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Wideband-frequency tunable optoelectronic oscillator based on injection locking to an electronic oscillator

MICHAEL FLEYER, ALEXANDER SHERMAN,* MOSHE HOROWITZ, AND MOSHE NAMER

Department of Electrical Engineering, Technion–Israel Institute of Technology, Haifa 32000, Israel
**Corresponding author: sh.alexander@gmail.com*

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We experimentally demonstrate a wideband-frequency tunable optoelectronic oscillator (OEO) based on injection locking of the OEO to a tunable electronic oscillator. The OEO cavity does not contain a narrowband filter and its frequency can be tuned over a broad bandwidth of 1 GHz. The injection locking is based on minimizing the injected power by adjusting the frequency of one of the OEO cavity modes to be approximately equal to the frequency of the injected signal. The phase noise that is obtained in the injection-locked OEO is similar to that obtained in a long-cavity self-sustained OEO. Although the cavity length of the OEO was long, the spurious modes were suppressed due to the injection locking without the need to use a narrowband filter. The spurious level was significantly below that obtained in a self-sustained OEO after inserting a narrowband electronic filter with a *Q*-factor of 720 into the cavity.

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High-frequency electronic synthesizers can be tuned over a broad frequency region. Such synthesizers are often based on frequency multiplication of a signal generated by a quartz crystal. In case the carrier frequency is high, the high-frequency multiplication limits the phase noise performance of the oscillator. Long-cavity optoelectronic oscillators (OEOs) enable generating microwave signals with ultralow phase noise due to the ultrahigh quality factor of their resonator [1]. In many applications, a wideband-frequency tunability of the oscillation frequency is required. Usually, the frequency of OEOs is determined by a narrowband electronic filter that is inserted into its cavity [1]. Tunable narrowband RF bandpass filters such as yttrium iron garnet (YIG) filters can be tuned over a broad frequency region [2]. However, the accuracy of the filter frequency is limited to the order of tens of MHz. Moreover, although the quality factor of YIG filters can be on the order of 1000, the filter bandwidth is insufficient to suppress spurious modes (spurs) generated by long-cavity OEOs. Such spurs are obtained at the natural modes of the OEO cavity that do not oscillate. For a 5-km length OEO, the frequency spacing between adjacent modes is only about 40 kHz. This frequency spacing is too narrow to filter out a single cavity mode around a frequency of 10 GHz. Several methods to reduce the spurious level, based on injection locking of two OEOs, have been demonstrated [3,4]. However, such methods enable the suppression of only some of the spurs, and are optimized for a given carrier frequency [5].

Several methods have been demonstrated for obtaining tunable OEOs. Wideband tunability can be obtained by removing the narrowband electronic filter and controlling the OEO frequency by using a tunable photonic filter [6,7], Fabry–Perot etalon [8], Fabry–Perot laser diode biased below the lasing threshold [9], two cascaded phase modulators and a phase-shifted fiber Bragg grating [10], and by using a tunable laser source and dispersive fibers [11]. Photonic filters may enable tuning the OEO frequency over a very broad region; however, the accuracy of the frequency is limited. The long fiber in the OEO cavity is sensitive to the surrounding environment, and hence, the long-term frequency accuracy and stability are limited [6]. Moreover, photonic filters are not sufficiently narrow to suppress spurs in a long-cavity OEO.

In this Letter, we experimentally demonstrate a wideband-frequency tunable OEO based on injection locking to a tunable electronic oscillator. The OEO cavity does not contain a narrowband electronic filter. The frequency of the OEO is determined by the electronic oscillator, and it can be continuously tuned over a broad frequency region of 8.5–9.5 GHz. The injection locking is based on adjusting the frequency of a resonance mode of the OEO cavity in order to minimize the injected power. The weak injection power enables obtaining phase noise that is similar to that in a long-cavity self-sustained OEO. Although the OEO cavity length was 5200 m long and the frequency difference between adjacent spurs was only 38 kHz, the injection locking caused the suppression of the spurs. The spurious levels that are closest to the carrier frequency were about 55 dB smaller than those obtained in a self-sustained OEO with a 720 *Q*-factor electronic filter that was inserted into its cavity.

In the wideband tunable OEO, described in this Letter, there is a need to minimize both phase noise and spurious level without using a narrowband filter. Injection locking of OEOs to external signals has been previously used for clock recovery in optical communication systems [12,13]. In such applications, there is a need to obtain a stable synchronization of the OEO to a noisy clock signal. Hence, a narrowband electronic filter is used in the OEO, and the injected signal amplitude should be strong enough in order to lock the OEO even when the OEO resonance frequency is different from the injected signal frequency.

