Further Examination of the Injection-Locked Dual Optoelectronic Oscillator*

K.M. Hudek
University of Colorado
Boulder, CO, USA

A. Hati, D.A. Howe, C.W. Nelson
National Institute of Standards and Technology (NIST)
Boulder, CO, USA

W. Zhou
U.S Army Research Laboratory
Adelphi, MD, USA

***Abstract* – Optoelectronic oscillators (OEO), utilizing the low loss nature of optical links, can generate oscillations with very high Q values. The long delay line used in the oscillator can, however, support many modes of oscillation. Mode spacing is inversely proportional to the delay length of the optical link. The oscillator Q can be improved by increasing the delay length at the expense of tighter mode spacing. The undesirable modes become more difficult to filter in the RF domain as the spacing becomes closer. There are many different techniques for minimizing the impact of the competing modes on the desired one. The injection-locked dual OEO was presented last year. It consists of a high-Q multimode OEO (master) and a low-Q single-mode OEO (slave), each injection-locked to each other. The slave OEO, which generates the output signal, is injection-locked to the master OEO. This transfers some of the high-Q stability to the output, without transferring all of the spurious competing modes of the master. The master is also injection-locked to the slave OEO, causing its multimode oscillation to collapse to a mostly single mode, further reducing the transfer of spurious modes to the slave. In this paper we analyze the injection lock parameter's behavior on the performance of the total system.**

I. Introduction

In a delay-line resonator, modes in a transmission line exist at frequencies ~c/nL, where c is the speed of light, and n and L are respectively the index of refraction and length of the line. The optoelectronic oscillator (OEO) implements a low-loss optical fiber as a delay-line resonator [1-3]. An OEO is based on an optoelectronic feedback loop that directly converts continuous light energy to oscillations at these modes. The long delay line used in the OEO can generate oscillations with very high Q values, however, it also supports many modes of oscillation. Usually only one mode is desired, and the undesired modes become difficult to filter at high Q. Strategies exist for significantly suppressing these modes [4-8]. Results of a dual-fiber, injection-locked OEO, or DFIO, developed by Army Research Laboratory (ARL) illustrate that spurs are eliminated at high offset frequencies while preserving low phase modulated (PM) noise [8]. The DFIO consists of a high-Q multimode OEO (master) and a low-Q essentially single mode OEO (slave), each injection locked to each other. We study several aspects of the DFIO and evaluates its PM-noise trade-offs as a function of injection or coupling each way between the master and slave OEOs.

II. Experimental Set-up and Results

The goal of this paper is to study the trade space between spur rejection and phase noise in the DFIO presented in [8]. The phase noise achieved in these experiments is limited by the noise of the sustaining amplifiers as expected by theory. The results could have been greatly improved by using a low phase noise amplifier. The trade off between spur rejection and phase noise should still be applicable with such a lower noise amplifier.

Fig. 1 shows the block diagram of a DFIO. It consists of a high-Q multimode OEO (master) and a low-Q single mode OEO (slave), each injection-locked to each other. In each OEO, light from an electro-optic modulator is detected by a photo detector (PD) and then amplified, filtered and fed back to the electrical input port of the modulator. If the modulator is properly biased and the gain in the loop is properly chosen, self sustained electro-optic oscillation starts.

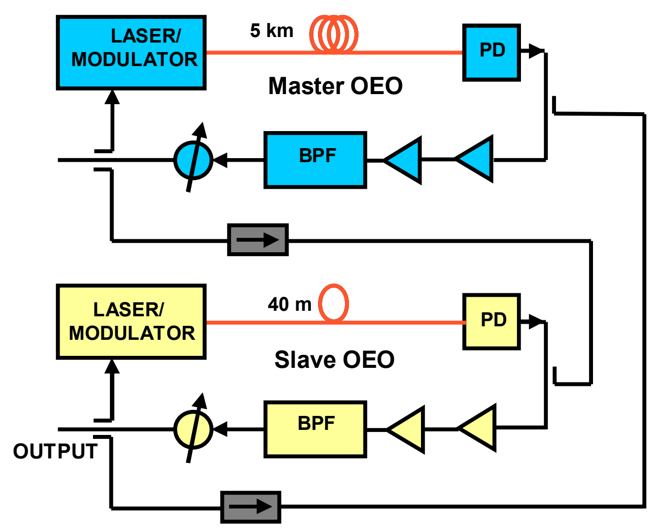

Figure 1. Block diagram of a dual-fiber, injection-locked optoelectronic oscillator (DFIO).PD: photo detector; BPF: bandpass filter.

