High-Speed Wideband Voltage-Controlled Oscillator via an Injection-Locked Laser

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***Abstract*— We demonstrate a microwave voltage-controlled oscillator able to synthesize a wide range of frequencies in the GHz regime based on an optically injected semiconductor laser. The ability to understand and experimentally characterize the entire injection-locking domain is crucial for the realization and optimization of such a device. This characterization facilitates the identification of steady-state bias conditions, which lead to microwave oscillations. More importantly, it also identifies a regime in which the oscillation frequency can be tuned solely by adjusting the optically injected power, a parameter, which can easily be changed on a nanosecond time scale. In this letter tuning from 6–16 GHz is demonstrated, while tuning rates of $\sim 1 \times 10^{18}$ Hz/sec are achieved using a < 1 V drive signal, resulting in a voltage-controlled oscillator with rapid tuning speed when compared with conventional, e.g. YIG-based, oscillators.**

***Index Terms*— RF oscillators, tunable oscillators, injection locking.**

I. Introduction

THE period-one state of optical injection locking represents a situation in which the optical emission of an isolated "master" laser is injected into a "slave" laser and in-so-doing un-damps the slave's relaxation oscillations. When the output of a slave laser, configured in this regime, is detected by a high-speed photodiode, a microwave signal in the GHz-regime is produced. While the stable and chaotic regimes of injection locking have historically attracted the most attention [1], the ability to use the microwave signals generated in these dynamic regimes for applications has gained interest over the last decade [2]. Although prior studies have demonstrated tuning over several GHz, the properties of these systems were typically investigated at static injection strengths or by thermally detuning frequencies between the master and the slave lasers.

Theoretical studies have shown that the behavior which gives rise to the period-one state of injection locking exhibits a non-trivial dependence on the detuning frequency between the master and slave lasers and on the optical power injected into the slave laser [2]. For the majority of this parameter space, the period-one frequency primarily depends on the detuning frequency. However, it was demonstrated that localized regions violate this behavior [2]. These regions were recently confirmed experimentally in a distributed feedback semiconductor laser where it was verified that the period-one operating region exhibits a reduced sensitivity to changes in the detuning frequency between the master and slave lasers [3]. This behavior has sparked interest not only because it has evaded investigation for many years but for any improvement it may offer in the creation of a narrow-linewidth injection-locked photonic oscillator. Indeed, there is considerable interest in optically synthesizing microwave sources able to compete with existing electrical systems in the GHz frequency regime [4].

Previous work in the field of injection-locked semiconductor lasers has resulted in injection-locking maps which coarsely define the boundaries between different operating regimes, e.g. stable locking, period-one, period-two, chaos, etc. [5]. The experimental characterization of this system via the generation of high-resolution maps enables us to locate the ideal region of the period-one dynamics in order to construct a tunable voltage-controlled oscillator. One key difference in this work is that the detuning parameter is varied with step sizes as low as 200 MHz. This systematic approach affords the fidelity necessary to capture the localized period-one states and trace their evolution as a function of injected power and detuning frequency.

While it is well-known that a laser's carrier frequency can be tuned using thermal or mechanical means, this typically limits tuning speeds to millisecond time scales. In the proposed system, the sensitivity to injected power, which can be changed on a nanosecond timescale via an electro-optic modulator without changing laser frequency, enables the high-speed tuning of this injection-locked-laser-based voltage-controlled oscillator (ILL-VCO). This key feature facilitates the experimental realization of an ILL-VCO operating in the microwave regime with tuning occurring at microwave frequencies.

