Loop-length Dependent Sources of Phase Noise in Optoelectronic Oscillators

Eric J. Adles, Andrew Docherty,
Curtis Menyuk, and Gary Carter
Dept. of Electrical and
Computer Engineering
Univ. of Maryland Baltimore County
Baltimore, MD 21250
Email: ejadles@gmail.com

Olukayode Okusaga
and Weimin Zhou
U.S. Army Research Laboratory
Adelphi, MD 20783

Etgar Levy, Asaf David,
and Moshe Horowitz
Technion – Israel Institute of Technology
Haifa, Israel

Abstract— **Optoelectronic oscillators are a promising source of spectrally pure, easily tunable microwave signals. These oscillators use a low-loss fiber optic delay line as a very high Q resonant cavity. However, length-dependent sources of phase noise prevent the full Q of the resonant cavity from being realized. Here we show evidence that this length-dependent phase noise is in part dependent upon the optical power and laser noise. This dependence is consistent with the conversion of laser noise to phase noise via the Kerr effect.**

I. INTRODUCTION

Optoelectronic oscillators (OEOs) use an optical delay line in a feedback loop to form a high-Q cavity with ultra-low phase noise [1], [2]. Because OEOs are inexpensive, easily tunable, and produce signals in the optical or RF domain they are under investigation for a wide range of applications. The length of the fiber delay line leads to a tradeoff between the Q and mode spacing of the OEO: longer delay lines increase the Q of the resonant cavity but decrease the mode spacing. This decrease in mode spacing leads to spurious oscillating modes (spurs) within the bandwidth of the OEO's filter. In other work we show that a dual-injection-locked OEO configuration can result in a 60 dB reduction in spurs [3], [4]. To find the optimal configuration that results in ultra-low phase noise and low spurious modes we have begun a systematic study of phase noise sources and techniques for mitigating these sources. In previous work we have shown that a length dependent flicker-noise is present [5], [6]. For small offset frequencies from the carrier this length-dependent flicker-noise results in a deviation in the phase noise dependence on loop-length from the original theoretical model developed by Yao and Maleki [1], [2].

To further reduce the phase noise and find the optimum configuration we have begun a systematic study of phase noise sources. These sources can be broadly categorized as length-independent and length-dependent. Examples of length-independent sources include the RF amplifier and laser driver. Length-dependent phase noise is of particular interest because this phase noise counters the nominally higher Q achieved by using longer delay lines. In this work we focus on identifying sources of optically induced length-dependent phase noise, including Kerr nonlinearity, chromatic dispersion and stimulated Brillouin scattering. We show evidence that is consistent with the hypothesis that the source of the length-dependent phase noise is the conversion of laser noise into phase noise via the Kerr effect. Because phase noise measurements only measure the dominant source of phase noise, these results do not exclude other length-dependent sources of phase noise, such as vibration and thermal effects.

Additionally, we will show that for short loops, the phase noise at low-offset frequencies is dominated by electrical noise in the RF section of the OEO. For long fiber lengths the phase noise is dominated by optically induced phase noise.

II. METHODS

We used a single-loop OEO configuration consisting of an 80 mW DFB laser with a wavelength of 1550 nm, a Mach-Zehnder electro-optic amplitude modulator, photodetector, three low phase noise microwave amplifiers that provide 60 dB of gain and an RF bandpass filter with a 10 GHz center frequency and an 8 MHz bandwidth. The large amount of RF gain was necessary so that we could investigate a broad range of optical powers. To minimize intrinsic sources of 60 Hz and harmonics our laser drivers and photodetectors are powered by batteries. To investigate the length dependence of the phase noise, we used fiber delay lines of length 40 m, 500 m and 6 km. To investigate the optical power dependence and the laser noise dependence of the phase noise, we varied the optical power into the fiber delay line using two different approaches. In the first approach we operated the laser at the full rated power of 80 mW, and adjusted the optical power into the fiber with a variable optical attenuator, placed between the modulator and the fiber delay line. In the second approach, we adjusted the drive current of the laser to vary the optical power into the fiber delay line. Fig. 1 shows that the laser noise increases with decreasing drive current. Thus the first approach holds constant the signal-to-noise ratio (SNR) of the laser, while the second approach varies the SNR of the laser. The maximum optical power that we could inject into the fiber delay line was 12 dBm. This power level was determined by the combined losses of the amplitude modulator, the optical attenuator and the associated connectors. We measured the