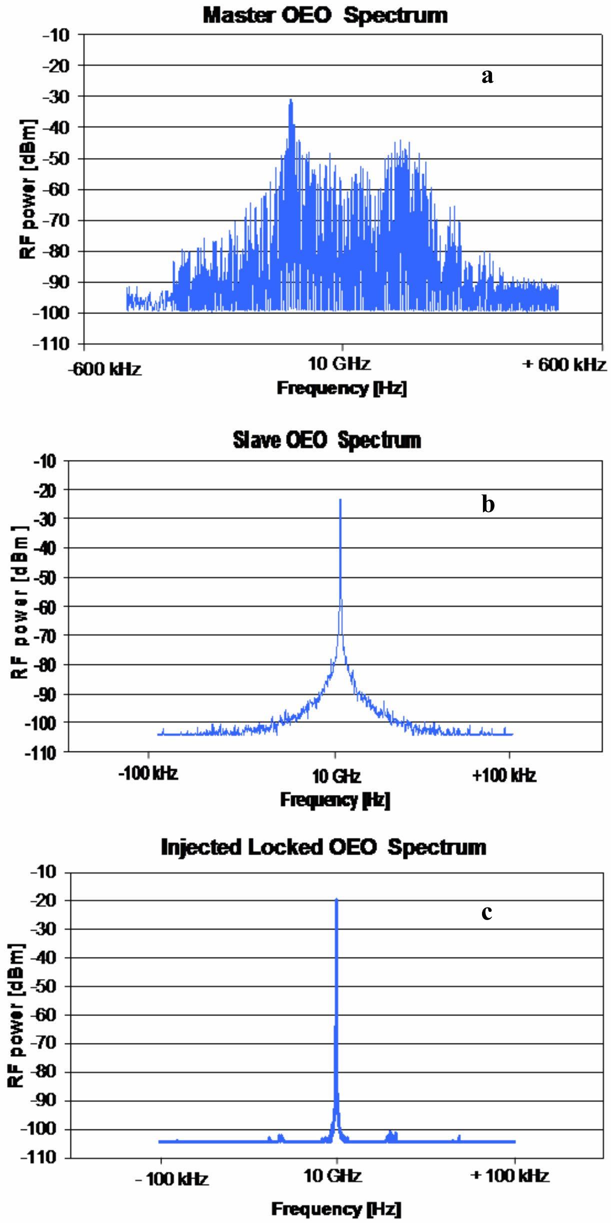

Figure 2. RF Spectrum of (a) Master OEO, (b) Slave OEO and (c) Injection Locked OEO at 10 GHz.

In the DFIO's final form, the high-Q, 5-km fiber master OEO is cross-coupled with the low-Q, 40-m fiber slave OEO via 10 dB directional couplers. For a 5-km fiber, the mode spacing is approximately 39.4 kHz, and for a 40-m fiber the mode spacing is 5.91 MHz. 8 MHz band pass filters are used in both loops to limit the range of oscillation and force the slave OEO into a single mode. The output of the oscillator is taken from the slave loop. This transfers some of the high-Q stability of the master to the output without transferring all of the spurious competing modes. The master is also injection-locked to the slave OEO, causing its multimode oscillation to

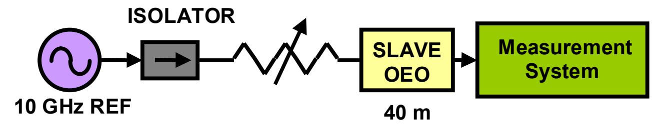

Figure 3. Experimental setup of 40 m single loop OEO injection locked to sapphire loaded cavity oscillator at 10 GHz.