There are a number of alternative configurations to realize optically based microwave sources including the Fourier synthesis of mode-locked pulses [6], [7], opto-electronic oscillators [8], etc. In addition, the ILL-VCO system has been explored for a number of years [9], [10] and is now the focus of other efforts [11], [12]. Nevertheless, we point out that similar studies addressed either the feasibility of [9], [11], or specific applications for these systems (e.g. as a radar disambiguation function with high tuning speeds [12]). In this Letter, we address the key issue of tuning speed, a value which to the best of our knowledge exceeds those of prior studies. Another important aspect of this work is our ability to generate and use the microwave mapping of the injection-

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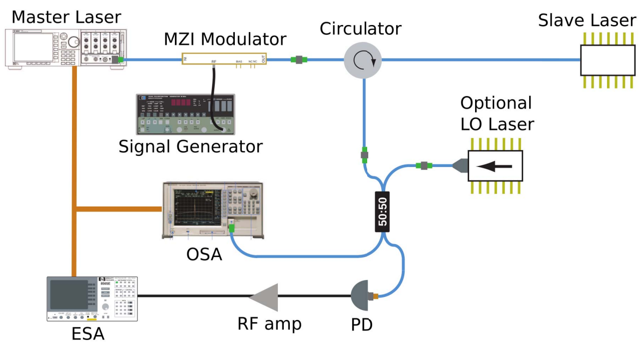

Fig. 1. Schematic of the experimental setup. PD: 50-GHz photodiode; RF amp: 2–50 GHz low-noise RF amplifier. All fibers used in this experiment were single-mode polarization-maintaining with FC/APC connectors to minimize reflections and any in-loop polarization drift.

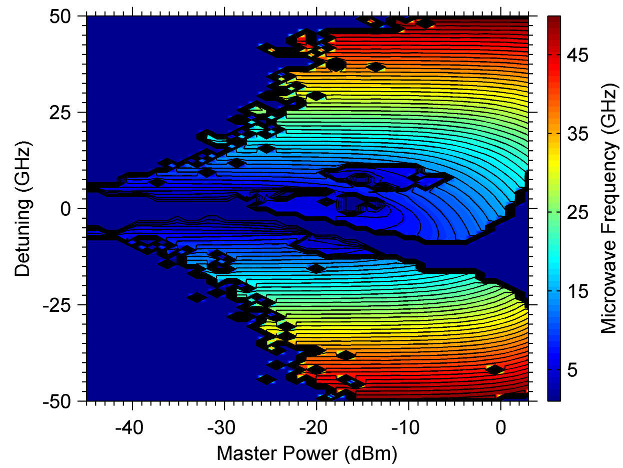

Fig. 2. Experimental map of the dominant microwave frequency found as a function of detuning and injection strength extracted from the slave laser under test (from Ref. [10]).

locking regime, which allows us to judiciously choose the ideal operating points for a desired application.

II. Experimental Setup

To optimize the functionality of this system, it is instructive to systematically characterize the microwave frequency response of the injected slave as function of the detuning frequency and injected power. Figure 1 provides a schematic of the layout used in this work and serves as one topology for an ILL-VCO. The Mach–Zehnder intensity (MZI) modulator allows for rapid variation ($>$ 10 GHz) of the injection strength. The optical circulator directs the master's output into the slave laser while isolating the slave from unwanted feedback from the output arm. The slave's output is sent to both an optical spectrum analyzer and a photodiode, whose output is subsequently amplified (via the RF amplifier) before being sent to the electronic spectrum analyzer (ESA) for diagnostic purposes. The dominant microwave frequency and corresponding amplitude at any given system operating point is monitored as a function of detuning frequency and injection amplitude using the ESA.

III. Measurements and Results

A. Static Measurements

In producing Fig. 2 the master laser's optical wavelength was changed in 10-pm ($\delta\nu \approx 1.25$ GHz) steps over a total detuning span of 100 GHz. At each point the optical spectrum, microwave spectrum, and optical power of the slave laser are recorded. This process is repeated as the injection strength is logarithmically swept from 1 nW to 3 mW (see Fig. 2). The most vital information is contained in the microwave spectrum wherein the dominant frequency at each point is extracted once a threshold amplitude (5 dB above the noise floor) is met. The result of this process is shown in Fig. 2 which depicts the dominant frequency as a function of the detuning and injection strength.

The color scheme in Fig. 2 represents the microwave frequency while the contours trace lines of constant frequency. Here, the region of interest is where the contour lines are parallel to the y-axis and can therefore be crossed by changing the injection strength at a fixed detuning — this region is exploited to realize this ILL-VCO.

