Microwave Optoelectronic Oscillator with Optical Gain*

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***Abstract* – Optoelectronic oscillators (OEO) are unique compared to radio-frequency (RF) oscillators in that they do not fundamentally require a RF gain element in order to satisfy the amplitude threshold condition for oscillation. All of the energy required for oscillation can be obtained from the optical carrier. This, however, was not initially possible, due to the inefficiency and power limitations on the optical components used in the OEO. Recent improvements driven by the need for optical-RF links have improved modulator and detector technology. Electro-optic modulators (EOM) with ultra-low half-wave voltage (V_π), and high optical power capabilities, when coupled with high-power photodetectors, have achieved optical links with gain. With sufficient gain from the photonic components in the OEO, the RF loop amplifier becomes unnecessary. Eliminating this amplifier removes one of the major noise contributing elements of the oscillator. Here we present designs and phase noise results of several OEOs, operating at RF frequencies up to 10 GHz, constructed with only optical gain.**

I. INTRODUCTION

In the basic feedback oscillator there are two primary noise sources, the feedback gain element and the resonator element. For oscillators operating at microwave frequencies, resonator topologies can be chosen so that intrinsic short term resonator noise is negligible compared to noise from the feedback amplifier. The phase noise of the amplifier converts to frequency noise in the oscillator [1]. Reducing the flicker noise of the loop amplifier and increasing the quality factor (Q) of the resonator are two primary methods of increasing spectral purity. One approach to increasing the Q of resonators for the synthesis of low phase noise microwave oscillators is the photonic delay-line based OEO [2]. RF photonic links are those that modulate, transmit and demodulate an optical carrier signal, usually through optical fiber, with a radio-frequency (RF) signal. The RF photonic link serves primarily as a long distance, low loss carrier of RF signals. In 2000, the Defense Advanced Research Project Agency (DARPA) launched the Radio Frequency Lightwave Integrated Circuits (RFLICs) program to develop optical methods for the transmission of RF signals that were wideband and very low loss.

The successor DARPA program ULTRA T/R successfully achieved RF gain at 10 GHz (x-band) through a photonic link [3]. Yao and Maleki had realized in their initial publication [2] that if the optical link gain was greater than the loop loss in the OEO, the RF amplifier became superfluous [4].

The basic OEO configuration, shown in Fig. 1, has several major sources that contribute to the overall noise of the OEO. The laser carrier itself has both amplitude (intensity) and phase noise, which can appear in the photonic link and thus can also appear at the output of the OEO [3, 4]. Laser amplitude, or relative intensity noise (RIN), can become OEO amplitude noise if loop components are not operating in saturation. Laser phase noise can convert to RIN after traveling through a dispersive fiber delay line [5, 6]. The photodiode contributes flicker noise as well as shot noise [7]. The RF amplifier contributes flicker and thermal noise. At higher optical powers the laser interacts with the fiber and optical components, producing noise from several different scattering and interference effects [8, 9].

NIST is investigating RF-photonic links with gain, with the goal of eliminating the phase noise from the RF loop amplifier of an OEO. This paper cites preliminary experimental results obtained with this approach.

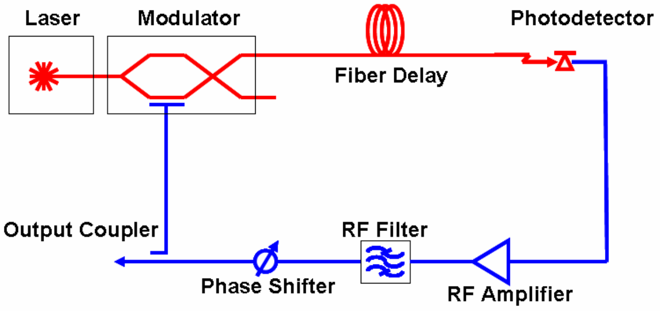

Figure 1. Basic OEO configuration.