collapse to a mostly single mode, further reducing the transfer of spurious modes to the slave (Fig. 2). Various configurations and tests were studied. The experimental setup in Fig. 3 was used to examine the phase noise of the slave OEO as a function of injection power of a sapphire loaded cavity oscillator (SLCO) at 10 GHz of known low phase noise characteristics. Fig. 4 shows the data obtained from the experimental setup shown in Fig. 3. As the injection power from the low phase noise SLCO is increased, the noise performance of the slave OEO is improved and approaches the noise performance of the SLCO.

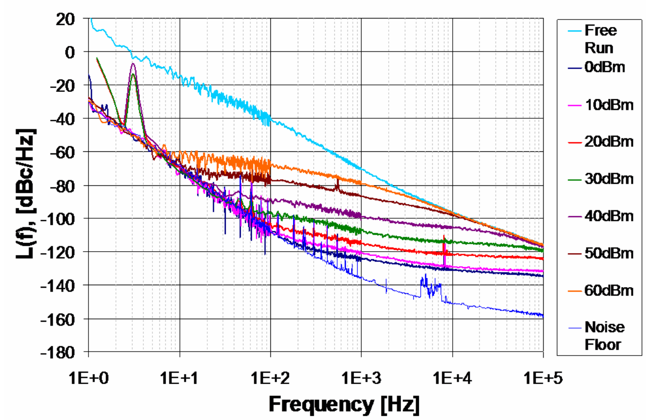

Figure 4. PM noise measurement of the slave OEO injection locked to a SLCO at various injection levels at 10 GHz. Top plot has no injection; bottom plot is the SLCO-only PM noise. Note: injection powers represent negative dBm.

The experimental setup in Fig. 5 was utilized to characterize the phase noise of the master OEO as a function of slave OEO injection power.

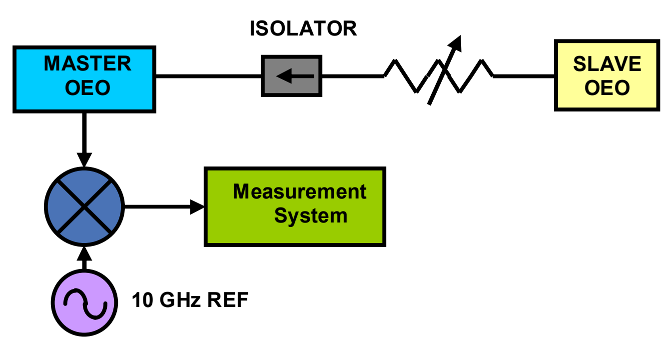

Figure 5. Experimental setup of the master OEO injection locked to the slave OEO.

Isolators were used to limit the injection only to slave-to-master, and variable attenuators were used to vary injection power. This oscillating mode was at 9.953 GHz because narrow band-pass filters were readily available.

Fig. 6 shows the data obtained from the experimental setup shown in Fig. 5. The master OEO with no injection from the slave has the best overall noise performance as a function of offset frequency. However, it has the largest adjacent spurious modes, owing to the tighter mode spacing and the sharing of power between modes. Alternatively, as the slave injection power is increased, the overall noise performance of the master OEO is degraded. However, the slave, which oscillates at basically only one mode with such wide spacing, forces the master to collapse most of its power into the mode nearest to the slave's oscillating frequency. This causes the spurs to decrease. The desired mode of oscillation was approximately chosen by matching the mode naturally set up by each individual OEO with a phase shifter.