These experimental "maps" agree with both previous experimental work and numerical simulations (e.g. Refs. [2], [3], [10]) and serve as a blueprint for the design and optimization of an ILL-VCO. For example, Fig. 2 enables one to select an optimal detuning frequency while simultaneously identifying the VCO output frequency as a function of injection strength ("Master Power").

A detuning of -2.5 GHz was selected in this work. At this detuning, the resulting period-one microwave frequency, as a function of the injected power, is shown in Fig. 3. This clearly depicts a tuning range of 10 GHz over a 13-dB change in injection strength.

Once the range of injection strengths necessary to scan the frequencies of interest are determined, the voltage biasing and modulation inputs to the MZI modulator can be established. We note the tuning speeds of MZI modulators ($>$ 50 GHz) exceed the slave laser's carrier lifetime, which for a quantum-well laser is typically on the order of 5 ns. As a consequence, it should be possible to produce an ILL-VCO which is capable of tuning over a $\sim$ 10-GHz window in less than 10 ns where it is anticipated that the carrier lifetime will likely serve as the dominant physical mechanism limiting the tuning speed of the system; photon lifetime also plays an important role in the system properties. The tuning range is related to the properties of the slave laser under test; different slave lasers can be used to tune over higher frequencies, for example by using smaller laser cavities or different bias conditions [10], [11], [13]. Finally, it was experimentally confirmed that the tuning window can be shifted by configuring the system using a different detuning frequency — in this work, frequencies beyond 25 GHz were accessible.

B. Dynamic Measurements

While the results of the optical characterization presented in the previous section serve to identify the general behavior and confirm static tuning, the primary motivation of this work was to understand the response of the electrical output of this system when used as a high-speed VCO. To observe the performance of the system, the voltage of the MZI modulator

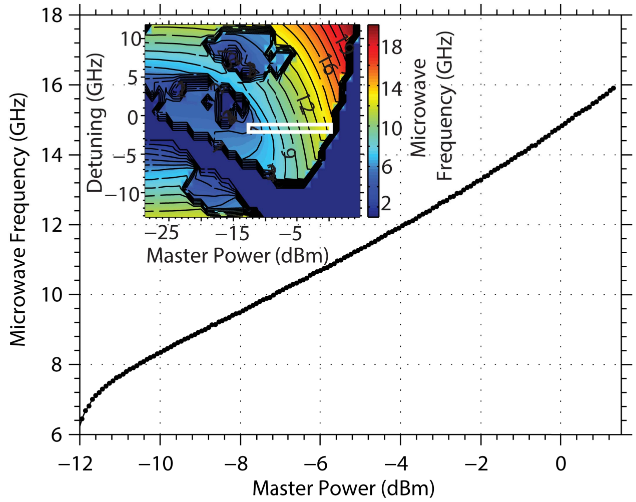

Fig. 3. Experimental plot of the microwave frequency as a function of injection strength when the detuning is -2.5 GHz. (inset) A 200-MHz high-resolution version of the "injection map" shown in Fig. 2 highlighting the regime under study in the rest of this work.

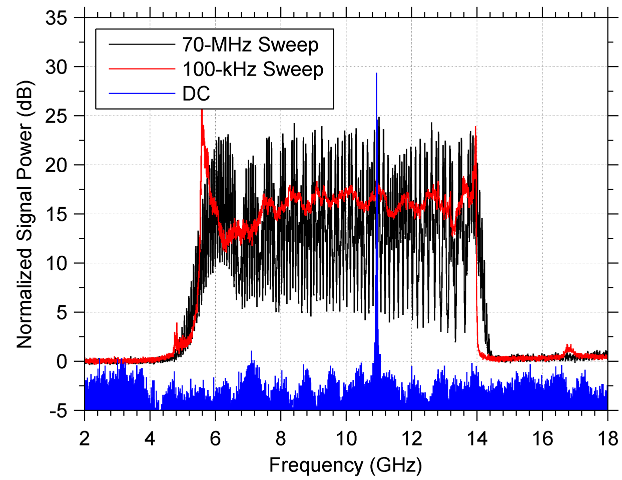

Fig. 4. The spectrum of the ILL-VCO modulated at 70 MHz (black) and 100 kHz (red) alongside a representative RF spectrum of the system under DC biasing (blue).