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II. EXPERIMENTAL SETUP

An optoelectronic oscillator without the RF loop amplifier is shown schematically in Fig. 2. If the gain of the photonic fiber link is greater than the loss in the rest of the feedback loop, consisting of the filter, phase shifter and output coupler, oscillation can occur. The RF gain of a photonic fiber link can be expressed as [3]

$$g_l = s_m^2 r_d^2 , \tag{1}$$

where s_m is the slope efficiency of the modulator and r_d is the responsivity of the photodiode. The slope efficiency of a Mach-Zender modulator biased at quadrature is given by

$$s_m = \frac{\pi P_I T_{ff} R_s}{2V_\pi} , \tag{2}$$

where P_I is the optical power incident on the modulator, T_{ff} is the fiber-to-fiber transmission coefficient, R_s is the impedance of the source, and V_π is the half wave voltage of the modulator. The primary means for increasing link gain is increasing P_I and T_{ff}, as well as decreasing V_π. Increasing the P_I T_{ff} product has the additional requirement of raising the power capacity of the photodetector, even if r_d does not increase.

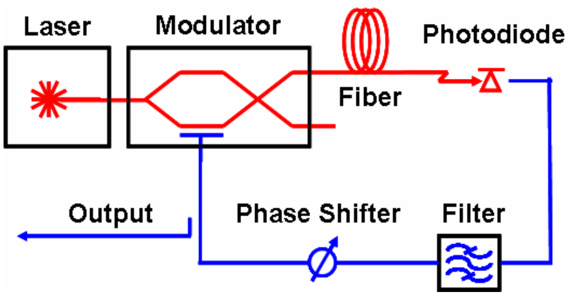

Figure 2. Block diagram OEO without RF amplifier.

In order to obtain gain through the fiber RF link, a 1 W fiber laser with a 3 kHz linewidth was chosen as the optical source. The laser is configured as a master oscillator power amplifier (MOPA) consisting of a distributed Bragg reflector (DBR) erbium fiber laser and an erbium-doped fiber amplifier (EDFA). An operating wavelength of 1550 nm was needed to exploit the minimum loss in single mode fiber (SMF). An electro-optical modulator (EOM) was chosen to generate the RF sub carrier on the optical signal. A lithium niobate Mach-Zender interferometer with a low V_π of 1.9 V at 10 GHz and optical insertion loss of 9 dB was selected.

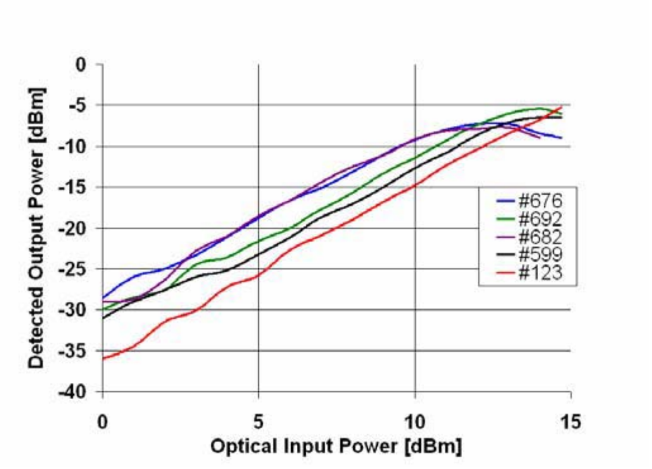

Figure 3. 10 GHz photodiode response versus optical power

A photodiode with high power capacity is necessary to handle the large optical power required to achieve RF gain. A selection of InGaAs, p-type, intrinsic, n-type (PIN) photodiodes was tested at 10 GHz versus optical power, and the results are shown in Fig. 3. The four upper curves are all from a sample of similar photodiodes, while the bottom curve is from a large area photodiode with a gradient index (GRIN) lens used to evenly spread out the incident light. The four similar photodiodes varied with their saturated power by as much as 2.5 dB, while the dc conversion efficiencies varied from 0.7 to 0.8 A/W. The GRIN lens photodiode had a dc conversion efficiency of 0.6 A/W, and its efficiency at 10 GHz was as much as 10 dB lower, due to the higher capacitance of its large active area. All photodiodes were of the internally unterminated variety; open stub tuning was utilized to achieve maximum power transfer.

