi)+r(\omega_0-\Omega)\cos((\omega_0-\Omega)t-\varphi)]\},$$
$$E_2(\phi_{DC},t)=\frac{\sqrt{2}}{2}\sqrt{\alpha\beta G_0}E_0\{r(\omega_0)\cos(\frac{\phi_{DC}}{2})\times$$
$$\cos(\omega_0 t+\frac{\pi}{2})J_0(\frac{\gamma}{2})+\sin(\frac{\phi_{DC}}{2})J_1(\frac{\gamma}{2})[r(\omega_0+\Omega)\times$$
$$\cos((\omega_0+\Omega)t+\varphi+\frac{\pi}{2})+$$
$$r(\omega_0-\Omega)\cos((\omega_0-\Omega)t-\varphi+\frac{\pi}{2})]\}. \quad (3)$$

After transmission over SMF with different optical paths, the signals of the two paths are combined by a PBC. To adjust optical losses and polarization states, two PCs (PC3 and PC4) are inserted in the two paths, respectively. The combined signal is then represented by

$$E_{PBC,O}(\phi_{DC},t)=\frac{\sqrt{2}}{2}[\sqrt{\xi_1}E_1(\phi_{DC},t-\tau_1)+$$
$$\sqrt{\xi_2}E_2(\phi_{DC},t-\tau_2)], \quad (4)$$

where τ_1 and τ_2 are time delays of loops 1 and 2, respectively, and ξ_1 and ξ_2 are the fiber losses of the two loops, respectively.

Because the polarizations of the light-waves from the two paths are orthogonal after multiplexing in the PBC, they would not interfere with each other. The output optical signal is then converted into an electrical signal at a PD, which takes the form of

$$V(\phi_{DC},t)=\rho\,|E_{PBC,O}(\phi_{DC},t)|^2 R=$$
$$\frac{1}{4}\alpha\beta G_0\rho RE_0^2 r(\omega_0)\sin(\phi_{DC})J_0(\frac{\gamma}{2})J_1(\frac{\gamma}{2})\times$$
$$\{\xi_1\cos[\Omega(t-\tau_1)+\varphi]+\xi_2\cos[\Omega(t-\tau_2)+\varphi]\}\times$$
$$[r(\omega_0+\Omega)+r(\omega_0-\Omega)]\approx\frac{1}{16}\alpha\beta G_0\rho RE_0^2 r(\omega_0)\times$$
$$\sin(\phi_{DC})\gamma\{\xi_1\cos[\Omega(t-\tau_1)+\varphi]+$$
$$\xi_2\cos[\Omega(t-\tau_2)+\varphi]\}[r(\omega_0+\Omega)+r(\omega_0-\Omega)], \quad (5)$$

where ρ is the responsivity of the PD, R is the load impedance of the PD, and $J_n(\mu)\approx\mu^n/(2^n\cdot n!)$ when μ is less than 0.5. Therefore, the open-loop RF gain $G(\phi_{DC}, \Omega)$ can be written by

$$G(\phi_{DC},\Omega)\approx\frac{\pi^2}{128V_\pi^2}\alpha^2\beta^2 G_0{}^2\rho^2 E_0^4 R^2 r^2(\omega_0)\times$$
$$\sin^2(\phi_{DC})[r(\omega_0+\Omega)+r(\omega_0-\Omega)]^2\times$$
$$[\xi_1^2+\xi_2^2+2\xi_1\xi_2\cos\Omega(\tau_2-\tau_1)]. \quad (6)$$

In order to generate oscillation for the OEO, the RF gain $G(\phi_{DC}, \Omega)$ must be larger than unity. According to Eq.(6), when the loop is closed, the total field of all circulating fields can be expressed as

$$\tilde{V}(\phi_{DC},\Omega)=V_{AC}\exp(j\Omega t)\cdot\sum_{m=1}^{\infty}\{\frac{\pi}{16V_\pi}\alpha\beta G_0\rho Rr(\omega_0)\times$$
$$E_0^2\sin(\phi_{DC})[r(\omega_0+\Omega)+r(\omega_0-\Omega)]\times$$
$$[\xi_1\exp(-j\Omega\tau_1)+\xi_2\exp(-j\Omega\tau_2)]\}^m=$$

