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 tunable 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 approaches 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.

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 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 [13], 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 [14] was tunable from 6.9 to 12.8 GHz with −112 dBc/Hz phase noise 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 [15], 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 [16] 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 microwave optical signals without the need for high-frequency electronic sources. In [17] and [18], 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 [19]–[24]. Lasers with integrated optical feedback have been shown numerically and experimentally to generate periodic pulsating dynamics in [25]–[29]. These devices are fabricated to include two separate integrated phase tuning and amplifier sections that must be powered separately. The integration of the feedback cavity leads to short, fixed, delays (100s of μm). Pulsations in the 10-50 GHz range with phase noise ~ -75 dBc/Hz at 10 kHz have been reported [27]. In [29], it was shown that the beating of a multi-wavelength version of these devices with optical and amplified optoelectronic feedback could be utilized to achieve a tunable (28-41 GHz) stable (≥ -106 dBc/Hz at 10 kHz) oscillator. As we discuss below, we also exploit the intrinsic nonlinear dynamics of lasers to produce microwave-modulated optical

Manuscript received June 20, 2018; revised July 18, 2018; accepted July 23, 2018. Date of publication July 27, 2018; date of current version August 16, 2018. This work was supported in part by the Conseil Régional du Grand Est and in part by the Fonds Européen de Dévelopement Regional (FEDER). *(Corresponding author: Michael J. Wishon.)*

M. J. Wishon, D. Choi, T. Niebur, N. Webster, 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 also with Georgia Tech-CNRS UMI 2958, Georgia Tech Lorraine, 57070 Metz, France (e-mail: mwishon@gatech.edu).

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

E. A. Viktorov is with the Department of Laser Systems and Technologies, ITMO University, 199034 Saint Petersburg, Russia.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2018.2859748

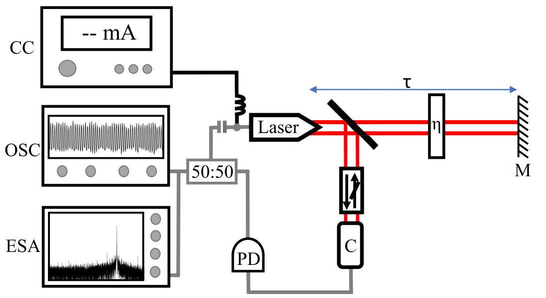

Fig. 1. Schematic diagram of the free-space OEO. Mirror, M, is placed an adjustable distance from the laser, which causes the laser's output to be re-injected after time delay τ. The feedback strength is η, and is set by the angle between a fixed linear polarizer and a quarter-wave plate on a rotational 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.

signals, but without the need for a separate injection laser, microwave source, or specialized stabilization components.

Recently, a relatively simple X-band tunable OEO was demonstrated that did not require optical-to-electrical conversion 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 $\sim$ 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 $f_{\mathrm{RO}} \propto \sqrt{J - J_{\mathrm{th}}}$ 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). The OEO is based on the dynamics of several periodic solutions that can be observed for wide ranges of feedback strength η [31]–[33], 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 [32] 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 [32]. 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]–[33]. 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. The first stability improvement was based on optoelectronic feedback of the system as shown schematically in Fig. 1. 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 selecting the OEO's frequency. Heuristically, it reinforces the oscillation through a self-modulation of the injection current by the photodetected optical signal. We note, stabilization of the oscillations resulting from the optical injection of a master laser into a slave laser through an optoelectronic feedback loop directly onto the slave laser [10] or onto a phase modulator in the master-slave path [34] have been proven to improve the linewidth [10] and phase noise properties [34]; in particular, in [34] a tunable oscillation from 10-46 GHz with the best phase noise -105 dBc/Hz at 10 kHz is demonstrated. One can note, however, that optically injected systems are somehow 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. Therefore, the second improvement was to set f_{RO} to be close to an integer multiple of f_τ. 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 $f_{\mathrm{RO}} \approx m f_\tau$ 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 [31], [33], 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. Figure 2 shows the calculated FFT spectra of the unstabilized and stabilized time series $V(t)$. From the spectra, there is an increase in stability given by a reduction in the peak-to-pedestal ratio (12 dB). To quantify

