Experimental and Simulation Study of Dual Injection-Locked OEOs

Olukayode Okusaga and Weimin Zhou
U.S. Army Research Laboratory,
Adelphi, MD USA
Email: ookusaga@arl.army.mil

Etgar Levy and Moshe Horowitz
Electrical Engineering,
Technion – Israel Institute of Technology,
Haifa, Israel

Gary Carter and Curtis Menyuk
Computer Sci. and Elec. Eng.,
Univ. of Maryland Baltimore County
Baltimore, MD USA

Abstract—**We investigate the physics of bidirectional injection-locking in optoelectronic oscillators (OEO). In particular, we identify the effects of injection strength on phase noise and spurious modes for a dual injection-locked OEO. Our experimental data is then used to design a numerical model of a dual injection-locked OEO. This model will be used in the future to optimize the multi-dimensional injection-locking parameters to achieve minimal phase noise and spurious mode levels.**

I. Introduction

Optoelectronic oscillators (OEOs) have proven to be promising sources of low phase noise radio frequency (RF) signal sources, particularly at frequencies of about 10 GHz [1-3]. The basic single-loop OEO uses a long optical fiber as a delay line in a feedback loop of optical and electronic paths. The long fiber loop can provide delays on the order of 20 µs with a losses as low as 2 dB. Because of the combination of large delay with low loss, the fiber loop acts as an ultra-high *Q* cavity. The basic OEO model, first proposed by Yao and Maleki [3], shows that the OEO's phase noise scales quadratically with delay. It can be shown that at equilibrium, the power spectral density of the OEO is given by

$$S_{\mathrm{RF}}(f`) = \frac{\delta}{\left(\delta/2\tau\right)^2 + (2\pi)^2(\tau f)^2}, \qquad (1)$$

where f is the frequency offset from the oscillation frequency and δ is the noise to signal ratio of the OEO and is given by

$$\delta \equiv \frac{|S_N|^2 G_A^2}{P_{\mathrm{OSC}}}. \qquad (2)$$

We can see that the bandwidth of the noise spectrum is inversely proportional to τ^2. Therefore, minimizing the OEO's phase noise requires that we maximize the delay τ. However, the frequency spacing between resonant modes in the OEO is given by $\Delta f \approx 1/2\tau$. Thus, as we increase the delay we narrow the mode spacing of the OEO. For a 4 km long fiber loop, the modes spacing is approximately 50 kHz. This is too narrow for conventional 10 GHz RF filters to isolate a single mode. For this reason, a high-*Q* single-loop OEO is multimode. However, for most oscillator applications, multimode oscillation is undesirable. In order to suppress multimode behavior in a high-*Q* OEO, it is necessary to adopt a multi-cavity architecture. In this work, we will focus on the dual injection-locked optoelectronic oscillator (DIL-OEO) first proposed by Zhou and Blasche [4]. The DIL-OEO consists of a high-*Q* "master" loop with a long optical fiber and a single-mode "slave" loop with a short optical fiber. The OEOs are injection-locked to each other by injecting a small amount of microwave radiation from each loop into the other as shown in Fig. 1. The phase of the signal that is injected from the slave is tuned via a phase shifter so that its oscillating mode coincides in frequency with one of the modes of the master loop. The master-to-slave injection is referred to as "forward injection," while the slave-to-master injection is referred to as "backwards injection." The forward injection serves to transfer a portion of the master's *Q* to the slave. The reverse injection serves to drive the master into a quasi-single-mode state by suppressing all but one of the modes.

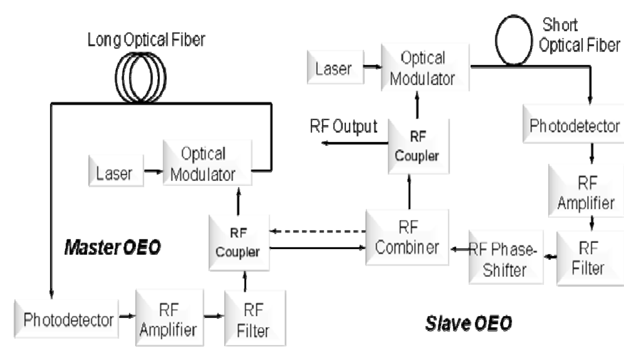

Figure 1. Figure 1: Dual injection-locked OEO diagram

Our earlier study demonstrated that bidirectional injection is necessary to achieve spurious mode suppression with low phase noise [5]. However, the optimal injection-locking

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conditions have yet to be found. In this work, we investigate injection-locking experimentally and used our data to create a numerical model capable of optimizing the DIL-OEO.

