10 GHz Dual loop opto-electronic oscillator without RF-amplifiers

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ABSTRACT

We report the first demonstration of a 10 GHz dual-fiber-loop Opto-Electronic Oscillator (OEO) without RF-amplifiers. Using a recently developed highly efficient RF-Photonic link with RF-to-RF gain facilitated by a high power laser, highly efficient optical modulator and high power phototectectors, we have built an amplifier-less OEO that eliminates the phase noise produced by the electronic amplifier. The dual-loop approach can provide additional gain and reduce unwanted multi-mode spurs. However, we have observed RF phase noise produced by the high power laser include relative intensity noise (RIN) and noise related to the laser's electronic control system. In addition, stimulated Brillouin scattering limits the fiber loop's length to ~2km at the 40mW laser power needed to provide the RF gain which limits the system's quality factor, Q. We have investigated several different methods for solving these problems. One promising technique is the use of a multi-longitudinal-mode laser to carry the RF signal, maintaining the total optical power but reducing the optical power of each mode to eliminate the Brillouin scattering in a longer fiber thereby reducing the phase noise of the RF signal produced by the OEO. This work shows that improvement in photonic components increases the potential for more RF system applications such as an OEO's with higher performance and new capabilities.

Keywords: Opto-Electronic Oscillator, RF-Photonics, Microwave Photonics, Phase Noise,

1. INTRODUCTION

OEO's have been studied extensively over the past ten years.[1-10] A typical single loop OEO uses a very long optical fiber as a delay line in a high Q feedback loop completed by both optical and electronic paths. At the end of the fiber, a photodetector converts the modulated light signal back into microwave signals which are amplified electronically to generate enough gain to sustain the oscillations. The microwave signals are filtered by a microwave filter. The selected microwave signal is used to modulate a laser via an electro-optic modulator, closing the feedback loop. The OEO's long fiber cavity has an optical Q as high as 10^{10}. Therefore an OEO has the potential to achieve ultra low phase noise near the carrier frequency. Since the RF- microwave filter's Q is many order of magnitude smaller than the optical Q, many additional oscillation modes can not be eliminated by the filter and become unwanted "spurs". To reduce those spurs, later OEO studies always use multi-loop/cavity configuration approachs. [3-10]

Despite the predicted high optical Q, the experimental results always show higher phase noise levels than indicated by the estimated Q[3]. That is because all the components in the OEO loop may contribute in phase noise generation or signal loss which makes the "loaded" Q in the in system much smaller than the optical Q provided by the long fiber. Earlier studies suggest the RF-amplifier in the loop maybe the major contributor to the phase noise while noise generated by the laser, environmental fluctuations in the long fiber, photodetector, etc are to a lesser degree phase noise contributors. Therefore eliminating the RF-amplifiers in the OEO loop is desirable.

Recent advances in RF-Photonic component development, especially low V-pi optical modulators and high power photodetectors allow RF-photonic links to have a RF-to-RF link gain when converting RF to optical

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signal and then coverting back to an RF-signal. This gain is provided in optical domain instead by an electronic amplifier. This makes possible for us to build an OEO without any RF-amplifiers in the loop.

2. EXPERIMENTAL

2.1. Amplifier-less Dual-loop OEO Set-up

Figure 1 schematically shows a block diagram of our experimental set up. A dual-loop OEO is assembled by a commercial fiber laser made by NP-photonics with up to 1W single mode laser output power at 1552nm of wavelength. About 700mW output of the laser is sent to a custom made (by EOspace, Inc.) low-Vpi LiNbO3 Mach-Zenhder optical modulator via polarization maintaining fiber. The Vpi is below 2V at 10GHz RF modulation. The modulator has two optical outputs that are connected to two single mode optical fibers, ~1.4Km and ~2.3Km long, sending the laser light to two high power unterminated photodetectors (manufactured by Discovery Semiconductor Inc.), respectively. Small amounts of the laser light are tapped by fiber couplers and sent to a ditherless modulator bias controller and to an optical output port for monitoring or phase noise measurement. After the taps and insertion loss from the modulator, about 30-40 mW of laser light arrive at each of the photodetectors' input. The dectectors can produce up total 40mA of current (DC+AC) with a responsivity ~0.65A/W. To reduce the RF signal loss, a custom made impedance matching circuit is used with the photodetector.