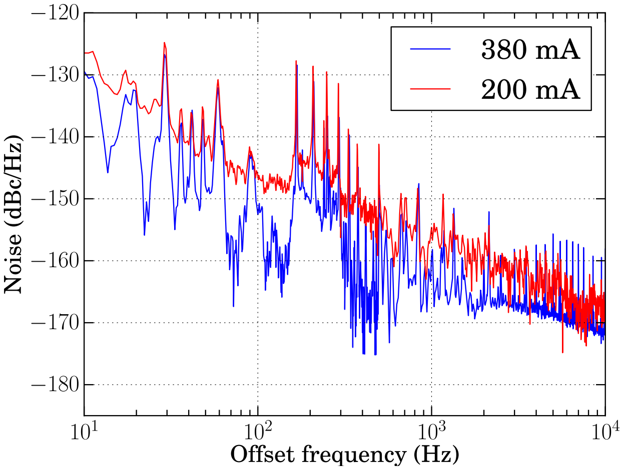

Fig. 1. Laser noise with drive current of 380 mA (blue) and 200 mA (red). The noise of the laser increases with decreasing drive current.

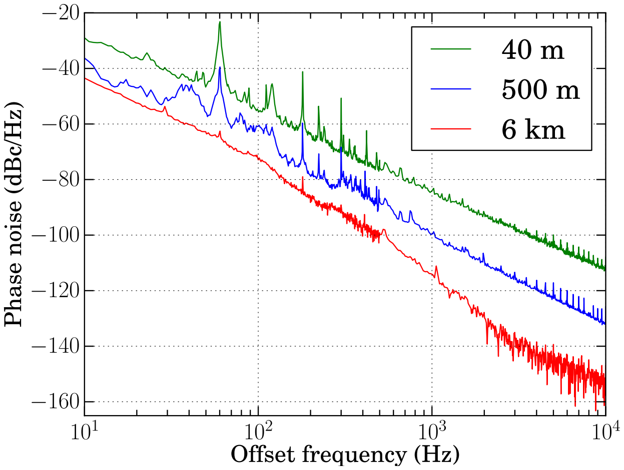

Fig. 2. Phase noise of a 40 m (green), a 500 m (blue) and a 6 km (red) OEO with 12 dBm of optical power into the fiber delay set by adjusting the laser drive current.

phase noise of the OEO with a dual-photonic-delay cross-correlation system[7].

We investigated two other potential optical sources of length-dependent phase noise. One effect is the conversion of frequency noise into phase noise via chromatic dispersion. The other is stimulated Brillouin scattering. To investigate the effect of chromatic dispersion we compared the phase noise of a 6 km OEO with a single-mode fiber (SMF) delay line with a 6 km OEO with a dispersion-shifted fiber (DSF) delay line.

To investigate the possible presence of stimulated Brillouin scattering (SBS) we measured the back-reflected optical power in a 6 km OEO for optical powers fro –2 to 12 dBm. Because the loss from the optical modulator limits the maximum optical power we can inject into the fiber delay line, we also measured the back-reflected optical power an 80 mW laser that was connected directly to a 6 km fiber spool.

III. RESULTS AND DISCUSSION

We focus our discussion on the phase noise for carrier offset frequencies of 10 Hz to 1 kHz. This range of frequencies is within the Leeson bandwidth and is therefore dependent upon the Q of the cavity. For offset frequencies greater than 10 kHz, the phase noise is dominated by the ratio of the signal from the photodetector to the additive noise of the RF amplifiers. This dependence will be discussed further elsewhere. However we note here that to achieve high signal levels from the photodetector, high optical powers must be injected into the fiber delay.

We first consider the length dependence of the phase noise. Fig. 2 shows the phase noise of a 40 m, a 500 m and a 6 km OEO where the optical power into the delay line was set to 12 dBm by varying the laser driver current. The absence of phase noise due to 60 Hz and harmonics in the 6 km data indicate that as the fiber delay length increases there is a transition between the dominant sources of phase noise. For the 40 m OEO the close-in phase noise is dominated by 60 Hz and harmonics, which in our configuration arise primarily from the RF amplifiers. Because the 60 Hz phase noise is additive, the relative contribution from 60 Hz to the phase noise of the OEO above the level set by the Q will remain the same. The phase noise of a 40 m OEO at 60 Hz offset is approximately 20 dB above the level set by the Q of the cavity. In the 6 km OEO the tip of the 60 Hz phase noise is just barely visible. This result suggests that length dependent sources of phase noise increases the phase noise by approximately 20 dB.