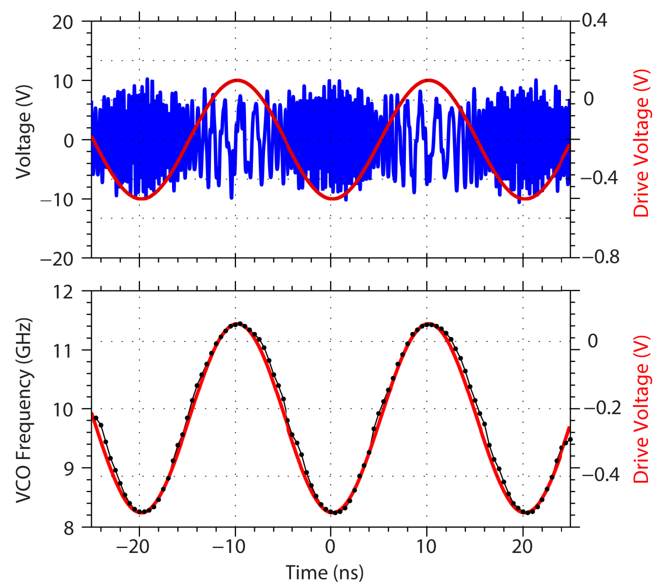

Fig. 5. Temporal response of the ILL-VCO when tuned over 3.5 GHz using a 50-MHz sinusoidal drive voltage. The down-converted signal is recorded as a voltage (top blue) while the VCO's output frequency has been extracted and is depicted (bottom black). In both cases scaled versions of the sinusoidal drive voltage are shown for comparison purposes (in red). The LO used for down conversion was fixed at 12 GHz to facilitate the acquisition of this data without aliasing or LO crossover effects.

was first swept using a sinusoidal voltage source. Here the voltage sweep changes the injection power by an amount that corresponds to a ∼ 9-GHz change in microwave frequency. Figure 4 shows the electrical spectrum recorded over a 20-GHz span when the voltage is sinusoidally swept at a rate of 70 MHz (black) or at a rate of 100 kHz (red).

Regardless of the sweep rate, the system response demonstrates tuning from 5 to 14 GHz. A typical spectrum found under DC biasing has been superimposed on the data and is shown in blue for comparison. The frequency dependent power fluctuations (100-kHz sweep) were similar in magnitude to the static power fluctuations (∼ 10 dB). For the 70-MHz sweep, the power fluctuations were confirmed to be primarily an artifact related to a walk-off effect associated with the tuning speed of the ESA's local oscillator (LO). The ESA's LO sweep rate was in milliseconds while the ILL-VCO was swept on a nanosecond time scale. As a consequence, the ILL-VCO's output makes multiple passes (in this case 70× more than for the 100-kHz sweep) during a single sweep of the ESA and the resultant spectrum contains larger amplitude variation artifacts when compared to the 100-kHz sweep.

To understand the performance of the system in the temporal domain and confirm that the above oscillations are indeed a measurement artifact, the microwave signal was next routed to an oscilloscope. Due to the limited bandwidth of the real-time oscilloscope used in this work (6 GHz), the signal was first down converted using a microwave mixer and a 12-GHz microwave reference (Agilent E8257C) serving as a LO. The response of the ILL-VCO, when driven sinusoidally at 50 MHz using a modulation voltage of only 600 mV, is depicted in Fig. 5. The down-converted signal is displayed temporally as a voltage in Fig. 5(top). A windowed fast Fourier transform of this signal was computed at different times over the 50-ns span to generate a spectrogram (not shown) to depict the temporal evolution of the frequency content. The carrier frequency was subsequently extracted from the spectrogram and is compared in Fig. 5(bottom) to a scaled and shifted version of the sinusoidal modulation.