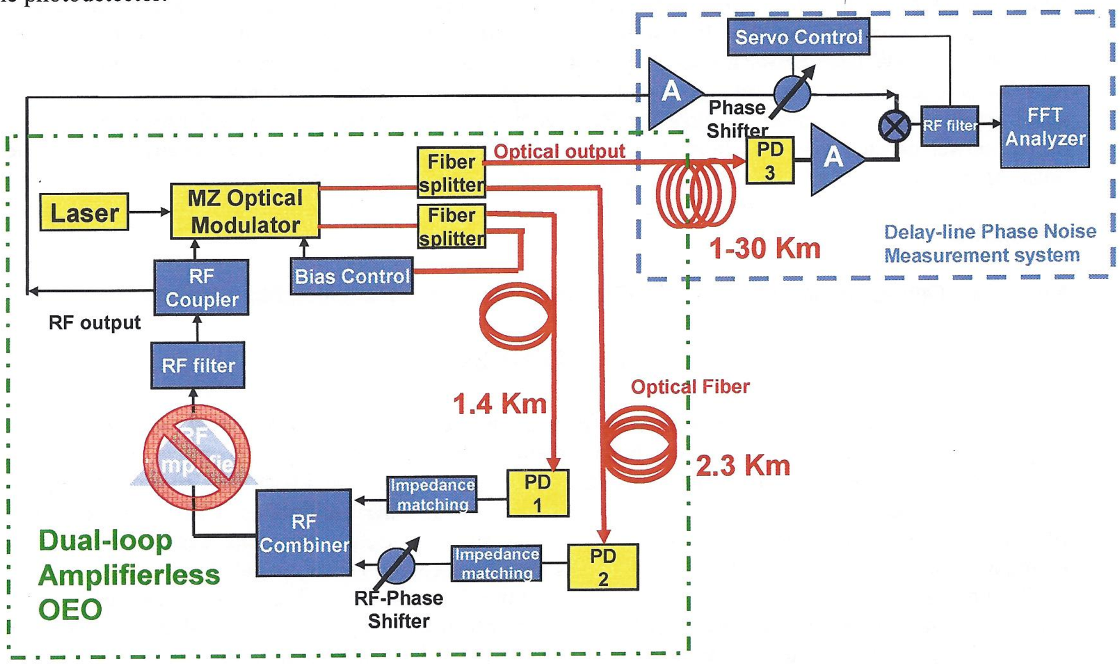

Fig.1. Schematic illustration of the Amplifierless dual-loop OEO configuration and the delay-line measurement set-up.

We have performed a RF-photonic link measurement by modulating the optical modulator with an external RF signal without completing the loop. About 1 to 2 dB RF–to-RF signal gains were observed at each of the photodetectors' outputs. Then, the two RF- signals from the photodetectors are combined by a phase shifter and 2x1 RF combiner, due to the insertion loss of these RF components, the combined RF signal does not provide much additional gain. However, the goal to combine them was to complete a dual loop OEO configuration to reduce the spurious oscillation level.

To close the loop of the dual loop OEO, the combined RF output is connected to a low insertion loss 10GHz RF-filter, the output of the filter is then connected directly to the optical modulator by passing the normally present RF-amplifier. The "no" sign on the RF-amplifier indicates where a 40 to 50 dB gain RF amplifier has been removed from the OEO. A -30dB directional RF coupler is used to get the RF output from the loop.

2.2. Experimental Results:

By tuning to RF-phase shifter to select a common mode from each OEO loops, single mode oscillation is observed around 10GHz. An Advantest R3271A spectrum analyzer is used to record the RF spectrum with a frequency span for 200 kHz and resolution bandwidth of 10Hz, as shown in Fig.2. Although, the spectrum analyzer can provide a ~90 to 100dB signal to noise level by adding a pre-amplifier at the input of the spectrum analyzer, it is not enough for the measurement of the phase noise of the OEO.

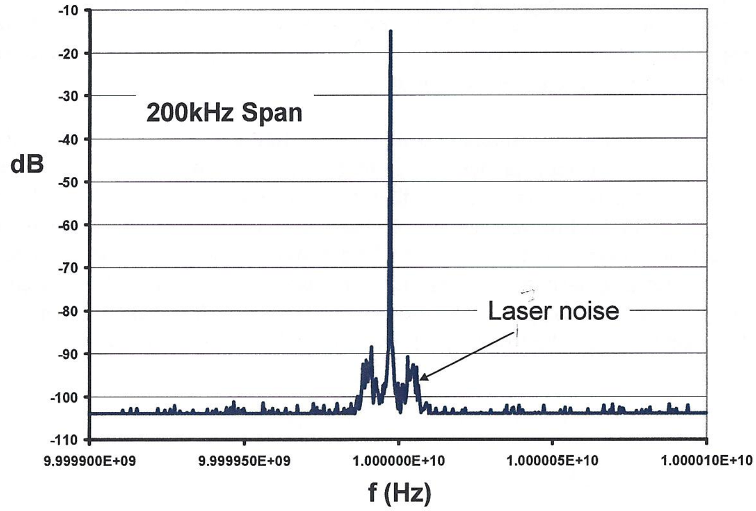

Fig. 2. RF oscillation signal spectrum of the OEO from a spectrum analyzer.