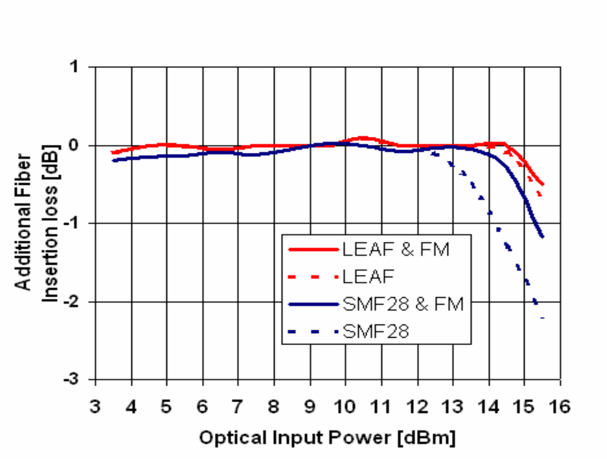

Figure 4. Stimulated Brillouin scattering thresholds in two different 6 km fibers, with and without laser frequency modulation (FM).

Optical transmission through fiber is limited at high powers by stimulated Brillouin scattering (SBS) [9]. The SBS threshold in two types of single mode fiber is shown in Fig. 4. The effect of SBS is exacerbated by narrow optical line-widths, so frequency modulation or any broadening of the optical spectrum allows for the transmission of more optical power. A 6 km fiber is limited to maximum power transmission of about 15 dBm, which also corresponds roughly to the saturation point of the selected photodiodes.

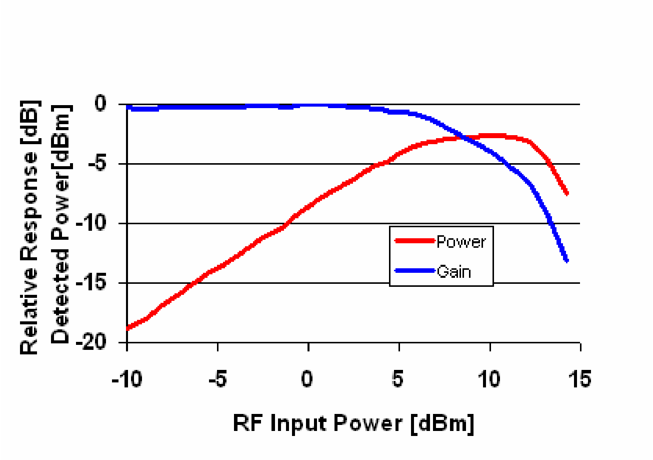

Figure 5. Electro-optic modulator saturation curves.

The modulator showed a 1dB RF compression point at 6 dBm input RF power, as plotted in Fig. 5. To avoid saturation in the photodiode, this test was performed at a lower optical power.. Using performance data from the individual components and Eq. (1-2), the theoretical link gains for 6 km of optical fiber were calculated to be 3.7 dB and 0.2 dB for 1 and 10 GHz, respectively.

Oscillation was achieved at operation frequencies of 1.25 GHz, 2.5 and 5 GHz, with the setup shown in Fig. 2, using a 6 km optical fiber. To achieve sufficient link gain for oscillation at 10 GHz, the experimental setup was modified to use two fibers and incorporated a balanced photodetection scheme as shown in Fig. 6. A shorter fiber length of 1 km was also required.

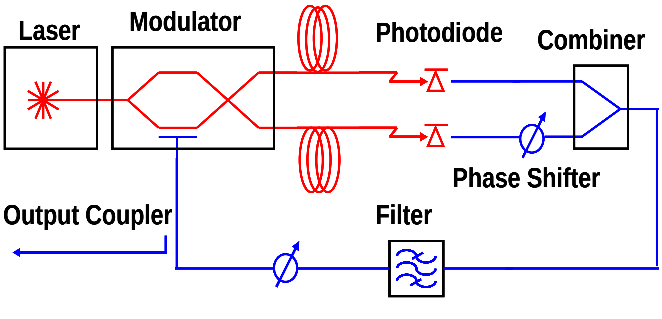

Figure 6. Balanced two fiber setup used to achieve oscillation at 10 GHz. 1 km fiber delays were used.

III. LASER RIN AND WIDEBAND RIN SUPPRESSION SERVO

The phase noise spectrum of the OEO showed excess noise that looked similar to the RIN of the laser. To study this correlation, laser RIN and photonic link noise were measured. The setup of the link phase noise measurement is shown in Fig. 7. A residual measurement was not performed; instead a simple heterodyne measurement between two low noise 10 GHz references, using a digital measurement system was utilized. The link phase noise, shown in Fig. 8, indicates excess noise at 8 kHz, which correlates well with the laser RIN shown as the upper curve in Fig. 9.