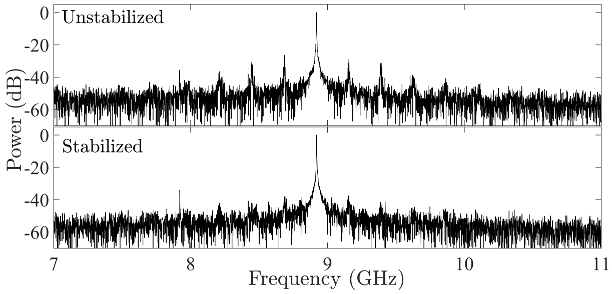

Fig. 2. Spectra obtained from the time-dependent voltage $V(t)$ of a representative OEO operating at 8.9 GHz without (top) and with (bottom) stabilization. A significant reduction 12 dB in side-band noise from $\sim$ 26 to $\sim$ 38 dB is observed in the spectra with stabilization indicating a reduction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

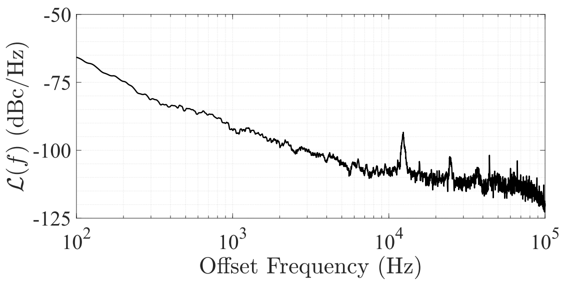

Fig. 3. Example single side-band phase noise measurement, $\mathcal{L}(f)$, for the stabilized OEO utilizing a spectrum analyzer. The average phase noise for 20 measurements at a 10 kHz offset is -107.3 dBc/Hz. For the example shown here $L = 20$ cm, $J = 84$ mA, and $m = 14$.

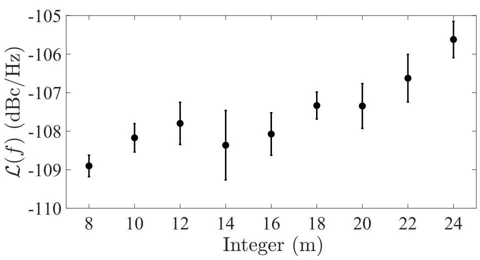

Fig. 4. Average single side-band phase noise, $\mathcal{L}(f)$, is shown versus the locking integer m. The average phase noise and standard deviation for 10 measurements at a 10 kHz offset are shown.

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 $\sim$ 28 dB over the unstabilized OEO [30]. We suggest the strong reduction in noise are the result of increased coherence created by optolectronic 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

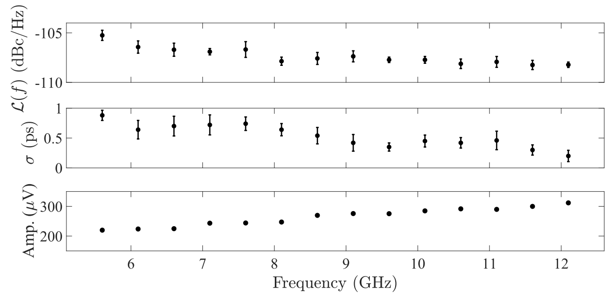

Fig. 5. Average phase noise ($\mathcal{L}(f)$), jitter (σ), and amplitude are shown as a function of frequency for 10 measurements.

phase 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 [33]. On the route to chaos clear limit-cycles (utilized here) are observed when 4-7 % of optical power is being fed back on the front facet of the laser. We have performed preliminary experimental investigations of the influence of the gain and length of the optoelectronic feedback loop. The delay was increased from 26 ns to 40 ns with no change in performance. The experimental conditions are such that the dynamics are mainly determined by the optical feedback, while the optoelectronic feedback serves as a perturbative stabilization loop. The gain of the optoelectonic feedback loop was decreased by modifying the free-space-to-fiber coupling efficiency; an optimal gain level of ~ -4 dB attenuation with respect to optimal coupling was observed. 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 ($\sim$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 $f_{\mathrm{RO}} = m f_\tau$ and any desired frequency in the band. 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 photodiode.

A stable optoelectronic oscillator tunable across the X-band is demonstrated using a laser subjected to optical and opto-electronic 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 by utilzing, in tandem, the two stabilization techniques described above. 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).