The experimental setup of the wideband tunable OEO is shown in Fig. 1. A tunable synthesizer (Keysight N5183A MXG) generates the RF signal that is used for the injection locking of the OEO. A continuous wave (CW) semiconductor laser with an optical power of about $P_0 = 15$ dBm that operates at a wavelength of 1546 nm is connected to a Mach–Zehnder modulator (MZM) with an electro-optic bandwidth of about 16 GHz and $V_\pi = 3$ V. The output of the MZM was connected through a $L = 5200$ m length fiber (Corning SMF-28) to a photodetector (PD) with a 3-dB bandwidth of 24 GHz. The PD output is fed into an RF amplifier (G_1) with a 3-dB bandwidth of 8.5–11 GHz, which is connected to a 6-dB directional RF coupler that is used to tap 75% of the signal for measurements. The remaining 25% of the signal power is fed into a high-pass filter (HPF) and isolators with a 3-dB cutoff frequency of 8.5 GHz, and a maximum frequency of about 13.5 GHz. The injected signal is fed into the OEO cavity through a 20-dB directional coupler, and the combined signal is amplified by a second RF amplifier (G_2) with a bandwidth of 9–11 GHz. An electronically controlled RF phase shifter (PS) with a 410° tuning range that can operate at a frequency region of 8–12 GHz is used to adjust the OEO frequency. The injected power at the input of a G_2 amplifier was about −35 dB lower than the estimated OEO RF power at this location.

The open-loop transfer function of the OEO cavity that was measured after disconnecting the output of the 6-dB coupler is shown in Fig. 2. The measurement was performed by an RF network analyzer, and the RF power was similar to that in the injection-locked OEO. Hence, the maximum transfer function is close to one. Figure 2 indicates that the transmission of the loop changes by about 0.7 dB over the frequency region of 8.5–10 GHz. The specified measurement accuracy is about ±0.3 dB.

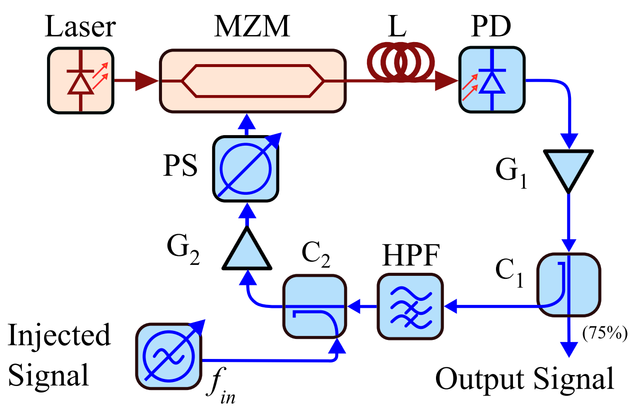

Fig. 1. Schematic description of the experimental setup. MZM is a Mach–Zehnder modulator, L is a 5200 m length fiber, PD is a photodetector, G_1 and G_2 are RF amplifiers, C_1 and C_2 are 6-dB and 20-dB couplers, respectively, HPF is a high-pass filter, and PS is an electronically controlled RF phase shifter.

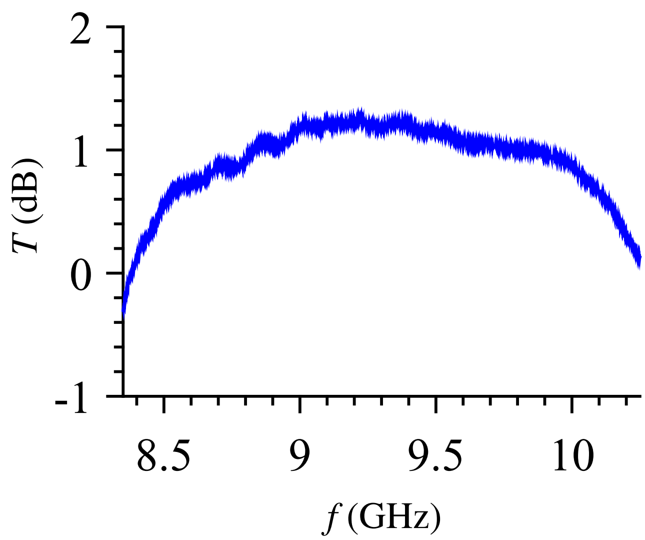

Fig. 2. Transfer function of the open OEO cavity measured by a network analyzer at the input of amplifier G_2.