II. Experiments

A. Experimental Setup

Fig. 2 shows a simplified schematic of the injection-locking process in the DIL-OEO system used in our experiment. The master OEO has a long optical fiber delay line (~4km) while the slave OEO has a very short fiber delay (~40m). The Slave OEO's fiber length is chosen so that it has only one resonant mode within the pass band (8 MHz) of an RF filter centered at 10GHz. The free-running master OEO oscillates in multiple modes with a mode spacing of approximately 50 kHz.

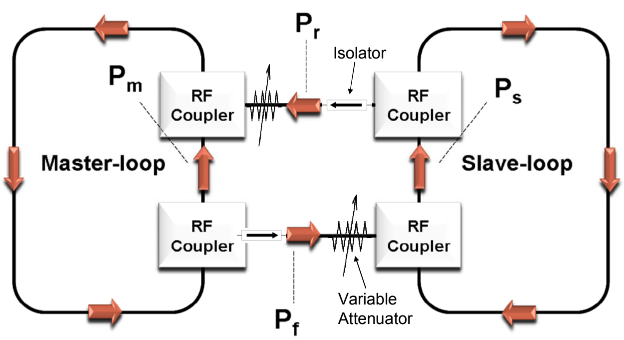

Figure 2. Figure 2: DIL-OEO schematic with emphasis on the bidirectional injection-locking bridge.

We now focus specifically on the bidirectional injection bridge. We place isolators and variable attenuators in each path of the bidirectional injection bridge allowing us to tune the master-to-slave and slave-to-master injection levels independently.

B. Injection-Locking Paramaters

The injected signals from master-to-slave and from slave-to-master are the key locking parameters investigated in this work. We will now define them more precisely. Fig. 2 shows the master and slave loop along with the bidirectional injection bridge with all appropriate signal powers labeled. The power in the master and slave loops are given by P_m and P_s respectively. The master-to-slave and slave-to-master injection powers are given by P_f and P_r respectively. Given these powers, we now define our injection locking ratios. The forward injection ratio r_f is given by P_f / P_s. The backwards injection ratio r_b is given by P_r / P_m. We find that the injection ratios – not the absolute injection powers – are the key parameters that determine the phase noise and spurious mode behavior of the DIL-OEO.

C. Noise Measurement System

In order to measure the very low phase noise levels produced by the DIL-OEO in this study, we built a cross-correlation delay-line noise measurement system capable of measuring noise levels as low as −122 dBc/Hz at 1 kHz offset from a 10 GHz carrier signal. The cross-correlation delay-line measurement system was first developed by Rubiola et. al [6]. Our measurement system is based on the Rubiola design. Fig. 3a shows a schematic of the cross-correlation measurement system.

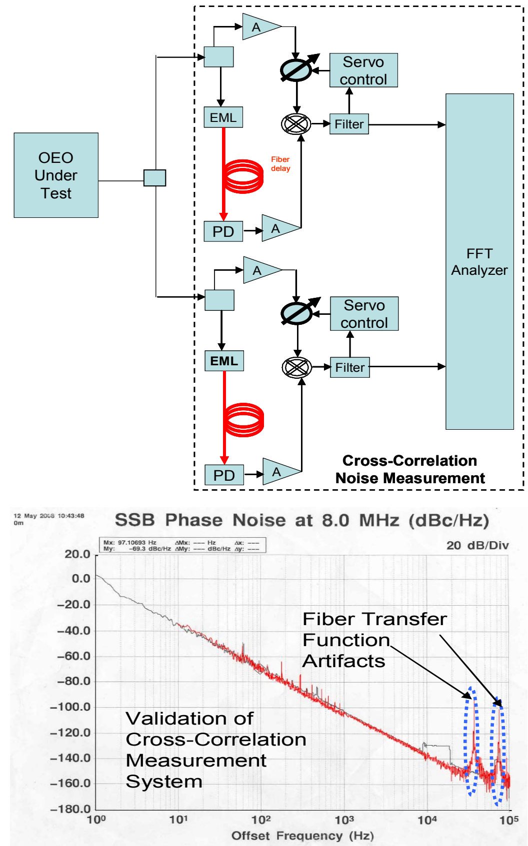

Figure 3. Figure 3a: Cross-correlation measurement system schematic. 3b: Validation of phase noise data.