The authors acknowledge Rahim Ramdane for providing the laser diode.

References

[1] X. S. Yao and L. Maleki, "High frequency optical subcarrier generator," *Electron. Lett.*, vol. 30, no. 18, pp. 1525–1526, 1994.

[2] X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," *J. Opt. Soc. Amer. B*, vol. 13, no. 8, pp. 1725–1735, 1996.

[3] L. Maleki, "Sources: The optoelectronic oscillator," *Nature Photon.*, vol. 5, no. 12, p. 728, 2011.

[4] P. Devgan, "A review of optoelectronic oscillators for high speed signal processing applications," *ISRN Electron.*, vol. 2013, 2013, Art. no. 401969, doi: 10.1155/2013/401969.

[5] X. Zou *et al.*, "Optoelectronic oscillators (OEOs) to sensing, measurement, and detection," *IEEE J. Quantum Electron.*, vol. 52, no. 1, 2016, Art. no. 0601116.

[6] M. Zanola, M. J. Strain, G. Giuliani, and M. Sorel, "Monolithically integrated DFB lasers for tunable and narrow linewidth millimeter-wave generation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 19, no. 4, Jul./Aug. 2013, Art. no. 1500406.

[7] Y.-N. Tan, L. Jin, L. Cheng, Z. Quan, M. Li, and B.-O. Guan, "Multi-octave tunable RF signal generation based on a dual-polarization fiber grating laser," *Opt. Express*, vol. 20, no. 7, pp. 6961–6967, 2012.

[8] G. Carpintero *et al.*, "95 GHz millimeter wave signal generation using an arrayed waveguide grating dual wavelength semiconductor laser," *Opt. Lett.*, vol. 37, no. 17, pp. 3657–3659, 2012.

[9] M. A. Al-Mumin and G. Li, "Self-consistent Simulation of self-pulsating two-section gain-coupled DFB lasers," *IEEE J. Quantum Electron.*, vol. 41, no. 4, pp. 525–531, Apr. 2005.

[10] S.-C. Chan and J.-M. Liu, "Tunable narrow-linewidth photonic microwave generation using semiconductor laser dynamics," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 5, pp. 1025–1032, Sep. 2004.

[11] S. Pan, Z. Tang, D. Zhu, D. Ben, and J. Yao, "Injection-locked fiber laser for tunable millimeter-wave generation," *Opt. Lett.*, vol. 36, no. 24, pp. 4722–4724, 2011.

[12] B. Romeira, J. Javaloyes, J. M. L. Figueiredo, C. N. Ironside, H. I. Cantú, and A. E. Kelly, "Delayed feedback dynamics of Liénard-type resonant tunneling-photo-detector optoelectronic oscillators," *IEEE J. Quantum Electron.*, vol. 49, no. 1, pp. 31–42, Jan. 2013.

[13] Z. Tang *et al.*, "Tunable optoelectronic oscillator based on a polarization modulator and a chirped FBG," *IEEE Photon. Technol. Lett.*, vol. 24, no. 17, pp. 1487–1489, Sep. 2012.

[14] F. Jiang *et al.*, "An optically tunable wideband optoelectronic oscillator based on a bandpass microwave photonic filter," *Opt. Express*, vol. 21, no. 14, pp. 16381–16389, 2013.

[15] Z. Wei, R. Wang, T. Pu, G. Sun, T. Fang, and J. Zheng, "A tunable optoelectronic oscillator based on a tunable microwave attenuator," *Opt. Fiber Technol.*, vol. 19, no. 5, pp. 383–386, 2013.

[16] B. Gao, F. Zhang, P. Zhou, and S. Pan, "A frequency-tunable two-tone RF signal generator by polarization multiplexed optoelectronic oscillator," *IEEE Microw. Wireless Comp. Lett.*, vol. 27, no. 2, pp. 192–194, Feb. 2017.

[17] T. B. Simpson, J.-M. Liu, M. AlMulla, N. G. Usechak, and V. Kovanis, "Linewidth sharpening via polarization-rotated feedback in optically injected semiconductor laser oscillators," *IEEE J. Sel. Topics Quantum Electron.*, vol. 19, no. 4, Jul./Aug. 2013, Art. no. 1500807.