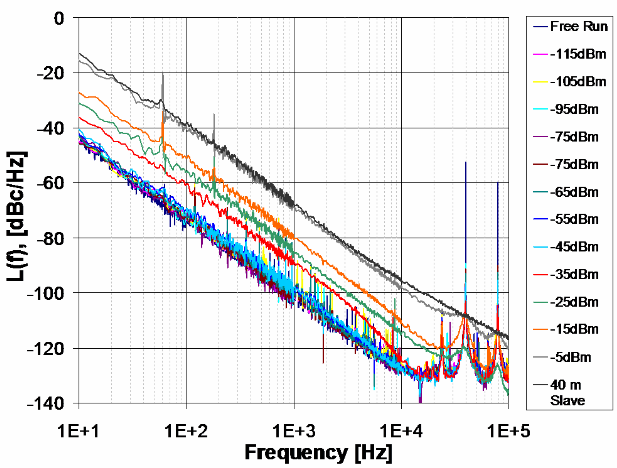

Figure 6. PM noise measurement of the master OEO at various levels of slave-to-master injection. Bottom plot has no injection; top plot is slave OEO only.

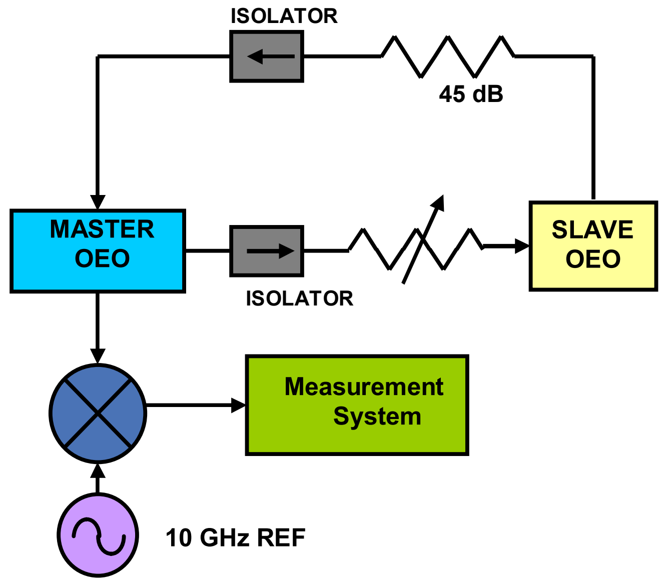

Figure 7. Experimental setup of the injection-locked dual OEO to study far-from-carrier noise.

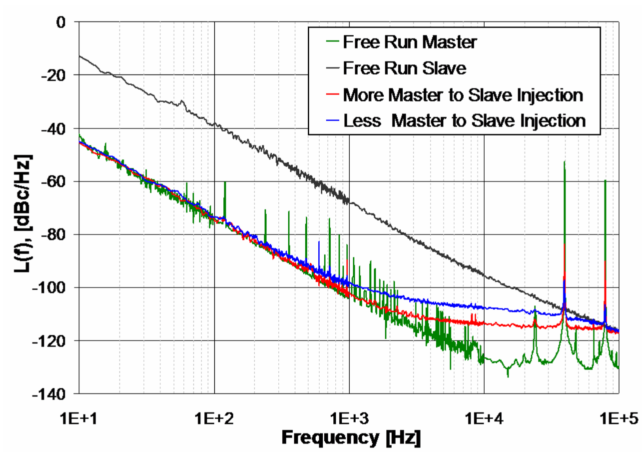

Figure 8. Dual injection-locked OEO with fixed slave-to-master injection at 9.953 GHz. Note the far-from-carrier noise floor increase with less master-to-slave injection, while the spurious levels decrease.

In order to examine the far-from-carrier (high offset) phase noise characteristics of the DFIO, the setup shown in Fig. 7 was utilized. The slave-to-master injection was isolated and held fixed at -45 dB. Note that the master-to-slave cross injection was isolated and variable at the injection power region around -30 dBm to -20 dBm, which seemed to be in an optimal region for obtaining lowest overall phase noise performance.

Fig. 8 shows various outcomes of the experimental setup shown in Fig. 7. As before, the overall noise performance of the master OEO is significantly better than the slave OEO; however, it exhibits large spurs due to the tight mode spacing. As the slave injection power is increased, the far-from-carrier noise increases, while the spurious modes decrease.

