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Low-noise X-band tunable microwave generator based on a semiconductor laser with feedback

Michael J. Wishon, Daeyoung Choi, Tobias Niebur, Nathan Webster, Yanne K. Chembo, Evgeny. A. Viktorov, D. S. Citrin, and Alexandre Locquet

Abstract—The stabilization of a relatively simple microwave oscillator tunable across the full X-band based on a laser subjected to optical feedback is achieved. Specifically, a resonance effect based on locking the two inherent dynamic frequencies of the system, as well as optoelectronic feedback are utilized to achieve a sub-ps jitter and typical phase noise in the range of -107 dBc/Hz at 10 kHz offset from an oscillation frequency that can be tuned from 5.5 to 12.1 GHz. Further, the microwave signal is extracted from the laser-diode injection terminals and eliminates the need for multiple lasers, radio-frequency filters, and external RF sources. This architecture therefore realizes a compact and low-cost microwave photonic oscillator.

Index Terms—Microwave generation, feedback stabilization

SINCE the first demonstrations of optoelectronic oscillators (OEO) as highly stable radio-frequency (RF) sources [1], [2], they have continually grown in popularity due to their many applications in radar and communications [3], [4], as well as in sensing and measurement [5]. OEOs are part of a broader class of photonic and optoelectronic devices that have been utilized to generate microwave-modulated optical signals. Techniques that involve modulating the injection current or the optical output themselves require microwave sources and as such suffer from noise and tunability issues associated with such sources, and we leave aside discussion of these approaches. One of the simplest purely optoelectronic approach involves beating two optical frequencies separated by the desired microwave frequency [6]–[9]. Numerous approaches, however, employ optical or optoelectronic feedback, which is known to enable self-generated oscillations with enhanced stability [10]–[12]. In this case, tunability to 10 GHz in the microwave frequency can be achieved by control of various components in the external feedback loop. In [13], **optoelectronic feedback on a phase modulator, in a optically injected system with many other components is demonstrated to produce a tunable oscillation from 10-46 GHz with the best phase noise -105 dBc/Hz at 10 kHz.**

OEOs featuring frequency tunability across the X-band (8–12 GHz) are of particularly high importance because this frequency range is associated with several applications in aerospace engineering, such as satellite communications, radar

M. J. Wishon, D. Choi, N. Webster, T. Niebur, D. S. Citrin, and A. Locquet are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0250 USA and Georgia Tech-CNRS UMI-2958, Georgia Tech Lorraine, 2 rue Marconi, 57070 Metz, France.

Y. K. Chembo is with Georgia Tech-CNRS UMI-2958, Atlanta Mirror Site, School of Electrical and Computer Engineering, Atlanta 30332-0250, Georgia USA.

E. A. Viktorov is with ITMO University, Birzhevaya Liniya 14, 199034 Saint Petersburg, Russia.

Correspondence: Alexandre Locquet - aloquet@georgiatech-metz.fr

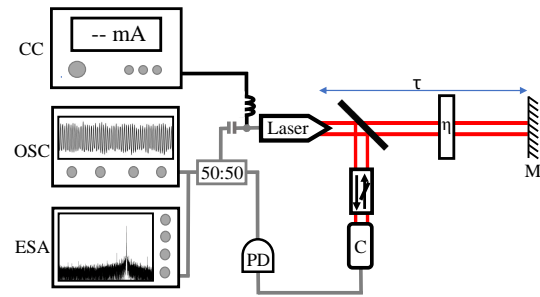


Fig. 1. Schematic diagram of the free-space OEO. Mirror, M, is an adjustable distance from the laser, which causes the laser’s output to be **re-injected** after time delay τ . The feedback strength is η , and is set by the angle between a fixed linear polarizer and a quarter-wave plate on a rotational stage. PD, C, and 50:50 stand for photodiode, free-space fiber coupler, and splitter, respectively. A bias-tee is connected to the laser to separate the DC and AC components of the signal. In the optical detection path, an optical isolator and fiber coupler are utilized to limit back reflections and couple the free-space optical intensity into fiber for detection and optoelectronic feedback. **CC, OSC and ESA stand for current controller, oscilloscope, and electrical spectrum analyzer, respectively.**