Finally, we validated our system with the aid of a conventional noise measurement system*. A 10 GHZ dielectric resonant oscillator (DRO) was used as a test device. Its phase noise was measured at using a digital phase-locked loop measurement system with an ultra-low-phase-noise "Poseidon" oscillator [7] used as a standard. The DRO was then measured using our delay-line measurement system at the Army Research Laboratory (ARL). For the overlapping range of measured offset frequencies, (10 Hz to 10 kHz) there was very good agreement between both measurement systems. Figure 3b shows the DRO phase noise as measured by both systems. The noise spikes seen in the ARL measurement below 1 kHz are harmonics of the 60 Hz tone from the AC power supply.

The delay-line measurement system has a transfer function given by

$$S_{\varphi o}(f) = \left|H_{\varphi}(f)\right|^2 S_{\varphi i}(f), \qquad (3)$$

where

$$\left|H_{\varphi}(f)\right|^2 = 4\sin^2(\pi f\tau), \quad (4)$$

and $S_{\varphi i}(f)$ is the input phase noise to be measured and $S_{\varphi o}(f)$ is the output noise power from the measurement system [6]. To obtain the input phase noise, we divide by the transfer function. However, for offset frequencies where $f\tau$ is an even integer the transfer function goes to zero, and we get divide-by-zero errors in our output data. These errors show up as spikes in our phase noise plots that we will point out throughout this work.

D. *Experimental Data*

In order to study the effects of injection-locking on the DIL-OEO's phase noise and spurious mode levels, we varied both the forward injection ratios while measuring the phase noise spectrum from both the master and slave loops in the DIL-OEO. We began by fixing both the forward and backwards injection ratios at -21 dB. We used a master loop with a delay of 4149 m and a slave loop with a delay of 44m. The oscillating signal powers in both loops were ~ 24 dBm. We measured the phase noise and spurious mode levels for both the free-running and injection-locked master and slave loops. The results are shown in fig. 4. Fig. 4a shows the phase noise of: the free-running slave; the injection-locked slave; the free-running master; and the injection-locked master for offset frequencies from 10 Hz to 100 kHz.

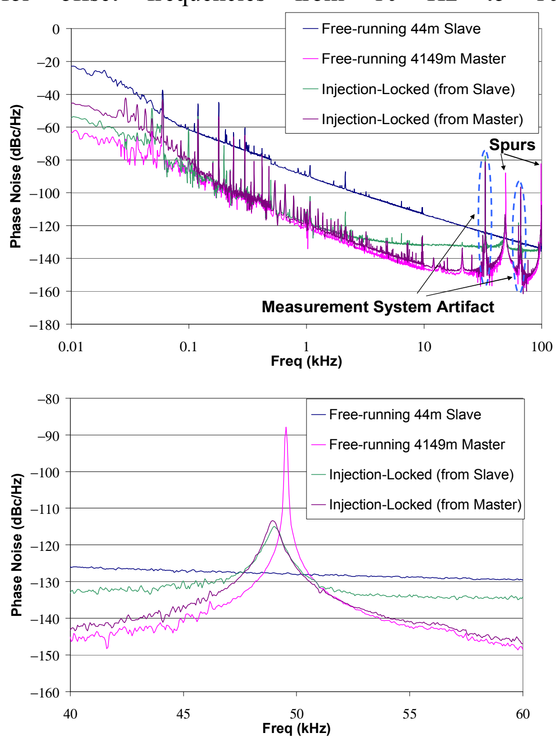

Figure 4. Figure 4a: DIL-OEO phase noise data; 4b: DIL-OEO 1st spur data

We see that the injection-locked master's phase noise is with 3 dB of the free-running master's phase noise for all offset frequencies. This suggests that injection-locking between a high-*Q* master and a low-*Q* slave can be achieved without significant degradation of the master OEO's *Q*. The injection-locked slave, however, shows slightly different phase noise behavior. The injection-locked slave's phase noise converges to that of the injection-locked master for offset frequencies below 1 kHz. For offset frequencies above 1 kHz, however, the injection-locked slave exhibits a phase noise plateau at a level equal to the free-running slave's phase noise at 100 kHz. This suggests that, at these injection ratios, there is a locking bandwidth of approximately 1 kHz, beyond which the slave OEO no longer converges to the high-*Q* master.