As can be seen from Fig. 6, the best compromise between overall noise performance and spur levels occurs somewhere between -10 dBm and -30 dBm of master-to-slave injection power. Fig. 9 zooms in on the trade between spurious mode levels and white noise levels of the DFIO as the master-to-slave injection power is varied by 2 dBm.

Fig. 10 is a graph of the spurious modes as a function of master-to-slave injection power. The 39.4 kHz and 78.8 kHz spurs drop approximately linearly with injection power in this regime. The sub harmonic at 28.3 kHz grows relative to the white noise level as the injection power is decreased; however, the overall level of the spur shows no dependence on injection power.

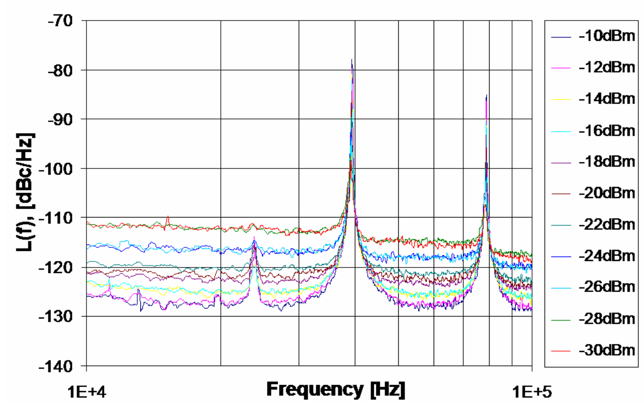

Figure 9. PM noise measurement of the spurious levels and far-from-carrier noise as master-to-slave injection is varied.

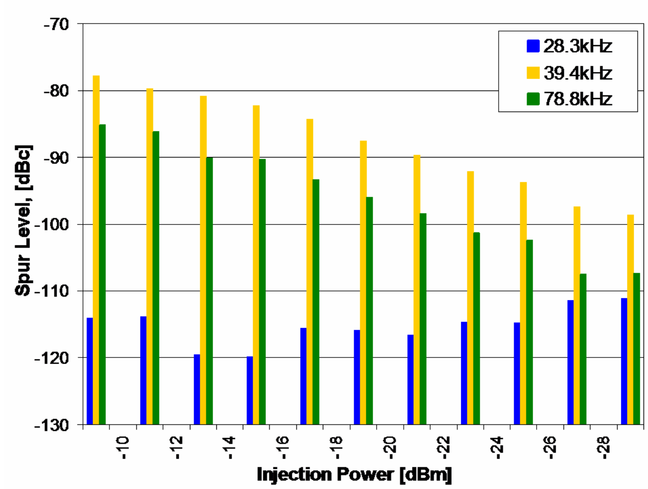

Figure 10. Graph showing the spurious levels as a function of master-to-slave injection.

III. AUTOMATIC CONTROL OF INJECTION-LOCKED DUAL OEO

A proposed automatic locking and monitoring scheme is shown in Fig. 11. This system utilizes a microprocessor to control the locking procedure as well as maintain the lock between the OEOs. The microprocessor can also control the bias of the modulators and photodiodes, as required. Electronic phase shifters in the OEO loops can be adjusted to change the operating frequencies of each loop. Adjustable attenuation can be used to control the strength of the injection lock. By maximizing the attenuation the OEOs can be isolated and independently adjusted, which may be required when the locking procedure is initially started.. The strength of the injection parameter will most likely be different while acquiring the lock, as compared to optimizing the noise and spur levels. Both the slave and master outputs are divided down to radio frequencies and compared to each other by a referenced digital counter. This allows one to determine whether the system is locked. The counter can also determine the frequency offset between the two OEOs if they are not locked. Knowledge of this offset and its sign will assist in achieving the initial injection lock.