Figure 3 shows the output RF spectrum measured without locking the OEO to the external source. Since no narrowband filter is used, the OEO oscillates in several modes around a frequency of 9.1 GHz. The spectrum is very broad and fluctuates on time.

The injected signal power was about 35 dB lower than the OEO power at the entrance of amplifier G_2. When the OEO was turned on, or if the external source frequency was changed, there was a need to lock the OEO to the external source. During the locking process, the injected power was increased by about 5 dB in order to broaden the OEO locking range [14]. The locking was performed by controlling the PS to obtain the maximum power at the injected signal frequency. The OEO phase noise was measured by using a Keysight E5052B Signal Source Analyzer. Figure 4 shows four different phase noise measurements of the injection-locked OEO at frequencies of 8.6, 8.8, 9.1, and 9.2 GHz. The results are compared to the corresponding measured phase noise of the synthesizer used to lock the OEO. The OEO carrier frequency in each measurement was determined by the frequency of the injected signal. Similar results were obtained over the entire frequency region of 8.5–9.5 GHz. Figure 4 shows that for sufficiently high frequency offset, the phase noise of the injection-locked OEO is significantly lower than that of the synthesizer. For example,

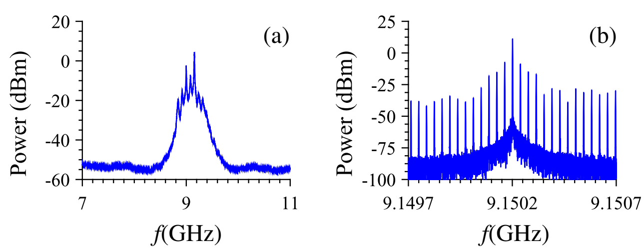

Fig. 3. RF spectrum of a self-sustained OEO measured with a RBW of (a) 3 MHz and (b) 100 Hz, respectively.

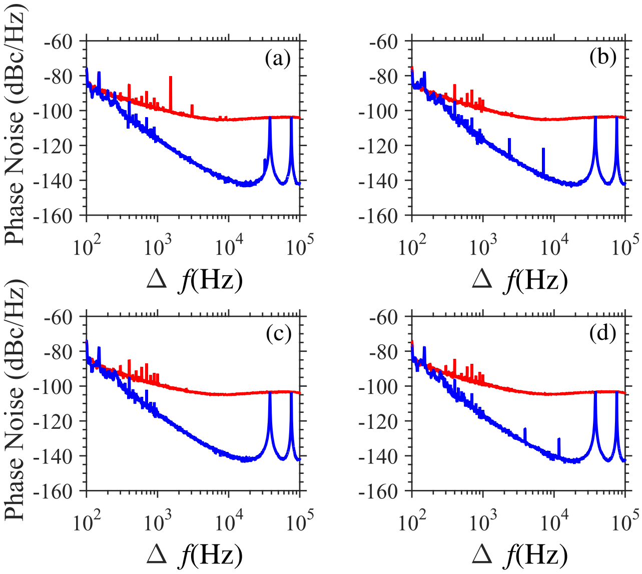

Fig. 4. Phase noise of the injection-locked OEO (blue) and the injected signal (red) measured for four different frequencies of the injected signal (a) 8.6, (b) 8.8, (c) 9.1, and (d) 9.2 GHz. The peaks in the OEO phase noise at 38.5 and 77 kHz are caused by the first two spurious modes of the OEO.

