Wideband and frequency-tunable microwave generation using an optoelectronic oscillator incorporating a Fabry–Perot laser diode with external optical injection

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Received January 19, 2010; revised May 7, 2010; accepted May 10, 2010; posted May 13, 2010 (Doc. ID 122885); published May 28, 2010

Wideband and frequency-tunable microwave signal generation using an optoelectronic oscillator incorporating a Fabry–Perot laser diode (FP-LD) with external optical injection is proposed and demonstrated. Through external injection, the FP-LD functions as a tunable high-Q photonic microwave filter, and the frequency tuning is realized by either tuning the wavelength of the externally injected optical light or changing the temperature to adjust the longitudinal modes of the FP-LD. An experiment is performed; a microwave signal with a frequency tunable from 6.41 to 10.85 GHz is generated. The phase noise performance of the generated microwave signal is also investigated. © 2010 Optical Society of America

OCIS codes: 230.4910, 350.4010, 060.2310.

Optoelectronic oscillators (OEOs) have shown high performance in microwave generation [1,2] and have also been applied to perform optical signal processing such as optical clock recovery [3,4], nonreturn-to-zero to return-to-zero format conversion [5], serial-to-parallel conversion (or optical time-division multiplexing) [6,7], and synchronous modulation-based regeneration [8]. In general, an OEO is an optoelectronic feedback loop consisting of an intensity modulator, an optical fiber delay line (or an electrical phase shifter), a photodetector (PD), an electrical amplifier (EA), and an electrical high-Q bandpass filter (EBPF). If the loop gain is higher than the loss, when a cw light is injected into the intensity modulator, the OEO will start to oscillate at one of its eigenmodes determined by the center frequency of the EBPF. The spacing between two adjacent eigenmodes is determined by the total length of the loop. To obtain a microwave signal with a very low phase noise, the loop length should be long, so the eigenmodes would be closely spaced. An EBPF with a very high Q value should be employed to effectively suppress the side modes, to ensure a high spectral purity. Since it is difficult to design and implement a high-Q EBPF with a large tunable range, a conventional OEO can only generate a microwave signal with a very small frequency tunable range [9]. For example, the OEOs reported in [10,11] could be tunable, but the tuning range is as small as 2 GHz. To have a large tunability, the system complexity and cost would be significantly increased.

In this Letter, a simple method to implement an OEO with large frequency tunability is proposed and demonstrated for the first time to the best of our knowledge. A microwave signal with a tunable frequency from 6.41 to 10.85 GHz is generated. The tuning range can be further extended by increasing the bandwidth of the EA in the OEO. The phase noise performance of the generated microwave signal is also investigated.

The schematic of the proposed frequency-tunable OEO is shown in Fig. 1. A light wave from a tunable laser source (TLS) is fiber coupled to a Mach–Zehnder modulator (MZM) via a polarization controller (PC). The MZM is connected to a Fabry–Perot laser diode (FP-LD, Thorlabs S1FC1550) via a second PC (PC2) and a circulator. The optical output from the FP-LD is converted to an electrical signal at a PD and then fed back to the MZM to form the OEO loop. An electrical phase shifter is incorporated to adjust the cavity length, and an EA is used to provide sufficient electrical gain.

To study the open-loop response of the OEO, we assume that the loop is opened at point D in Fig. 1 and that the MZM is driven by an electrical signal with a frequency of f_m. The microwave modulated optical signal is then injected into the FP-LD. The optical signal after the FP-LD is then written as

$$E_1 \approx \sqrt{G(\omega_0)}J_0(\beta)\cos\omega_0 t + \sqrt{G(\omega_0+\omega_m)}J_1(\beta)\cos(\omega_0+\omega_m)t + \sqrt{G(\omega_0-\omega_m)}J_1(\beta)\cos(\omega_0-\omega_m)t, \quad (1)$$

where ω_0 is the angular frequency of the optical carrier, $\omega_m = 2\pi f_m$, β is the phase modulation index of the MZM, J_n is the nth-order Bessel function of the first kind, and $G(\omega)$ represents the effective gain of the FP-LD, which is defined as the broadband gain from the gain region

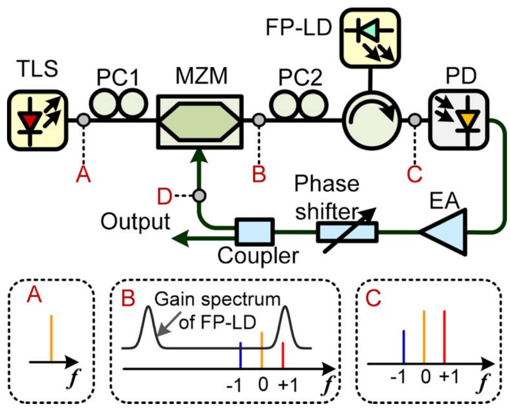

Fig. 1. (Color online) Schematic of the proposed frequency-tunable optoelectronic oscillator.