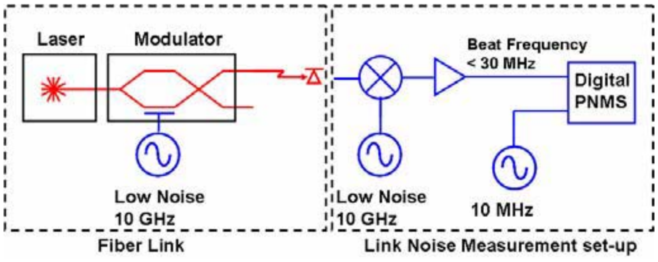

Figure 7. Experimental setup for fiber link noise measurement. PMNS: phase noise measurement system.

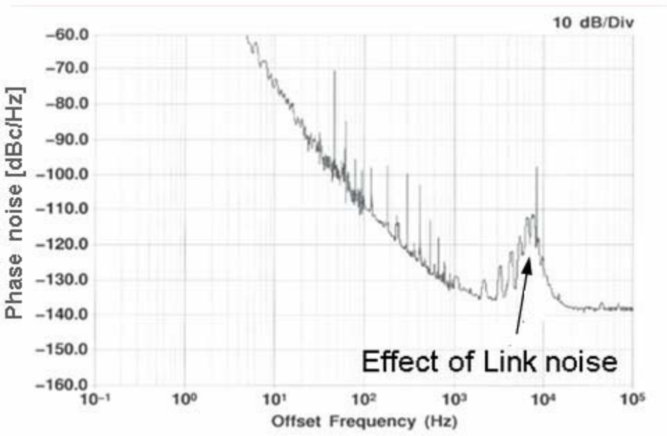

Figure 8. Phase noise measurement between two low noise 10 GHz oscillators, one being passed through the photonic link. The link noise is dominant above 1 kHz, while source noise dominates at frequencies below.

For maximum AM modulation efficiency the Mach-Zender modulator needs to be biased so that the optical powers in its two outputs are equal. A servo can be implemented by detecting the power in both outputs and adjusting the modulator bias to equalize them. The bias servo can also be made to function as a RIN suppression servo, as shown in Fig. 10. A small amount of light is coupled from each arm of the balanced modulator and detected in transimpedance-amplified photodiodes. The reference signal is heavily low pass filtered so that a low noise dc reference voltage is created. This reference voltage is then subtracted from the signal channel and integrated to provide the modulator bias voltage. An adjustable offset voltage is summed prior to the integrator to allow for small adjustments of the bias point. At very low offset frequencies, the signal arm tracks the reference arm power, providing the proper AM modulation bias; however, outside the bandwidth of the low pass filter the circuit acts to suppress RIN. The bandwidth of the integrator is set as high as possible to allow wideband RIN suppression. The RIN of the laser after suppression is shown as the bottom curve in Fig. 9. A bandwidth of about 10 MHz, as well as 50 dB of RIN suppression at 8 kHz, was achieved. The improved link phase noise with the RIN suppression servo active is shown in Fig. 11.

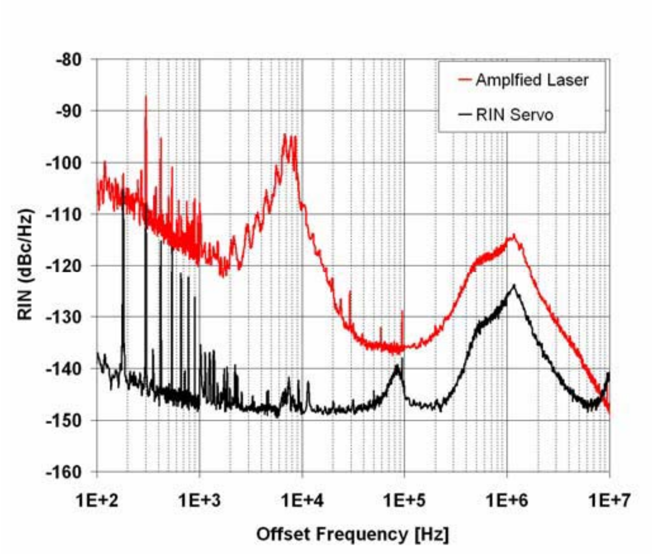

Figure 9. Relative intensity noise of 1550 nm laser with and without RIN suppression servo. Note that the structure around 8 kHz is identical to that of the link noise in Fig. 8.