systems, telecomm, and navigation. The classical architectures of OEOs involving km-long fiber delay lines typically provide excellent phase noise performance in this band (below -140 dBc/Hz at 10 kHz offset from the carrier), but generally lack tunability, even though the capability to generate several frequencies in the X-band with the same oscillator appears to be an evident advantage. For this reason, various architectures of tunable OEOs across the X-band have been proposed in recent years. For example, tunability was achieved in the 5.8–11.8 GHz frequency range with a phase noise of -104.6 dBc/Hz at 10 kHz offset in Ref. [14], with an OEO based on a tunable microwave photonic filter consisting of a polarization modulator, a chirped fiber Bragg grating, and a polarization beam splitter. The OEO proposed in Ref. [15] was tunable from 6.9 to 12.8 GHz with -112 dBc/Hz phase at 10 kHz offset, and it used a microwave photonic filter cascading a tunable multi-wavelength laser, a dispersion compensation module and an optical feedback loop. In Ref. [16], the power imbalance between the two ports of a dual-port Mach-Zehnder modulator was combined to frequency-chirping via a fiber Bragg grating to provide 5.8–11 GHz OEO tunability with -107.4 dBc/Hz phase noise at 10 kHz offset. The two-tone OEO demonstrated in Ref. [17] used a dual-polarization modulator, and could output a microwave tunable from 4 to 12 GHz, with a phase noise performance around -105 dBc/Hz at 10 kHz offset.

There has been recent interest in OEOs that self-generate

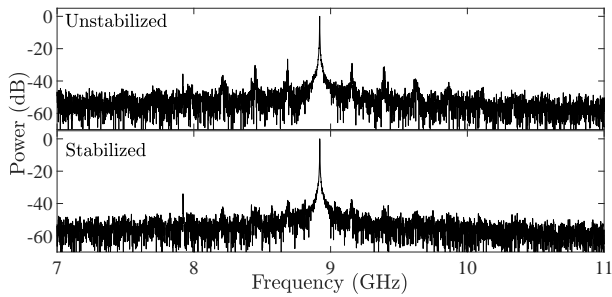


Fig. 2. Spectra obtained from time-dependent voltage $V(t)$ of a representative OEO operating at 8.9 GHz without (top) and with (bottom) stabilization. A significant reduction 12 dB in side-band noise from ~ 26 to ~ 38 dB is observed in the spectra with stabilization indicating a reduction in jitter and noise. For the spectra shown here $L = 20$ cm, $J = 72$ mA, and $m = 12$.

microwave optical signals without the need for high-frequency electronic sources. In Refs. [18], [19], period-one oscillation in optically injected lasers have been exploited for microwave-photonics applications, but require two separate lasers. In such photonic microwave oscillators, tunability over ~ 10 GHz has been demonstrated [20]–[25]. As for integrated laser devices which produce spontaneous dynamics, a numerical study, with a relatively short delay has been proposed in [26], and integrated amplified feedback lasers with relatively short delays, millimeters, have been demonstrated to generate pulsating dynamics numerically and experimentally [27]–[29]. These integrated devices are fabricated to include two separate sections phase tuning and amplifier which must be powered separately. These devices, demonstrate pulsations in the range of 10-50 GHz with poor phase noise ~ -75 dBc/Hz at 10 kHz [28]. As we discuss below, we also exploit the intrinsic nonlinear dynamics of lasers to produce microwave-modulated optical signals, but without the need for a separate injection laser, microwave source, or exotic stabilization components.

Recently, a relatively simple X-band tunable OEO was demonstrated that did not require optical-to-electrical conversion (although a microwave-modulated optical signal is produced as a by-product and can be used) by utilizing the high-frequency dynamics of the terminal voltage $V(t)$ from a semiconductor laser subjected to optical feedback [30]. Specifically, an OEO tunable from 6.79 to 11.48 GHz was demonstrated, but with substantial jitter and noise of ~ 10 ps and ~ -80 dBc/Hz at 10 kHz offset, respectively. In external-cavity semiconductor lasers (ECL), there are two major frequencies whose interplay creates rich dynamics. The first is the relaxation-oscillation frequency $f_{RO} \propto \sqrt{J - J_{th}}$ where J and J_{th} are the pump and threshold currents, respectively; f_{RO} appears in the dynamics when either the optical intensity or gain-medium carrier density are perturbed from steady-state leading to an exchange between the photon population and inversion in the laser-diode active region. The second frequency $f_{\tau} = 1/\tau = c/2L$ is the free-spectral range of the delay-induced external-cavity modes, with τ the external-cavity round-trip time, c the speed of light *in vacuo*, and L the external-cavity length (Fig. 1) [31]. The OEO is based on the dynamics of several periodic solutions that can be observed for wide ranges of feedback strength η [32]–[34],

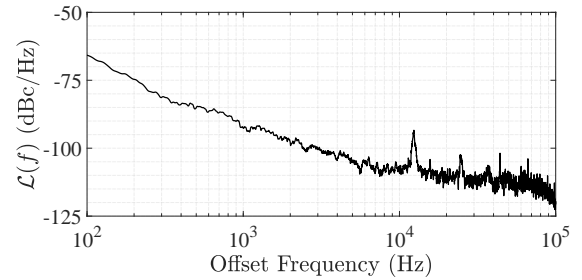


Fig. 3. Example single side-band phase noise measurement, $\mathcal{L}(f)$, for the stabilized OEO utilizing a spectrum analyzer. The average phase noise for 20 measurements at a 10 kHz offset is -107.3 dBc/Hz. For the example shown here $L = 20$ cm, $J = 84$ mA, and $m = 14$.

and the frequency of the observed microwave oscillation in the optical intensity $I(t)$ and $V(t)$ is the ECL's f_{RO} , which varies gradually with J [33] and therefore can be utilized as a tuning parameter.