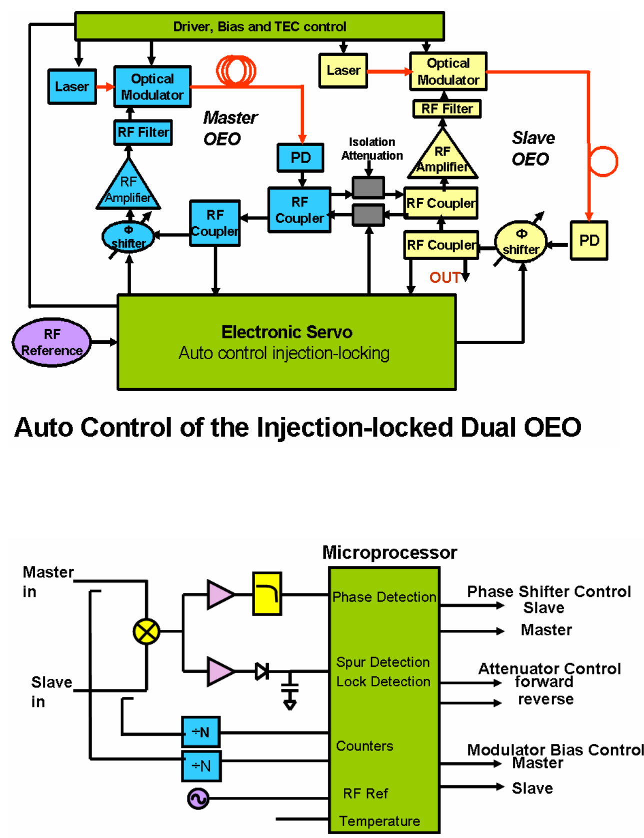

Figure 11. Proposed automatic control of the DIFO.

Once an injection lock has been achieved; the system must optimize the lock and be able to maintain it as the environment changes. By heterodyning the master and slave outputs with a mixer, further information about the lock can be acquired. Amplitude modulation (AM) detecting the heterodyned signal can provide information about the spurious content and be used to adjust the injection lock bandwidth. The phase offset between the master and slave oscillators can be determined by analyzing the dc component of the heterodyned signal. This information can be used to adjust the electrical phase shifter to maintain the injection lock as environmental and systematic effects cause the two OEO to drift apart.

IV. SUMMARY

We examined the parameter space of the injection-locked dual optoelectronic oscillator in order to find an optimal operating regime. We varied injection levels in both paths from master-to-slave as well as from slave-to-master OEO. The best compromise between overall noise performance and spur levels occurs somewhere between -10 dBm and -30 dBm of master-to-slave injection power. We also proposed an automatic locking and monitoring scheme that utilizes a microprocessor to control the locking procedure as well as maintain the lock between the OEOs.

REFERENCES

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

[2] X. S. Yao and L. Maleki, *"Converting light into spectrally pure microwave oscillation," Opt. Lett.*, vol. 21, pp. 483–485, Apr. 1996.

[3] S. Romisch, J. Kitching, E.S. Ferre-Pikal, L. Hollberg, and F.L.Walls, *"Performance Evaluation of an Optoelectronic Oscillator," IEEE T. Ultrason. Ferr.*, vol. 47, pp. 1159-1165, Sept. 2000.

[4] X. S. Yao and L. Maleki, *"Multi-loop optoelectronic oscillator," IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[5] X. S. Yao and L. Maleki, *"Dual microwave and optical oscillator," Opt. Lett.*, vol. 22, no.24, pp. 1867–1869, Dec. 1997.

[6] D. Eliyahu and L. Maleki, "Low Phase Noise and Spurious Level in Multiloop Opto-electronic Oscillators," *Proc. Joint 2003 IEEE Frequency Control Symposium and 17 European Frequency and Time Forum*, pp. 405-410, 2003.

[7] X. S. Yao and L. Maleki, *"Multi-loop optoelectronic oscillator," IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[8] W. Zhou and G. Blasche, *"Injection-Locked Dual Opto-Electronic Oscillator with Ultra-Low Phase Noise and Ultra-Low Spurious Level", IEEE Trans. on Microwave Theory and Techniques*, vol. 53, no 3, pp. 929-933, 2005.