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A multi-GHz chaotic optoelectronic oscillator based on laser terminal voltage

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A multi-GHz chaotic optoelectronic oscillator based on an external cavity semiconductor laser (ECL) is demonstrated. Unlike the standard optoelectronic oscillators for microwave applications, we do not employ the dynamic light output incident on a photodiode to generate the microwave signal, but instead generate the microwave signal directly by measuring the terminal voltage \( V(t) \) of the laser diode of the ECL under constant-current operation, thus obviating the photodiode entirely.

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Microwave signals are commonly used in communications, radar, and medical imaging. High-frequency microwave waveforms are conventionally generated in the electrical domain using the digital electronics and typically involve several stages of multipliers and amplifiers. This approach, however, may be inefficient at high frequencies. Another possibility is to generate microwave waveforms in the optical domain, to take advantage of the broad bandwidth and low attenuation in the optical system. Optical generation of microwave signals enables tremendous flexibility; the optical signal can be converted immediately to a microwave electrical signal via a fast photodiode (PD) or transmitted over low-loss optical fiber systems to be converted downstream to a microwave electrical signal.

Specific implementations of such optoelectronic oscillators (OEOs) can be based on the beating of two phase-locked optical waves,1,2 through OEOs based on optical injection of a master laser into a slave laser3 or electro-optic modulators.4,5 have been demonstrated. Moreover, on-chip OEO miniaturization and integration is possible,6 providing a further desirable feature of OEOs.

In addition to the interest in optical microwave generation of periodic1 and shaped-pulse2 signals, there has also been a stream of work on the generation of broadband chaotic signals through the use of electro-optic modulators subjected to feedback2–4 of a laser diode (LD) subjected to optoelectronic5 or optical feedback6,7 (ECL) or to optical injection.1,2,4 It is notable that certain applications16 of chaotic laser dynamics, and in particular, chaotic radar15 and ultrahigh-rate random-bit generation,16–18 do not intrinsically make use of the chaotic optical signal, but of an electrical signal detected by one or more PDs. These comments also apply for the work cited above on the generation of periodic microwave signals: a PD separate from the LD is always necessary to create an electrical signal while the optical signal itself is often not used directly [unless low-loss optical transmission of the signal is needed prior to optical-to-electrical (O/E) conversion]. Clearly, circumventing O/E conversion could significantly simplify various applications of such chaotic signals.

In this letter, we demonstrate a chaotic multi-GHz OEO based on an ECL with direct chaotic microwave electrical generation. In other words, our approach entirely obviates the use of a PD by directly monitoring the time-dependent voltage \( V(t) \) across the injection terminals of the laser diode under constant-current \( J \) injection. We verify that the dynamics exhibited by \( V(t) \) is indeed chaotic and of comparable dynamical complexity as that of \( I(t) \) by means of a largest-Lyapunov-exponent (LLE) analysis. The basis for our observation is that for small signals, \( V(t) \) is proportional to the inversion \( N(t) \) in the gain medium, as was pointed out in Refs. 19–21. The dynamics of \( N(t) \) and \( I(t) \), in turn, is closely linked, as is understood, for example, on the basis of the Lang-Kobayashi equations.22 Ref. 23 recently showed a measurement of the voltage \( V(t) \) across the LD but focused uniquely on its use, in conjunction with a phase measurement, to describe and understand the regime of low-frequency fluctuations.

The experimental setup is shown in Fig. 1. The single longitudinal-mode edge-emitting InGaAsP multi-quantum-well distributed feedback laser (DFB) LD emits at 1550 nm with free-running threshold current \( J_{th} \approx 29.8 \text{ mA} \). The heterostructure, containing 7 quantum wells, and the grating are designed and fabricated to achieve a \( k \) product of 50 cm\(^{-1}\) and the length \( L \) of the laser diode is measured to be 0.6 mm, resulting in a \( kL \) value of 3. The detailed structure has been described and investigated for feedback tolerance in Ref. 24. The experimental feedback strength \( \eta \) is determined by the relative angle between the polarizer and the quarter-wave plate (QWP), where \( \eta = 1 \) corresponds to maximum feedback strength \( \eta_{\text{max}} \approx 16\% \) of the optical power that is coupled back onto the collimating lens. The QWP is mounted on a motorized rotational stage with a step size of 0.01°. During the experiment, an RF probe (Cascade Microtech AE-ACP40-GSG-400) with a bandwidth of 40 GHz is used to extract \( V(t) \) from the LD injection.
The AC component of $V(t)$ is separated from the DC component with a bias tee (Keysight 11612A), and then amplified with an 18-dB amplifier (Newport 1422-LF) with a 20 GHz bandwidth. The AC components of intensity $I(t)$ and voltage $V(t)$ are both captured by a real-time oscilloscope (Agilent DSO80804B) whose cut-off frequency is 12 GHz. The external cavity length $L$ is chosen to be 30, 42, or 70 cm corresponding to the external cavity round-time $\tau = 2, 2.80, \text{or } 4.67 \text{ ns}$ and giving an external-cavity free-spectral range of $f_s = \frac{\tau^{-1}}{C_0} = 0.5, 0.35, \text{or } 0.21 \text{ GHz}$, respectively.