Two features of central importance for most OEO applications are frequency tunability and phase stability. Using the method based on optical feedback, we demonstrate that it is possible to access the entire X-band with simple adjustment of J . Thus, these systems offer wide tunability but to date lack the phase stability needed for many applications. Here we demonstrate how to stabilize such systems.

The OEO is based on an unpackaged multi-quantum well laser operating at 1550 nm subjected to optical feedback from an external mirror a fixed distance L away [33]. The optical intensity re-injected into the laser is represented by the feedback strength η in Fig. 1; it is controlled by the relative angle of a quarter-wave plate mounted on a rotational stage to a fixed linear polarizer aligned to the natural polarization of the laser [30], [32]–[34]. A beam splitter was placed in the optical path in order to obtain a signal for optoelectronic feedback as well as measurement. A photodiode (Newport 1544-B - 12 GHz), oscilloscope (Agilent 80804B - 12 GHz), and spectrum analyzer (Anritsu MS2830A - 26.5 GHz) were utilized to measure the jitter and single side-band phase noise, respectively. A high-frequency RF probe (Cascade Microtech - 40 GHz), bias-T (Mini-circuits - 18 GHz), and electrical splitter (Mini-circuits 12 GHz) were utilized. Finally, the linewidth was investigated using the built-in linewidth measurement tool of our optical spectrum analyzer (Aragon Photonics - BOSA 400) with a resolution of 10 MHz.

While $I(t)$ and $V(t)$ in an ECL, for the appropriate range of η for given L and J , undergo undamped relaxation oscillations typically in the X-band [30]; without further intervention those oscillations are subject to considerable phase noise. One of the aims of our present contribution is to tame this phase-noise problem. The first stability improvement was based on optoelectronic feedback of the system as shown schematically in Fig. 1. Essentially, a beam splitter was placed in the external cavity such that half the optical power could be extracted and converted to electrical signal by a photodiode. Half of the electrical signal was added to the laser's DC nominal injection current J using a bias-T and RF probe. The electrical feedback loop is utilized only for stabilization and *not* for

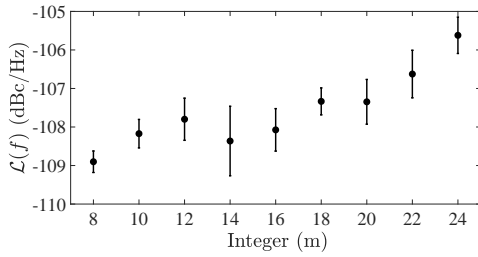


Fig. 4. Average single side-band phase noise, $\mathcal{L}(f)$, is shown versus the locking integer m . The average phase noise and standard deviation for 10 measurements at a 10 kHz offset are shown. A reduction in the phase noise is observed for decreasing integer values.

selecting the OEO's frequency. Heuristically, it reinforces the oscillation through a self-modulation of the injection current by the photodetected optical signal. **It is important to mention that such optoelectronic feedback loops have been previously utilized on the terminal voltage in optically injected lasers in order to improve stability [10], but these systems are more complex requiring two lasers and components associated with additional lasers and coupling them together. Further, in our system this stabilization alone is not enough.** The second improvement was to set f_τ to be close to an integer multiple of f_{RO} . Specifically, f_{RO} was fixed to the desired RF frequency using the DC pump current. Next, τ was adjusted by changing the mirror's position relative to the fixed laser (τ in Fig. 1), until $f_{\text{RO}} \approx m f_\tau$ with m an integer. In previous work, it has been shown that a laser diode subjected to optical feedback tends to oscillate at a frequency that is close to a multiple of f_τ [32], [34], even if f_{RO} is not itself close to an integer multiple of f_τ . Heuristically, by choosing an integer ratio between the two intrinsic frequencies, we reinforce the tendency of the dynamical system to lock its oscillation frequency to a multiple of f_τ , leading to a more stable oscillation.