$$V_{\mathrm{AC}}\exp(\mathrm{j}\Omega t)\cdot\sum_{m=1}^{\infty}|G_{\mathrm{eff}}(\Omega)|^{m}\cdot[\xi_1\exp(-\mathrm{j}\Omega\tau_1)+\xi_2\exp(-\mathrm{j}\Omega\tau_2)]^{m}=\frac{V_{\mathrm{AC}}\exp(\mathrm{j}\Omega t)}{1-[G_1\exp(-\mathrm{j}\Omega\tau_1)+G_2\exp(-\mathrm{j}\Omega\tau_2)]}, \quad (7)$$

where $G_1=G_{\mathrm{eff}}(\Omega)\xi_1$ and $G_2=G_{\mathrm{eff}}(\Omega)\xi_2$ are the complex gains of the two loops, respectively, where $G_{\mathrm{eff}}(\Omega)=\pi\alpha\beta G_0\rho Rr(\omega)E_0^2\sin(\phi_{\mathrm{DC}})\,[r(\omega_0+\Omega)+r(\omega_0-\Omega)]/16V_{\pi}$.

The corresponding microwave power $P(\phi_{\mathrm{DC}},\Omega)$ is then expressed by

$$P(\phi_{\mathrm{DC}},\Omega)=\frac{|\widetilde{V}(\phi_{\mathrm{DC}},\Omega)|^2}{2R}=\frac{|V_{\mathrm{AC}}|^2/2R}{1+G_1^2+G_2^2-2G_1\cos\Omega\tau_1-2G_2\cos\Omega\tau_2+2G_1G_2\cos\Omega(\tau_2-\tau_1)}. \quad (8)$$

To generate oscillation for dual-loop OEO, the oscillation frequency and power must satisfy[4]

$$f_{\mathrm{osc}}=k/\tau_1=n/\tau_2\ , \quad (9)$$

$$P(\phi_{\mathrm{DC}},\Omega_{\mathrm{osc}})=\max\{P(\phi_{\mathrm{DC}},\Omega)\}\ , \quad (10)$$

where k and n are integers. Substituting Eqs.(9) and (10) into Eq.(8) yields

$$P(\phi_{\mathrm{DC}},\Omega_{\mathrm{osc}})=\frac{|V_{\mathrm{AC}}|^2/2R}{[1-(G_1+G_2)]^2}\ . \quad (11)$$

In order to make sure the oscillation starts from noise moment, it must be satisfied that[4]

$$1-(G_1+G_2)=0\ . \quad (12)$$

In the numerical simulations based on the setup shown in Fig.1 and the theoretical analyses above, the major parameters are as follows. The wavelength of the LD is set at 1550 nm, the MZM has a bandwidth of 40 GHz and a half-wave voltage of 6 V, the central wavelength and the 3 dB reflection bandwidth of the FBG are 1550 nm and 0.3 nm, respectively; the small-signal gain and the saturated output power of the EDFA are 37 dB and 17 dBm, respectively, the lengths of the dual-loop are 4.4 km and 0.6 km, respectively, and the PD has a bandwidth of 10 GHz and a responsivity of 0.88 A/W.

Fig.2 shows the open-loop RF gain $G(\phi_{\mathrm{DC}},\Omega)$ from Eq.(6) for various output power of the LD as P_{in}=–5 dBm, 0 dBm, 5 dBm, 10 dBm and 15 dBm. It can be noticed that the RF gain $G(\phi_{\mathrm{DC}},\Omega)$ is decreased with the decrease of P_{in} on the low-biased point. In addition, the RF gain $G(\phi_{\mathrm{DC}},\Omega)$ can be maximized by moving the bias point from the quadrature point to the low-biased point, where the point depends on EDFA parameters and P_{in}. Meanwhile, the bias point of the maximum $G(\phi_{\mathrm{DC}},\Omega)$ is decreased with the increase of P_{in}.

Fig.3 shows the RF spectrum of the proposed dual-loop OEO from Eq.(8). In the calculation, we choose $G_{\mathrm{eff}}(\Omega_{\mathrm{osc}})\xi_1=G_{\mathrm{eff}}(\Omega_{\mathrm{osc}})\xi_2=0.5\times10^{-6}$, $|V_{\mathrm{AC}}|^2/2R=1$, and its refraction index of n_0=1.5. As can be seen in Fig.3, a strong oscillating mode at 10 GHz is present with two different frequency spans. Therefore, a single frequency oscillation of the OEO is obtained without inserting any electrical BPF or EA, and the SMSRs are suppressed over 70 dB with frequency span of 4 MHz and over 50 dB with frequency span of 20 GHz, respectively.