[18] A. Hurtado, R. Raghunathan, I. D. Henning, M. J. Adams, and L. F. Lester, "Simultaneous microwave- and millimeter-wave signal generation with a 1310-nm quantum-dot-distributed feedback laser," *IEEE J. Sel. Topics Quantum Electron.*, vol. 21, no. 6, Nov./Dec. 2015, Art. no. 1801207.

[19] P. Pérez *et al.*, "Photonic generation of microwave signals using a single-mode VCSEL subject to dual-beam orthogonal optical injection," *IEEE Photon. J.*, vol. 7, no. 1, Feb. 2015, Art. no. 5500614.

[20] M. C. Pochet, N. A. Naderi, V. Kovanis, and L. F. Lester, "Modeling the dynamic response of an optically-injected nanostructure diode laser," *IEEE J. Quantum Electron.*, vol. 47, no. 6, pp. 827–833, Jun. 2011.

[21] Y.-H. Liao and F.-Y. Lin, "Dynamical characteristics and their applications of semiconductor lasers subject to both optical injection and optical feedback," *Opt. Express*, vol. 21, no. 20, pp. 23568–23578, 2013.

[22] Y.-H. Hung and S.-K. Hwang, "Photonic microwave stabilization for period-one nonlinear dynamics of semiconductor lasers using optical modulation sideband injection locking," *Opt. Express*, vol. 23, no. 5, pp. 6520–6532, 2015.

[23] S.-C. Chan, S.-K. Hwang, and J.-M. Liu, "Period-one oscillation for photonic microwave transmission using an optically injected semiconductor laser," *Opt. Express*, vol. 15, no. 22, pp. 14921–14935, 2007.

[24] C. Cui, X. Fu, and S.-C. Chan, "Double-locked semiconductor laser for radio-over-fiber uplink transmission," *Opt. Lett.*, vol. 34, no. 24, pp. 3821–3823, 2009.

[25] A. A. Tager and K. Petermann, "High-frequency oscillations and self-mode locking in short external-cavity laser diodes," *IEEE J. Quantum Electron.*, vol. 30, no. 7, pp. 1553–1561, Jul. 1994.

[26] O. Brox *et al.*, "High-frequency pulsations in DFB lasers with amplified feedback," *IEEE J. Quantum Electron.*, vol. 39, no. 11, pp. 1381–1387, Nov. 2003.

[27] D. S. Yee, Y. A. Leem, S. T. Kim, K. H. Park, and B. G. Kim, "Self-pulsating amplified feedback laser based on a loss-coupled DFB laser," *IEEE J. Quantum Electron.*, vol. 43, no. 11, pp. 1095–1103, Nov. 2007.

[28] L. Yu *et al.*, "Monolithically integrated amplified feedback lasers for high-quality microwave and broadband chaos generation," *J. Lightw. Technol.*, vol. 32, no. 20, pp. 3595–3601, Oct. 15, 2014.

[29] B. Pan, D. Lu, L. Zhang, and L. Zhao, "A widely tunable optoelectronic oscillator based on directly modulated dual-mode laser," *IEEE Photon. J.*, vol. 7, no. 6, Dec. 2015, Art. no. 1400707.

[30] C.-Y. Chang *et al.*, "Tunable X-band optoelectronic oscillators based on external-cavity semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 53, no. 3, Jun. 2017, Art. no. 2000406.

[31] B. Kim, A. Locquet, D. Choi, and D. S. Citrin, "Experimental route to chaos of an external-cavity semiconductor laser," *Phys. Rev. A, Gen. Phys.*, vol. 91, no. 6, p. 061802, 2015.

[32] C. Y. Chang *et al.*, "A multi-GHz chaotic optoelectronic oscillator based on laser terminal voltage," *Appl. Phys. Lett.*, vol. 108, no. 19, p. 191109, 2016.

[33] M. J. Wishon, A. Locquet, C. Y. Chang, D. Choi, and D. S. Citrin, "Crisis route to chaos in semiconductor lasers subjected to external optical feedback," *Phys. Rev. A, Gen. Phys.*, vol. 97, no. 3, p. 033849, 2018.

[34] J. S. Suelzer, T. B. Simpson, P. Devgan, and N. G. Usechak, "Tunable, low-phase-noise microwave signals from an optically injected semiconductor laser with opto-electronic feedback," *Opt. Lett.*, vol. 42, no. 16, pp. 3181–3184, 2017.