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multiplied by the spectral response of the FP-LD consisting of a series of periodic resonances. Therefore, $G(\omega)$ has a spectrum with periodic peaks, as shown in the insets of Fig. 1. The optical output from the FP-LD is then converted into an electrical signal at the PD, amplified by the EA. Dividing the electrical signal by the drive signal, we obtain the open-loop response,

$$H(\omega_m) = \frac{V_{\text{out}}}{V_{\text{in}}} \approx \frac{R\sqrt{G(\omega_0)}\,J_0(\beta)J_1(\beta)\left(\sqrt{G(\omega_0+\omega_m)}+\sqrt{G(\omega_0-\omega_m)}\right)}{\beta V_\pi}, \tag{2}$$

where R is a parameter related to the responsivity and the load impedance of the PD, the gain of the EA, and the path losses, and $V\pi$ is the half-wave voltage of the MZM. As can be seen from Eq. (2), the profile of the open loop response is determined mainly by the effective gain of the FP-LD and the wavelength of the optical carrier. If the wavelength of the optical carrier is tuned to have a wavelength difference of $\Delta\lambda$ relative to one longitudinal mode of the FP-LD, a single bandpass photonic microwave filter with a center frequency given by $f = c\Delta\lambda/\lambda^2$ would be formed. When the wavelength of the injected light wave is changed or the longitudinal modes of the FP-LD are adjusted by temperature change, a change in $\Delta\lambda$ would result. The center frequency of the generated microwave filter will thus be tuned. The bandwidth of the photonic microwave filter is determined by the bandwidth of the effective gain at one longitudinal mode of the FP-LD. Since this bandwidth can be adjusted by increasing the drive current to have a value of several megahertz, the photonic microwave filter would have a high Q value. It should be noted that the drive current has an upper limit for a given injection optical power to avoid lasing of the FP-LD.

The parameters of the key devices used in the experiment are as follows: the MZM has a 3 dB bandwidth of 20 GHz; the PD has a 3 dB bandwidth of 45 GHz and a responsivity of 0.4 A/W; the electrical gain of the EA is about 55 dB when operating at 7 – 11 GHz; the free spectral range of the OEO is measured to be 3.13 MHz; the length of the FP-LD is about 300 μm, corresponding to a mode spacing of 1.17 nm; the optical power that is injected to the FP-LD is controlled to be around −8 dBm, and the corresponding output power is about −2 dBm; and the microwave power to the MZM is estimated to be 22 dBm, corresponding to a phase modulation index of 0.51π.

The key device in the proposed OEO is the FP-LD, which functions through external optical injection as a photonic microwave filter. To avoid the FP-LD being injection-locked by the optical carrier, large signal modulation is performed to produce relatively large sidebands. In addition, the injection current (~40 mA) of the FP-LD is set below the injection locking threshold. To measure the open-loop response, a vector network analyzer (VNA, Agilent E8364A) is used to scan the frequency of the microwave signal applied to the MZM and detect the corresponding microwave power at the output of the PD. The wavelength of the TLS is tuned to adjust the center frequency of the photonic microwave filter. Figure 2 shows several typical frequency responses of the FP-LD-based photonic microwave filter. For a center frequency from 6.25 to 9.08 GHz, the 3 dB bandwidth of the photonic microwave filter is 14 – 36 MHz, corresponding to a Q value from 252 to 446. The extinction ratio of the filter is around 4 dB, which is high enough to strongly suppress the undesirable eigenmodes of the OEO. It should be noted that the FP-LD used in the experiment utilizes a FC/PC connector as the output port. The FC/PC connector has a small reflection, which would affect the filter response, since new Fabry–Perot cavities are formed. As a result, a sidelobe appears near the main response peak. If the output of the FP-LD were directly spliced to the circulator, the sideband would be eliminated.

Figure 3 shows the optical spectrum and the electrical spectra when the OEO is configured to generate a 10 GHz microwave signal. From the optical spectrum we can see that an asymmetric double-sideband modulated optical signal is generated. The asymmetry makes the +1st sideband obtain the highest gain from the FP-LD, while the gain for the optical carrier and the other sidemodes is much smaller. By applying the optical signal to the PD, a sinusoidal signal with a frequency of 10 GHz is generated. Figure 3(b) shows the spectrum of the generated electrical signal. The 10 GHz spectral line is 37 dB higher than that of its second harmonic. The inset in Fig. 3(b) provides an enlarged view of the spectral component at 10 GHz, showing a 63 dB sidemode suppression ratio. The stability of the system is evaluated. To do so, the system is allowed to operate in a room environment for a period of 20 min. The 10 GHz tone is always shown on the electrical spectrum analyzer. Because of the instability of the FP-LD, which is not temperature controlled, a frequency shift of about 100 MHz and a power variation of about 3 dB are