Fig. 4b shows the phase noise data around 50 kHz which is the offset frequency of the first spurious mode in the master OEO. We see that the free-running master has a very high spurious mode level of -87 dBc/Hz. The free-running slave of course has no spurious mode around 50 kHz as it is singlemode within the electrical filter bandwidth. Both the injection-locked master and injection-locked slave OEO exhibit spurious modes at 49 kHz. While the injection-locked slave's spur is roughly 2 dB lower than the injection-locked master's, both are over 25 dB lower than the free-running master's spurious mode level. We have therefore demonstrated significant spurious mode suppression without a significant increase in phase noise in our DIL-OEO. We note that while the above data demonstrates the viability of the DIL-OEO, it is far from optimal. The injection-locking levels used were somewhat arbitrary and we believe a more systematic search for the optimal injection-locking levels will provide much better results.

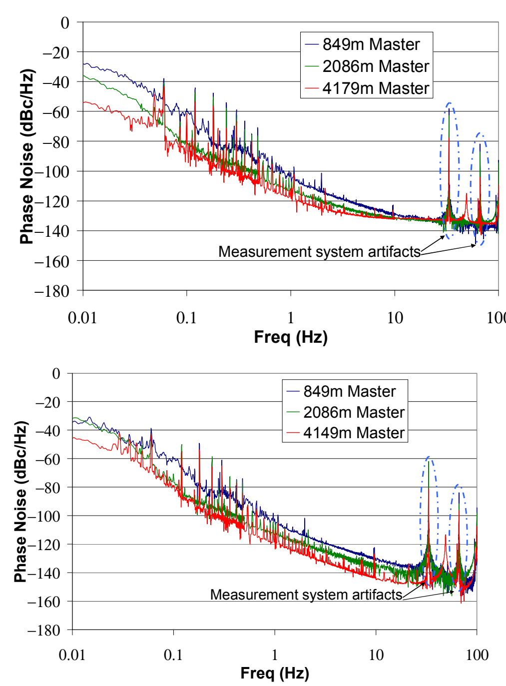

Figure 5. Figure 5: Phase noise for varying master loop lengths. 5a: measured from slave; 5b: measured from master.

We then varied the length of the master loop from 849m to 4149m as shown in fig 5. We observe the same qualitative behavior shown above. In the slave loop, the same plateau effect is seen for offset frequencies above 1 kHz, suggesting that the plateau region and level are set by the slave loop. The injection-locked master loops all exhibit phase noise levels similar to those of free-running OEOs of the same length.

Finally, we vary the forward injection level for a DIL-OEO with fixed master and slave loops. Fig. 6 shows the results of our phase noise measurements.

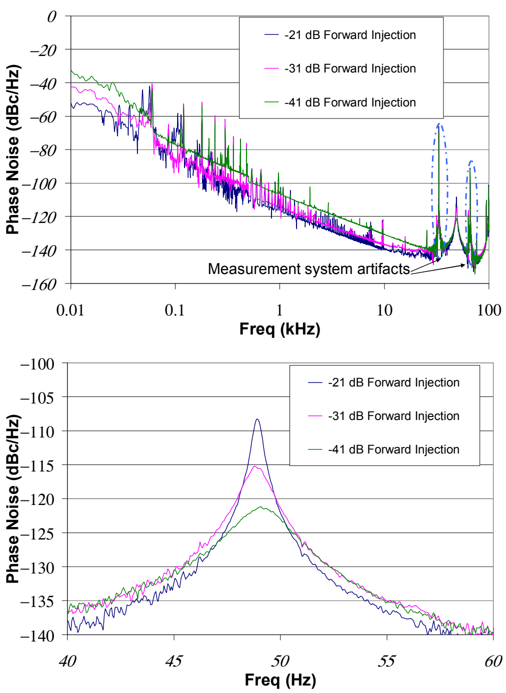

Figure 6. Figure 6a: DIL-OEO phase noise. Figure 6b: DIL-OEO spurious mode levels

As we reduce the forward injection level, we observe a significant and linear reduction in the level of the first spurious mode. The phase noise, however, varies in a nonlinear fashion with injection level. An initial reduction of 10 dB in the forward injection level generates only a 2.5 dB increase in phase noise while reducing the spurious mode level by over 7 dB. This suggests that there is an optimal forward injection level that will lead to reduced spurious mode levels without significant increases in phase noise.