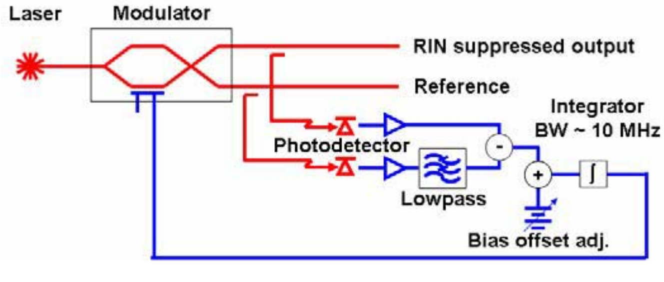

Figure 10. Dual modulator bias and wideband RIN suppression servo. As well as keeping the modulator bias at quadrature, this servo also reduces the RIN of one output, at the expense of increasing the RIN of the other.

IV. EXPERIMENT AND RESULTS

The phase noise of the OEO, operating at 1.25 GHz with a fiber length of 6 km, was studied in detail. This frequency was investigated because excess loop gain was available that allowed more control of loop saturation. The phase noise measurement configuration is shown in Fig. 12. The output of a low noise 10 GHz oscillator, divided by eight, was used to down-convert the OEO output to a beat frequency that can be measured with a digital phase noise system. This method allows for very accurate measurements close to the carrier but has a moderately high noise floor above a few kilohertz offset. The OEO phase noise under several operating conditions is shown in Fig. 13. The OEO performed about 20 to 30 dB above its theoretically expected level when the laser was operated without frequency modulation. The addition of laser frequency modulation at 6 kHz improved the performance by about 15 dB; further activation of the RIN suppression achieved theoretically expected performance at an offset of 1 kHz. Deviations from the expected values below 1 kHz are attributed to vibration and temperature fluctuations on the fiber spool. The vast improvement provided by frequency modulation of the laser signal can be attributed to suppression of interferometic noise [8], stimulated Brillouin scattering [9], or further reduction of RIN [10] .

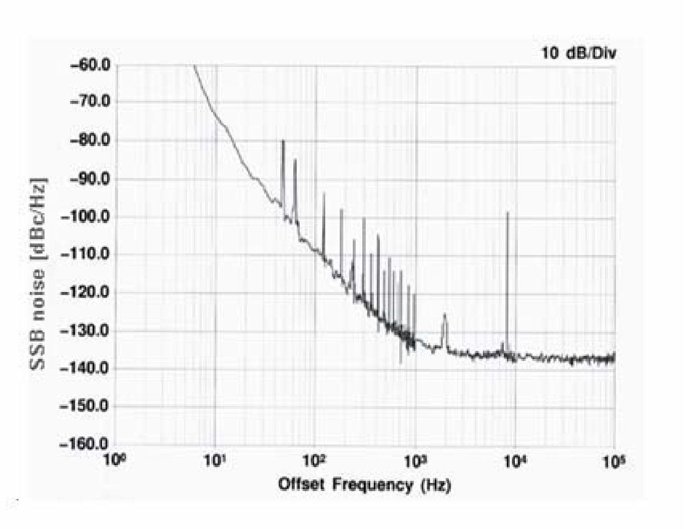

Figure 11. Improvement in link phase noise after using the RIN suppression servo shown in Fig. 10.

The noise level achieved is the expected noise if the primary phase noise source is flicker in the photodiode, as reported by Rubiola, et al., in [7] as L(1 Hz) = -123 dBc/Hz. This is a very encouraging result, since photodiode flicker levels may be lower than that in amplifiers for certain higher frequency bands. Similar tests were attempted with the OEO oscillating at 10 GHz. Since there was insufficient gain to achieve oscillation at 10 GHz with a 6 km fiber, an OEO was constructed with an amplifier with a low flicker level of L(1 Hz) = -133 dBc/Hz. Even with this addition, the photodiode's flicker phase modulation should still be the dominant noise source at offset frequencies below a few kilohertz. The phase noise results of this 10 GHz experiment are shown in Fig. 14.