2.3. Phase Noise Measurement:

To measure the phase noise, we used an optical fiber delay line approach to de-correlate the phase noise from the RF carrier.[11] As shown in Fig. 1., the optical output of the dual loop OEO is connected to a long fiber delay line of length from 1 km to 30 km depending on the bandwidth of the noise spectrum to be measured and the fiber's transfer function singularities. A photodetector is used to covert the modulated optical signal to RF signal. This delayed RF signal is then, amplified by an RF amplifier, and sent through an electronic RF-phase shifter controlled by an electronic servo to compensate the slow random phase walk caused by temperature drift in the long fiber. It is then sent to one of the inputs of a 10GHz RF mixer to mix with the undelayed RF signal that is coming from the RF output of the OEO and amplified by an RF amplifier. The two RF inputs of the mixer are 90 degrees out of phase to cancel the RF carrier signal at the output which is connected to a low pass filter to let the low frequency phase noise go to a FFT spectrum analyzer (HP89410A) for phase noise measurement. Figure 3. shows the phase noise measurement data.

To calibrate the phase noise spectrum, two steps are taken: 1) Experimentally injecting a reference RF tone with a known intensity relative to the RF carrier from the OEO, then using the baseband side tone after the mixer as a reference; 2) Correcting the power spectral density with fiber delay line's transfer function. Salik et al show in their review of delay line discriminator theory [11] that the single side band (SSB) phase noise can be expressed with the following equation:

$$L(f) = \frac{V_{out}^2(f)}{2K_\varphi^2 \left| H_\varphi(jf) \right|^2}$$

Where, $V_{out}(f)$ is the mixer output voltage, K_φ is the mixer voltage gain coefficient, and H_φ is the fiber delay transfer function given by the following equation:

$$\left|H_\varphi(jf)\right|^2 = 4\sin^2(\pi f\tau)$$

The mixer voltage gain coefficient relates the mixer output voltage to the phase difference between each of the mixer inputs. We determined K_φ empirically by using a reference tone of known intensity and frequency. Injecting both the reference and our signal into the mixer, we measure the resulting beat tone power and compare it with the known reference power to obtain K_φ.

The transfer function is periodic in frequency because the relatively fixed delay induced by the fiber loop (we ignore loop dispersion) induces a periodic frequency dependent phase shift. It is this phase shift – relative to the non-delayed arm – that determines the "loop gain" seen by each frequency. Noise at frequencies where the delay line induces a $\pi/2$ phase shift will see the highest gain whereas frequencies where the phase shift is an integer multiple of π will be completely lost. These frequencies with π phase shift are what we refer to as fiber singularities. It is essential that we select our delay line for each frequency range so as to avoid said singularities. Having selected the proper delay line for each frequency range, we divide by the fiber transfer function to obtain the true phase noise power density distribution.