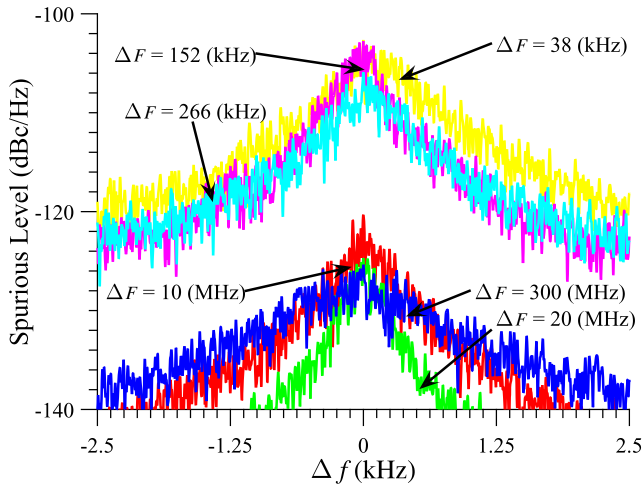

Fig. 5. Power spectral density of the first, fourth, and seventh spurs located around frequency offsets of $\Delta F = 38$, 152, and 266 kHz, respectively, and the spurs located near frequency offsets of $\Delta F = 10$, 20, and 300 MHz, measured by using an RF spectrum analyzer. The carrier frequency equals 9.2 GHz, and the spurs shown have higher frequency than the carrier frequency. The frequency difference between adjacent spurs equals 38 kHz. The spectrum analyzer RBW was set to 10 Hz and the OEO carrier power was about 10 dBm. The results shown in the figure are normalized by the carrier power and the RBW.

at a frequency offset of 10 kHz, the OEO phase noise is about 35 dB lower than the phase noise of the injected signal.

The use of a narrowband electronic filter in long-cavity OEOs is essential to suppress spurs. Without inserting such a filter into the OEO cavity, high spurious level is obtained that prevents using OEO in most applications. The injection-locked OEO described in this Letter does not contain a narrowband electronic filter, and the spurs are suppressed by the injection locking of the OEO. Since in the injection-locked OEO, spurs are obtained over a broad frequency region, we measured the spurs' spectrum by using an RF spectrum analyzer. Figure 5 shows the RF spectrum of the first, fourth, and the seventh spurs, and the spurs located near frequency offsets of 10, 20, and 300 MHz in an OEO with a carrier frequency of 9.2 GHz. The spurs are obtained at frequencies that are lower or higher than the carrier frequency. However, since the spectrum of the spurs was approximately symmetrical with respect to the carrier frequency, we show in Fig. 5 spurs with higher frequencies than the carrier frequency. The resolution bandwidth (RBW) of the spectrum analyzer was set to 10 Hz, and the carrier power was about 10 dBm. The results shown in the figure are normalized by the carrier power and the RBW. The FWHM bandwidth of the spurs was about 600 Hz. Figure 6 shows the spurious level as a function of the frequency offset (blue crosses). The amplitude of the closest spurs was around −103 dBc/Hz, and it decreases to about −125 dBc/Hz at a frequency offset higher than about 1 MHz. The noise floor of the spectrum analyzer was −145 dBm/Hz. The measured dependence of the spurious level on the frequency offset is similar to the phase noise spectrum of the synthesizer used to lock the OEO, and hence, we believe that the decrease in the spurs' amplitude above about 200 kHz is caused due to the decrease in the synthesizer phase noise at that frequency. Preliminary theoretical results indicate that the spurs can be further suppressed by decreasing the phase noise of the injected signal at the frequencies of the spurs.

To compare the performance of the injection-locked OEO to a self-sustained OEO, we replaced the HPF with a narrowband electronic filter with a central frequency of 10 GHz and a

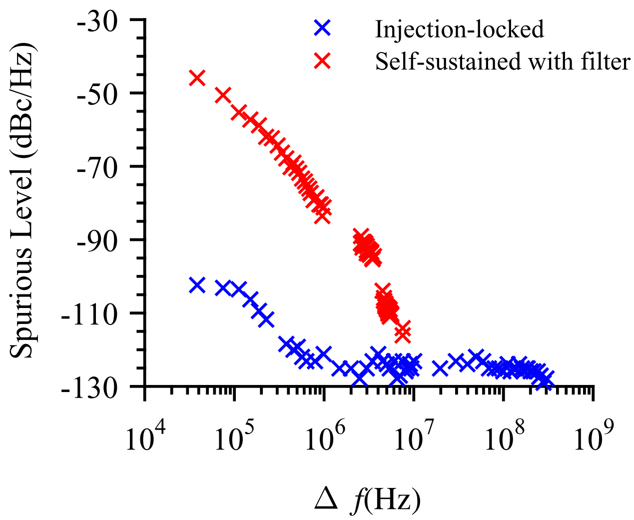

Fig. 6. Spurious level of injection-locked OEO with a carrier frequency of 9.2 GHz (blue crosses) and the spurious level of a self-sustained OEO with a carrier frequency of 10 GHz (red crosses) as a function of the frequency offset from the carrier frequency. In the self-sustained OEO, an electronic bandpass filter with a Q-factor of 720 around a central frequency of 10 GHz was inserted into the cavity. This filter is not used in the injection-locked OEO. The OEO length was about 5200 m, and the frequency spacing between adjacent spurs was 38 kHz.