In order to characterize the OEO, $V(t)$ was measured and analyzed to extract the jitter and ascertain spectral purity. Figure 2 shows the calculated FFT spectra of the unstabilized and stabilized time series $V(t)$. From the spectra, there is an increase in spectral purity and stability given by a reduction in the peak-to-pedestal ratio (12 dB). To quantify this, jitter was calculated using a demodulation technique [30]. Specifically, it was calculated by assessing the mean time variation in zero crossings between the experimentally measured oscillator and an ideal sinusoid at the carrier frequency. It was possible to ascertain that the jitter was reduced from 10 ps to sub-ps levels, but this method was limited by the oscilloscope's sampling frequency. In consequence, a phase-noise measurement was performed using a spectrum analyzer, Fig. 3. The phase noise was measured to be ~ -107 dBc/Hz at 10 kHz offset, which is a substantial improvement of ~ 28 dB over the unstabilized OEO [30]. We suggest the strong reduction in noise and jitter are the result of increased coherence created by optoelectronic feedback and resonant locking. Subsequently, the influence of the selected integer m or optical delay τ on phase noise was investigated. Specifically, ten phase-noise measurements were taken at each integer locking/delay and the mean and standard deviation are shown in Fig. 4. A decrease in phase

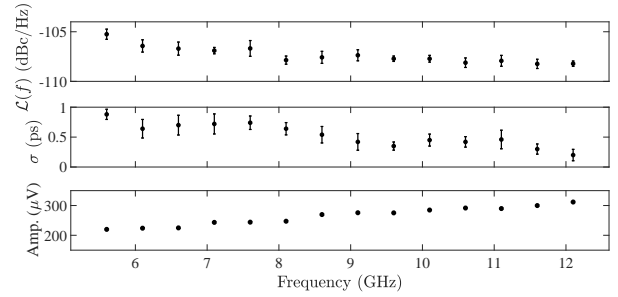


Fig. 5. Average phase noise ($\mathcal{L}(f)$), jitter (σ), and amplitude are shown as a function of frequency for 10 measurements. A reduction in the phase noise and jitter is observed for increasing frequency because of a relative reduction in the dominance of spontaneous emission noise. Finally, a consistent but increasing amplitude is observed across the tunable range.

noise is observed for smaller m or τ , which we attribute to a reduction in environmental factors, as well as, overall system stability resulting from a shorter free-space delay. **As far as optical feedback strength, a series of bifurcations and complex dynamics are observed [34]. We set aside full discussion of such bifurcations, but we observe clear limit-cycles which are utilized here when 4-7 % of optical power being fed back on the front facet of the laser. We also analyzed the gain and feedback length and how it changed the stabilization. For the length, we observe no change which we attribute to the fact that the optoelectronic feedback lengths tested were significantly longer (> 10). On the other hand, we were able to find an optimal optoelectronic feedback gain of -4 dB (1.4-1.8 mW) of optical power on the photodiode depending on the microwave frequency. Finally, the linewidth of the main peak in the optical spectrum was below the 10 MHz resolution limit of the optical spectrum analyzer. We note that the combination of the two phase-noise-reduction techniques were needed in tandem and that the phase-noise reductions are not additive.**

While plots of the results for an OEO with output at 8.9 GHz are shown in the figures, by varying J , f_{RO} and hence the OEO frequency can be tuned across the X-band with similar performance. Specifically, we found similar low-phase-noise, jitter, and amplitude characteristics for OEOs from 5.5 GHz to 12.1 GHz with phase noise and jitter less than -105 dBc/Hz and 1 ps, respectively, Fig. 5. The amplitude varies by about 35 % across the tuning range (~ 200 – 300 μV) giving a typical output power of 15 μW . Note that in all cases, we employed the same ECL, but had to adjust only η to ensure undamped relaxation oscillations, set L , and vary J to achieve the resonance condition $f_{\text{RO}} = m f_\tau$ and desired frequency. Of note, the lower limit of our tuning range originates in the dominance of spontaneous-emission noise for small J , while the upper limit originates from the cutoff frequency of our oscilloscope.

A stable optoelectronic oscillator tunable across the X-band is demonstrated using a laser subjected to optical and optoelectronic feedback (ECL). This system utilizes off-the-shelf telecom components and could be made very compact. The stability of the OEO is characterized by sub-ps jitter, a phase noise of -107 dBc/Hz at a 10 kHz offset in the laser-diode terminal voltage $V(t)$. The combination of OEO frequency

tunability from ~ 5.5 GHz to ~ 12.1 GHz and low phase noise makes our approach to microwave generation of great potential interest. Our device when compared to the current X-band tunable state-of-the-art discussed in the introduction has competitive or superior phase noise and tunability while offering a more compact and simpler design. Further, let us mention that, it is possible to exploit the microwave-modulated optical signal $I(t)$ for optical clock distribution and RF over fiber. However, our focus in this study is to directly use the microwave electronic signal $V(t)$. In this case, the device is functionally an *electronic* microwave source, even though the physical basis of its operation exploits photonic effects. We note in conclusion that based on the well-established understanding of the nonlinear dynamics of ECLs, we expect that this approach will also enable low-noise OEOs at up to several tens of GHz by choosing lasers with higher f_{RO} (such as VCSELs).

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