Figure 2 shows $I(t)$ and $V(t)$ with their RF spectra for various $\eta$ at $J = 70.12 \text{ mA}$ and $L = 42 \text{ cm}$ via FFT of the original time series. Under these conditions, the relaxation-oscillation frequency $f_{RO} = 8.04 \text{ GHz}$ and $f_s = 0.35 \text{ GHz}$. Both $I(t)$ and $V(t)$ are extracted simultaneously from the
oscilloscope and synchronized precisely by calibrating the
time delay in the optical versus the electrical path. We observe
that the ECL experiences a range of dynamical regimes (CW,
periodic, quasi-periodic, and chaotic) and can be accessed
both from the optical intensity and the laser voltage. We also
observe, as expected, that \( V(t) \) and \( I(t) \) are typically highly
 anticorrelated on the timescale of the relaxation-oscillation frequency \( f_{RO} \) and that the side-peak separation is close to \( f_r \). The undamping of these two frequencies probably results from the two successive Hopf
bifurcations in Refs. 10 and 25. Periodic dynamics is observed within the region \( \gamma \), and in Fig. 2(c), where a single peak dominates the RF spectrum. In this case, the peak is at
\( \sim 8.40 \) GHz, reflecting \( f_{RO} + f_r \), as already observed in
Ref. 25 in the case of a multi-quantum-well laser. The observation of such periodic windows in the route to chaos is consistent with the previous reports (Refs. 10 and 25) of periodic windows in the quasi-periodic route to chaos in an
ECL. Moreover, the observed frequency of \( \approx 8.46 \) GHz in
the region \( \gamma \), reflecting \( f_{RO} + f_r \), is also consistent with our
previous conclusion in Ref. 25.

As we further increase the feedback strength above \( \eta > 0.23 \), we enter region \( \delta \) of the BDs (Fig. 3); \( V(t) \) and \( I(t) \) reveal an apparently erratic behavior [Fig. 2(d1)] and the corresponding spectra show considerable broadening [Fig. 2(d2)], as the 6dB bandwidth is approximately \( 4.56 \) GHz. The suspected chaotic behavior in region \( \delta \) is confirmed by evaluating the (LLE) from the analysis of the RF spectrum in the form of a central peak at \( 8.46 \) GHz from the central peak. This quasi-periodic
behavior is expected to occur on the route to chaos for an
ECL, where the central peak frequency is close to that of the relaxation-oscillation frequency \( f_{RO} \) and that the side-peak separation is close to \( f_r \). The undamping of these two frequencies probably results from the two successive Hopf bifurcations in Refs. 10 and 25. Periodic dynamics is observed within the region \( \gamma \), and in Fig. 2(c), where a single peak dominates the RF spectrum. In this case, the peak is at
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confirmed the robustness of these observations by resolving BDs for various values of $L$ (30, 42, and 70 cm) and $J$ (50, 60, and 70 mA) which enables further tunability of the RF spectrum and chaos complexity. In region $d$, the bandwidth of $V(t)$, where the ECL is in coherence collapse (well-developed chaos), extends up to 8 GHz.

As ECLs are recognized as being simple and inexpensive sources of high-dimensional chaos, as is of interest for applications such as chaos radar and ultrahigh rate random-bit generation, our work demonstrates the ability to generate such microwave signals directly, and not requiring O/E conversion. In conclusion, we have demonstrated a multi-GHz OEO that entirely circumvents the need for O/E conversion. We have shown that the voltage $V(t)$ across the LD allows for the robust generation of periodic, quasi-periodic, as well as chaotic oscillations, of various complexity, that have similar characteristics to those obtained from the optical intensity.

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