3-dB bandwidth of 14 MHz that corresponds to a Q-factor of about 720. The OEO oscillation frequency was about 10 GHz, and the output power was about 1 dB lower than in the injection-locked OEO. The red crosses in Fig. 6 show the measured spurious level as a function of the offset frequency. In this case, the FWHM of the spurs was less than 10 Hz, in comparison with about 600 Hz that was obtained in the injection-locked OEO. The amplitudes of the 1st, 2nd, 5th, and 10th spurs in the self-sustained OEO were −46, −51, −59, and −68 dBc/Hz below carrier, respectively. The corresponding spurious amplitudes in the injection-locked OEO were −103, −103, −110, and −122 dBc/Hz, respectively. The specified minimum phase noise of the electronic amplifiers is obtained in the frequency region of 9–10.5 GHz. The phase noise of the self-sustained OEO operated at 10 GHz was only a few dB better than that obtained in the injection-locked OEO operated at 9.2 GHz.

The tunable OEO described in this Letter is based on injection locking of an OEO to an external signal generated by a controllable electronic synthesizer. To minimize the phase noise of the injection-locked OEO, the injected signal power should be as low as possible. This condition is obtained by controlling the phase accumulated in the OEO cavity such that the detuning between the frequency of the injected signal and one of the resonance frequencies of the OEO is minimized [14]. The adjustment of the OEO cavity mode frequency is performed in our experiments by controlling an electronic PS that was inserted into the OEO cavity. At the input of amplifier G_2, the injected power was about −35 dB below the OEO power.

The minimum injected power is determined by the locking range of the OEO [14] and by the frequency response of its cavity. The injected signal frequency should be located within the OEO locking range. The bandwidth of the locking range increases as the injected power is increased. Since the resonance frequencies of the OEO cavity drift over time due to changes in environmental conditions, the injected power should be high enough to allow a stable operation for a sufficient time. We could experimentally estimate the bandwidth of the OEO locking range for an injected power ratio of −35 dB, as was used in our experiments, by changing the frequency of the injected signal. A change of approximately $\delta f = 100$ Hz in the signal frequency has caused a breakup of the locking. In our experiments, a stable operation was obtained for about 10 minutes. To operate the OEO for a longer duration, a feedback system to compensate the OEO cavity mode drift is required. This feedback, which is based on controlling the PS and will be described elsewhere, enabled us to maintain a stable operation for almost unlimited duration. The minimum injected power and the tuning bandwidth of the injection-locked OEO are also determined by the frequency response of the OEO cavity. When the OEO is locked at a frequency where the transfer function amplitude is smaller than its maximum, the injected power should be sufficiently high to reduce the gain and to prevent oscillation at frequencies where the OEO gain is maximal. Preliminary theoretical results indicate that the maximum change in the spectral cavity response should be kept below about 0.3 dB along the whole operating bandwidth. However, this theoretical result cannot be experimentally verified from the measured transfer function, shown in Fig. 2, since the specified measurement accuracy is only about ±0.3 dB. Hence, we defined the OEO tuning bandwidth by the requirement that the injection ratio will be in the range of 35±3 dB. In this tuning frequency region of 8.5–9.5 GHz, we have verified that no significant change in the measured OEO phase noise was obtained. Outside this frequency region, a sharp increase in the minimum injected power was required.

The suppression of the spurs in the injection-locked OEO is caused due to the decrease in the OEO loop gain. The injected signal is added to the OEO signal, and hence, the required loop gain is decreased in comparison with that in the self-sustained oscillator. This gain reduction also decreases the loop gain at the frequencies of the spurs. Since the OEO noise at that frequency does not change significantly due to the injection, the spurious level is suppressed. The spurious level can be decreased as the injected power is increased. However, the injected power should be kept small to obtain low phase noise. The suppression of the spurs does not significantly depend on the loop length, and hence, OEOs with very long cavities that generate an ultralow phase noise signal can be obtained.

In conclusion, we have demonstrated a wideband-tunable OEO that does not contain a narrowband electronic filter inside its cavity. The suppression of the spurs in the long-cavity OEO is obtained due to the injection locking of the OEO, and it does not significantly depend on the cavity length. The phase noise that is obtained in the injection-locked OEO is only a few dB above the phase noise that is obtained in a self-sustained OEO. The maximum frequency tunability of the OEO is determined by the uniformity of the frequency transfer function of the OEO cavity. The tunable bandwidth can be increased by using an equalizing filter [15,16]. In order to obtain a stable operation over a long period of time, a feedback system should be implemented.

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