III. Theoretical Model

Our theoretical model is a modular, time-domain model that implements each of the components of each OEO individually. As such, it is versatile enough to model both single-loop OEOs and various dual-loop architectures. The model has been presented in previous papers [8-10]. Here we will provide a brief description of its modeling of the bidirectional injection-locking process and show its agreement with our experimental data. The signal in each loop of the DIL-OEO is modeled as a complex phasor. The phasor modified each round trip by the individual components in each loop. Noise is also added each round trip. Finally the bidirectional bridge is modeled as a complex 2-by-2 matrix that couples the master and slave phasors to each other. The diagonal elements of the bridge matrix correspond to the loss and phase delay introduced into each loop by the bridge. The off-diagonal elements of the bridge matrix correspond to the forward and backwards injection ratios defined in section 2.2. Given a slave loop round trip time T, the master and slave loop phasors are given by $a_1(T)$ and $a_2(T)$ respectively. Then for the kth slave loop round trip, the injection-locking process is modeled as:

$$\begin{pmatrix} a_1(T) \\ a_2(T) \end{pmatrix}_k = \begin{pmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{pmatrix} \begin{pmatrix} a_1(T) \\ a_2(T) \end{pmatrix}_{k-1}, \quad (5)$$

where the γ_{ij} are complex coefficients of the injection-locking bridge matrix. We use slave loop round trips for our time quantization since the round trip time through the slave loop is much shorter than that of the master loop.

We find very good agreement between our theoretical and experimental results. Fig. 7a shows agreement between theory and experiment for the phase noise of both a free-running and injection-locked slave loop. Fig. 7b shows agreement between theory and experiment for both first spurious modes in both injection-locked slave and master loops.

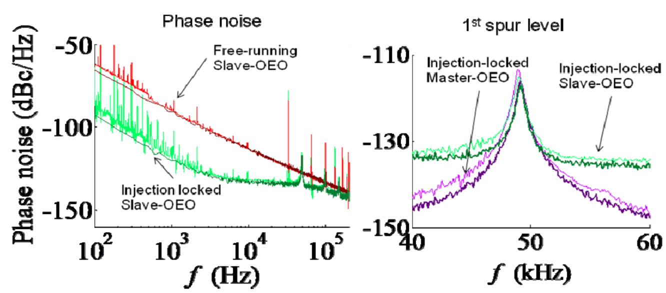

Figure 7. Figure 7: Theoretical versus experimental data for a DIL-OEO. Thin lines are experimental data; dark lines are theoretical data.

IV. Conclusions

Our study has provided insights into the effects of forward and reverse injection on the phase noise and spurious mode levels of the DIL-OEO. Over the range of injection ratios used in this study, we found that increasing the forward injection ratio lowered the phase noise while increasing the spurious mode levels in both the master and slave loops. Reducing the forward injection level reduced the spurious mode levels faster than it increased the phase noise between 100 Hz and 10 kHz in the master loop. Also, while the relationship between the forward injection level and spurious mode level is linear, forward injection levels have a nonlinear effect on phase noise. The above results suggest that there is an optimal forward injection level to minimize spurious mode levels without significantly increasing phase noise.

We also found that, for a range of injection ratios, the master and slave loop phase noise converge to a level close to that of the free-running master for offset frequencies within a certain locking-bandwidth. Beyond this bandwidth, the slave loop phase noise plateaus at a level determined by the slave loop Q and injection ratios. The locking-bandwidth is set in part by the injection ratios and by the relative lengths of the master and slave loops. The spurious mode levels in injection-locked slave loop are 2-3 dB lower than those in the injection-locked master loop. Taken together, the above results suggest that if one is mostly concerned with lowering phase noise, one should extract the signal from the master loop. If, however, one is primarily concerned with spurious mode suppression, one should extract the signal from the slave loop.

Finally, we developed the first ever multi-cavity OEO model. Our numerical model was used to simulate the DIL-OEO over the range of injection ratios used in our experiments. The resulting simulation results were in very good agreement with out experimental data. This model will prove valuable to optimizing the DIL-OEO as it accurately captures the physics of the injection-locking process.

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