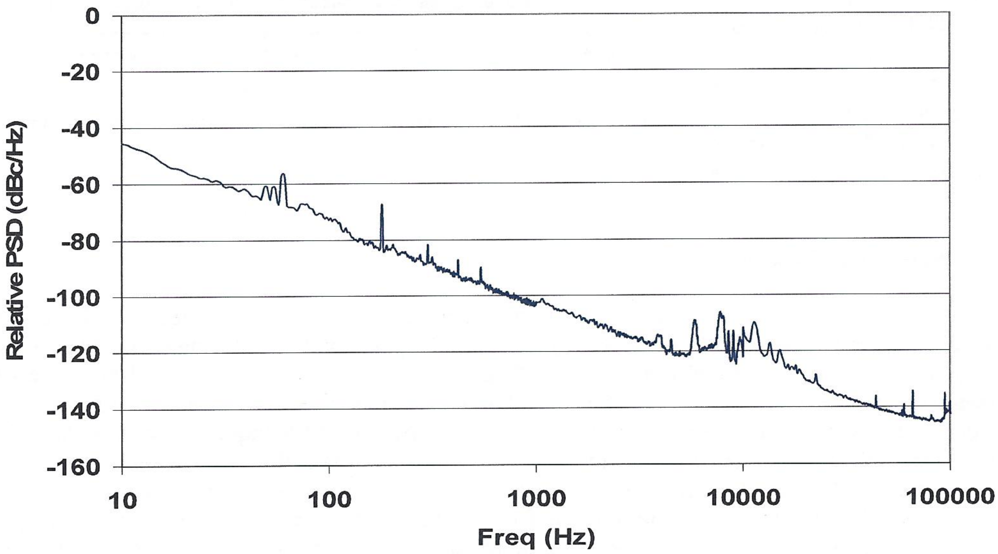

Fig. 3. Phase noise data of the amplifierless dual-loop OEO from the delay-line phase noise measurement.

However, the measurement systems noise floor is limited by the RF-amplifiers used to drive the mixer. A typical commercial 10GHz RF amplifier may have phase noise level near -110dBc/Hz around our measurement range, therefore the OEO's phase noise may be lower than the measurement noise floor after few kHz offset frequency. Indeed, we measured the noise floor, it shows a noise level around -110dBc/Hz around 1 kHz which is close to the phase noise of the OEO. We intend to replace the RF-amplifier in the measurement system with a very low phase noise (in the frequency range of interest) amplifier to lower the phase noise floor.

3. DISCUSSION

We have demonstrated that the dual loop OEO oscillates at 10GHz without using any RF amplifier in the OEO loops. However, the preliminary measurement data has not shown improved phase noise performance compared with a typical OEO with RF-amplifiers. This is caused by several effects: First, the lower offset frequency phase noise depends on the Q of the OEO which is controlled by the fiber length. Due to stimulated Brillouin scattering induced by the single mode laser we are using and the high laser power level requirement, the fiber length is limited to 1 to 2 km thus limiting the Q of the OEO system; Second, the high offset frequency (>1 KHz) data may be dominated by the delay line phase noise measurement system's noise floor. This can be easily corrected by replacing the regular RF-amplifiers with low-phase noise amplifiers or doing a cross-correlation phase noise measurement, thus reducing the measurement system noise floor. However, there are real noise peaks that were observed in the noise spectrum even with the spectrum analyzer data as shown in fig. 2. There are several noise peaks in the 7 kHz to 10 kHz range. After an investigation we find out that this noise is caused by an electronic circuit that regulates the laser output power. We have also observed the laser RIN noise in the RF phase noise spectrum. The RIN of the fiber laser is about -150dBc/Hz peaking at -110dBc/Hz around 1MHz from the laser line. Since the RF signal is amplitude modulated on top of the CW laser and the modulation depth is less than 100% the RIN is translated into the RF noise; Third, the flicker noise from the photodetector may become more important since these photodetector produce ~ 40mA current, much more than used in a ordinary OEO with an RF amplifier.

We are proposing several solutions to reduce the noise in the amplifierless OEO. 1). frequency modulate the CW laser to reduce the threshold for the stimulate Brillouin scattering. We have seen better than 10dB improvement in the low offset frequency noise,[10] but this modulation may add additional spurs elsewhere. 2). Therefore, we are trying a new approach by using a multi-longitudinal-mode laser to carry the RF signal, maintaining the total optical power but reducing the optical power of each mode to eliminate the Brillouin scattering in longer fiber. 3) Using a feedback servo electronic to compensate the RIN noise. We were able to reduce the RIN in the RF spectrum, but since we have to use some of the optical signal for that servo, there is not enough gain to make the OEO oscillate with RF amplification.[10] 4). Therefore, the next step is to split the laser input to two photodetectors and using balanced detector approach to cancel the RIN. 4) Lower the Vpi so to lower the optical power requirement for the RF gain which will require optical modulator improvement.

4. CONCLUSION

We have demonstrated a 10 GHz amplifierless dual-fiber-loop Opto-Electronic Oscillator, using a recently developed highly efficient RF-Photonic link with RF-to-RF gain. However, our experimental results suggested that to farther reduce the RF phase noise of the OEO, we need to reduce the noise produced by the high power laser include relative intensity noise (RIN) and noise related to the laser's electronic control system and photodetectors. In addition, we need to reduce the stimulated Brillouin scattering to increase the length of the fiber therefore increase the system's quality factor, Q. This work shows that improvement in photonic components increases the potential for more RF system applications such as an OEO's with higher performance and new capabilities.

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