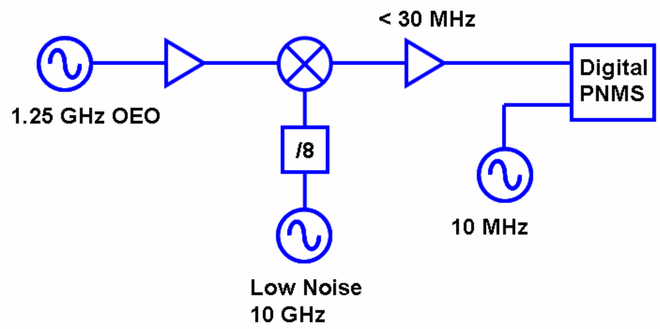

Figure 12. Setup for OEO phase noise measurement at 1.25 GHz.

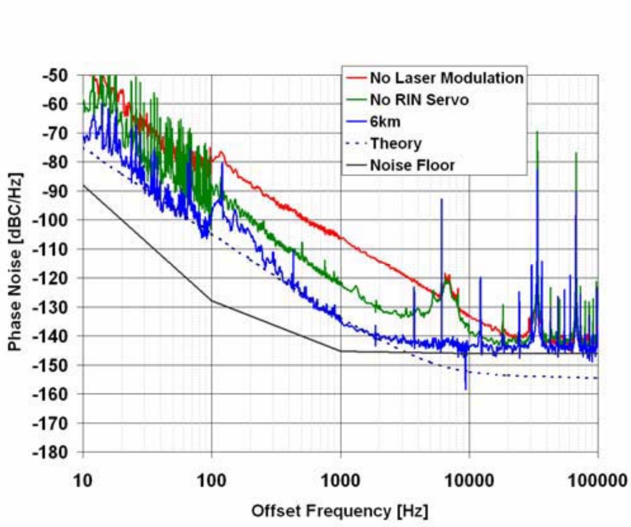

Figure 13. Phase noise for 1.25 GHz, 6 km fiber, amplifier-less OEO.

The results at 10 GHz did not achieve the theoretical values as they did at 1.25 GHz. The excess noise has a profile similar to that of the laser RIN, even though the RIN has been greatly suppressed. This could be attributed to RIN-to-phase noise conversion occurring in the RIN suppression servo. Due to less loop gain, the OEO was also operating with less loop saturation than the 1.25 GHz circuit, thus decreasing the loop's ability to suppress RIN.

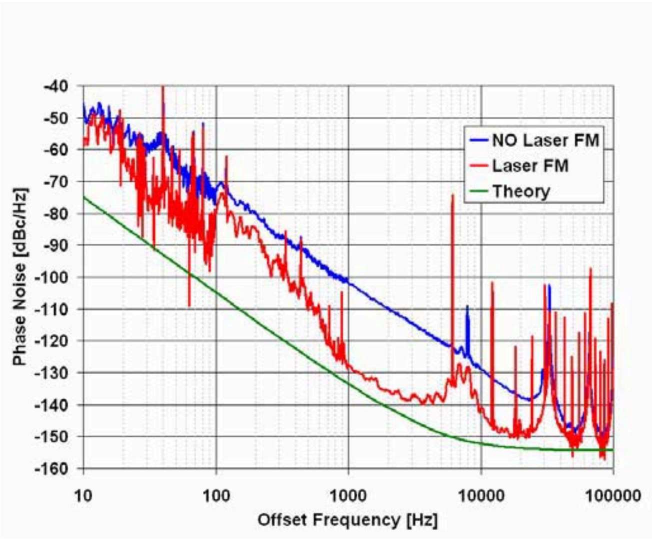

Figure 14. Phase noise for 10 GHz, 6 km fiber, OEO.

V. CONCLUSIONS

The experimental results achieved while operating the OEO without a loop amplifier at 1.25 GHz proved to be very encouraging. We were able to achieve photodiode flicker-limited performance close to the carrier. Since phase noise in an OEO is not proportional to oscillation frequency, operation at higher frequencies may have the potential for producing sources with very low phase noise, if the contribution laser RIN is reduced. Modulators and detectors now exist that operate above 50 GHz. Improvements in photonic link gain at these frequencies may lead to OEOs that rival non-photonic oscillators by the elimination of the sustaining amplifier's flicker noise. Further areas of improvement that we hope to investigate in the near future are

- Careful analysis of modulator operating point
- Additional attention to laser noise and RIN mitigation
- Alternate laser sources with higher frequency modulation capabilities
- Investigation of balanced photo detection for common mode laser noise rejection [11]
- Optimization of photodiode operating point
- Oscillation at higher operating frequencies.

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