At this biasing location the ILL-VCO tuned from 8.25 to 11.5 GHz and showed good agreement with the anticipated sinusoidal response. The center frequency can be changed by adjusting the DC bias of the MZI modulator (the bias used in Fig. 5 was -211 mV) while the frequency span is controlled by the RF voltage (600 mV was used in Fig. 5). Note, the use of a 12-GHz LO makes the low-frequency content appear to be related to a high-frequency signal and vice versa. While the use of an LO and a 6-GHz oscilloscope should enable the demonstration of rapid tuning over ∼ 12 GHz, aliasing effects make such a characterization confusing. As a consequence, the dynamic work considered tunings only on the lower side of the 12-GHz LO thus limiting the maximum tuning range

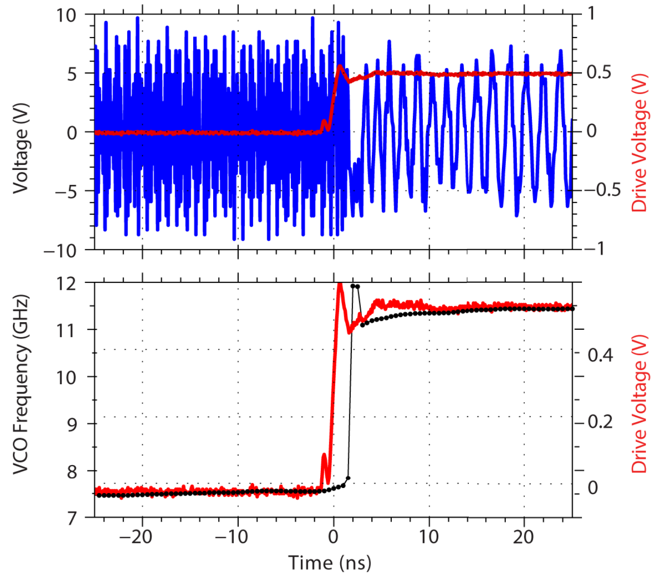

Fig. 6. Temporal response of the ILL-VCO to a square pulse (red). The down-converted signal is recorded as a voltage in (top blue) while the carrier frequency has been extracted and is depicted in (bottom black).

explored here; no effort was made to demonstrate the full ∼ 10-GHz tuning at these higher rates.

To determine the tuning speed and settling time of the system, a 500-mV square pulse was sent to the RF port of the modulator. This pulse, depicted by the scaled red curve in Fig. 6, induces a frequency shift from 7.5 GHz to 11.5 GHz as shown by the black trace. Here the steady-state frequency is reached in $<$ 10 ns. The delay observed in this figure is related to the path-length difference between the trigger and pulse arms and any additional delay in the system. While the system settles to within 10% of its final value in $<$ 2 ns the longer stabilization, toward its steady-state value, is closer to 10 ns consistent with the carrier lifetime in this slave laser.

Small fluctuations about the steady-state values at both 7.5 GHz and 11.5 GHz are most likely the result of external feedback from the optical elements of the circulator. Throughout this work, the measured linewidth for the static P1 frequency is around 100 kHz which corresponds to a convolution of the master and slave lasers' free-running linewidths. In addition, the P1 frequency can drift as much as 10 MHz over a one-second time span. This instability prohibits a meaningful single sideband phase-noise measurement in this work. Although the phase noise is expected to be worse during a dynamic sweep, we note that the ILL-VCO does not rely on an external cavity and hence it's linewidth/phase noise is not derived from the external cavity's properties as is the case for an OEO.

IV. Conclusions

We have demonstrated that an optically injected semiconductor laser can be employed as a high-speed voltage-controlled oscillator. The potential of this system as a VCO is dependent on both the ability to exploit and characterize the nonlinear region of the period-one dynamics which primarily depend on the injection strength. By configuring the system in the appropriate regime and leveraging the ability to control the injection strength via a Mach–Zehnder intensity modulator, we have shown tuning speeds as fast as 2 ns using control signals < 1 V. We believe this marks a significant improvement over the tuning speed of other VCOs. Furthermore, we expect that these results can be improved by investigations into the system parameters which control the nonlinear region used. Once integrated circulators become available on InP or Si platforms, such a system could be realized on-chip where it would be more compact and robust against environmental effects. We are also currently investigating other configurations, e.g. optoelectronic feedback, which improve the stability and linewidth of the microwave signal and these results will be addressed elsewhere.

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