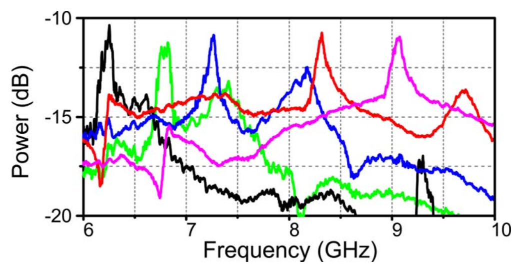

Fig. 2. (Color online) Frequency responses of the FP-LD-based photonic microwave filter.

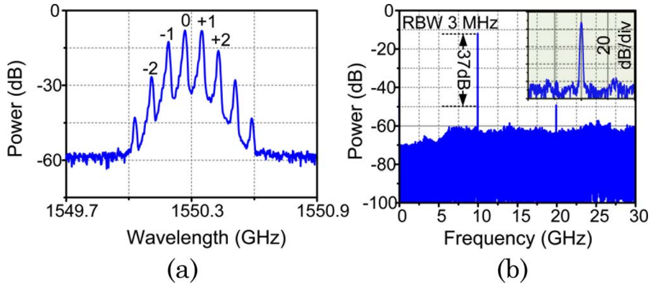

Fig. 3. (Color online) Generation of 10 GHz signal using the proposed OEO. (a) Optical spectrum. (b) Electrical spectrum. Inset, span = 10 MHz, and resolution bandwidth (RBW) = 91 kHz.

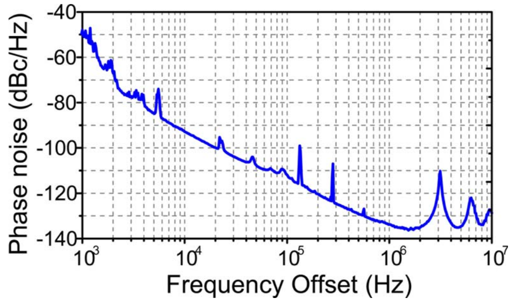

Fig. 4. (Color online) Phase noise measurement for the generated 10 GHz microwave signal.

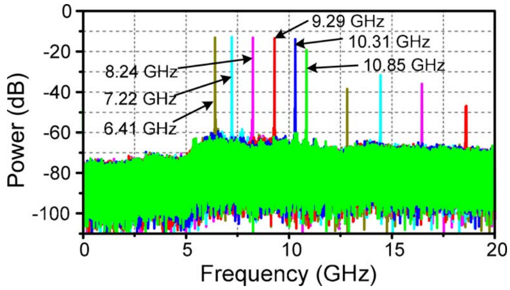

Fig. 5. (Color online) Spectra of the generated electrical signal with the frequency tuned from 6.41 to 10.85 GHz; RBW = 1 MHz.

observed. These variations should be reduced if the FP-LD is temperature controlled.

The phase noise performance of the generated electrical signals is also studied. Figure 4 shows the single-sideband phase noise spectrum of the generated 10 GHz microwave signal, which is measured by an Agilent E5052B signal source analyzer incorporating an Agilent E5053A downconverter. The phase noise of the 10 GHz signal is −92.8 dBc/Hz at a 10 kHz offset frequency. A peak at the 3.13 MHz offset frequency, corresponding to the free spectral range of the OEO resulted from the nonoscillating sidemodes, is seen in the single-sideband phase noise spectrum with a phase noise of −110 dBc/Hz. The phase noise performance can be further improved by using a long fiber delay line in the loop or by using multiple optoelectronic loops [12].

The frequency of the generated microwave signal can be continuously tuned over the operational bandwidth of the EA by changing the wavelength of the TLS and finely tuning the phase shift of the electrical phase shifter. Figure 5 shows the electrical spectra of the generated microwave signal with its frequency tuned from 6.41 to 10.85 GHz. For all the frequencies, the second harmonic is suppressed by more than 20 dB.

In summary, a novel OEO to generate a wideband and frequency-tunable microwave signal was proposed and experimentally demonstrated. The key device in the OEO was the FP-LD, which was functioning, through external injection, as a high-Q and frequency tunable photonic microwave filter. The central frequency of the high-Q filter was tuned by either tuning the injection optical wavelength or by changing the temperature to change the longitudinal mode of the FP-LD. A microwave signal tunable from 6.41 to 10.85 GHz was generated. The tuning range could be extended by increasing the bandwidth of the EA. The proposed OEO is simple and cost effective, which can find applications in optical and wireless communications, radar, and instrumentation.

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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