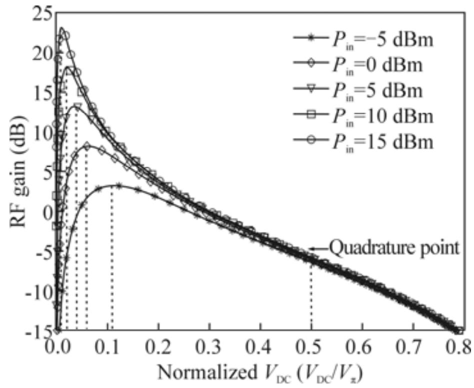
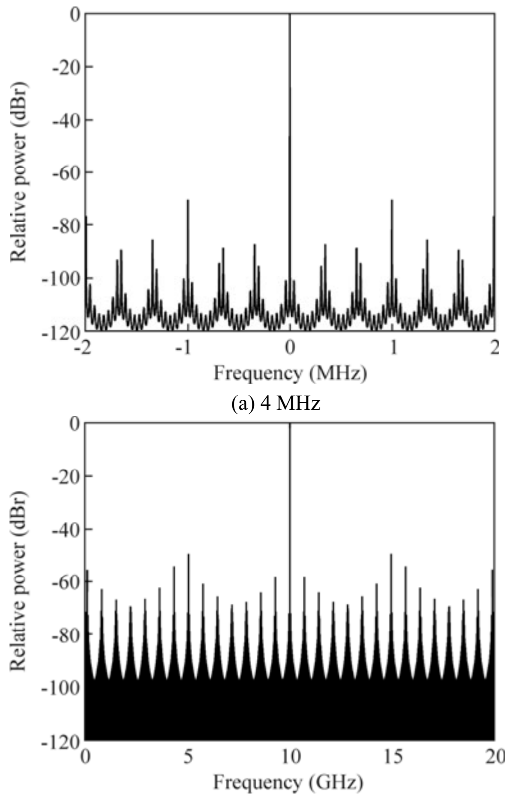


Fig.2 RF gain of the open-loop OEO as a function of normalized bias voltage for various input power



(a) 4 MHz

(b) 20 GHz

Fig.3 RF spectra of the generated 10 GHz microwave signals with two different frequency spans

To explore the spectral performance of the generated microwave signals, Fig.4 shows the single sideband (SSB) phase noise spectra of the generated 10 GHz microwave signals. From Fig.4, the SSB phase noise of the generated 10 GHz microwave signal is lower than –120 dBc/Hz at the frequency offset of 10 kHz. Several spurious peaks are observed for the frequency offset greater than 23 kHz, the spacing of spurious peaks is identical to the frequency spectral range of the OEO resulting from the non-oscillating sidemodes[14].

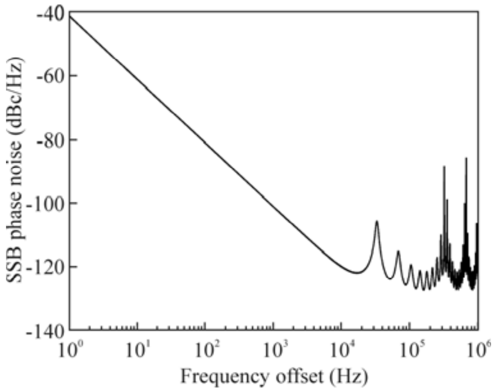


Fig.4 SSB phase noise of the generated 10 GHz microwave signal

We propose and demonstrate a dual-loop OEO based on all optical signal processing. The amplification and filter of the OEO are introduced by inserting an EDFA and an FBG on the optical domain, respectively. Through the theoretical analyses and simulations, the SSB phase noise of the generated microwave signal is lower than –120 dBc/Hz at frequency offset of 10 kHz, and high SMSR can be obtained. Therefore, the proposed system can effectively suppress the undesirable sidemodes and reduce the phase noise.

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