Figs. 3 and 4 show the phase noise of a 40 m and 6 km OEO respectively. These data show the phase noise for optical powers set by attenuator of –2, 6 and 12 dBm into the fiber delay line. For offset frequencies below a 1 kHz offset the phase noise of the 40 m OEO does not change significantly with optical power. However in the 6 km OEO, when the optical power injected into the spool is 12 dBm, the phase noise at a 10 Hz offset increases by more than 10 dB relative to optical powers of 6 and –2 dBm. Thus for long fiber delay lines, the phase noise depends on the optical power into the fiber.

Figs. 4 and 5 shows the phase noise for a 6 km OEO with the optical power set by attenuator and drive current respectively. Comparing Fig. 4 and 5, the data show that when the optical power is set by adjusting the laser drive current, there is no reduction in the close-in phase noise with lower optical power. Therefore, the close-in phase noise is dependent on the laser noise.

Combining these results, we conclude that the close-in phase noise is dependent on fiber length, optical power and laser noise. These results are consistent with the conversion of laser noise to phase noise via the Kerr effect.

Another possible physical mechanism we investigated is the conversion of laser frequency noise into phase noise via chromatic dispersion. Figs. 6 and 7 compare the phase noise

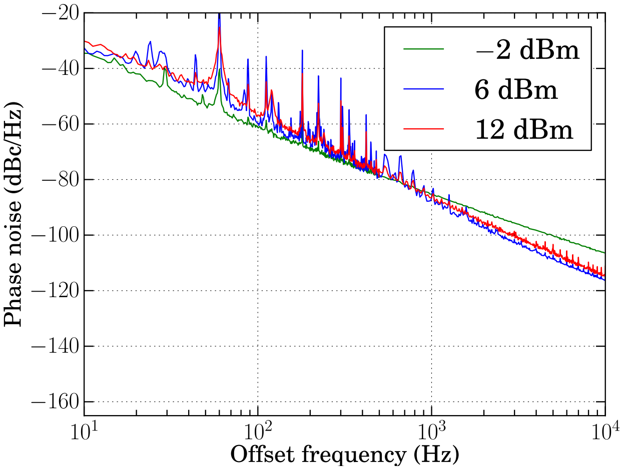

Fig. 3. Phase noise of a 40 m OEO. We used an attenuator to set the optical power into the fiber delay line to –2 dBm (green), 6 dBm (blue) and 12 dBm (red).

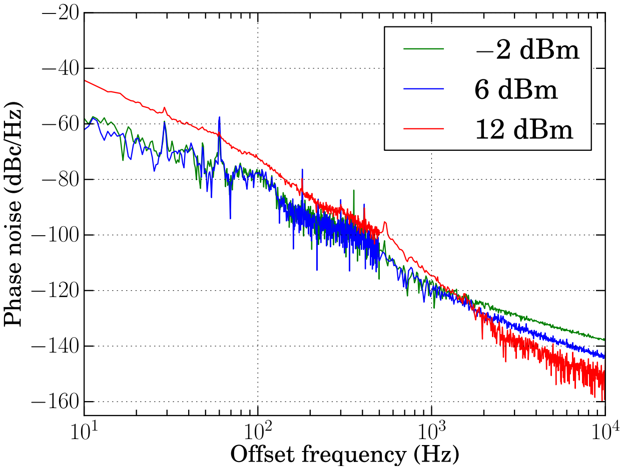

Fig. 4. Phase noise of 6 km OEO. We used an attenuator to set the optical power into the fiber delay line to –2 dBm (green), 6 dBm (blue) and 12 dBm (red).

of a 6 km OEO with either an SMF or DSF delay line, for 6 and 12 dBm optical power into the fiber spool respectively. If chromatic dispersion were the dominant source of length dependent phase noise then DSF OEO should have lower phase noise. However, no reduction is observed when DSF fiber is used.

Fig. 8 shows the back reflected optical power versus input optical power for a 6 km fiber spool and 6 km OEO. Higher optical powers were achieved for the fiber spool data because no modulator was placed between the laser and the fiber delay line. The data show that the onset of SBS occurs at optical powers of approximately 13 dBm. The backscattered optical power measured from the delay line of a 6 km OEO indicates that for optical powers from –2 to 12 dBm the OEO operates below the SBS threshold.

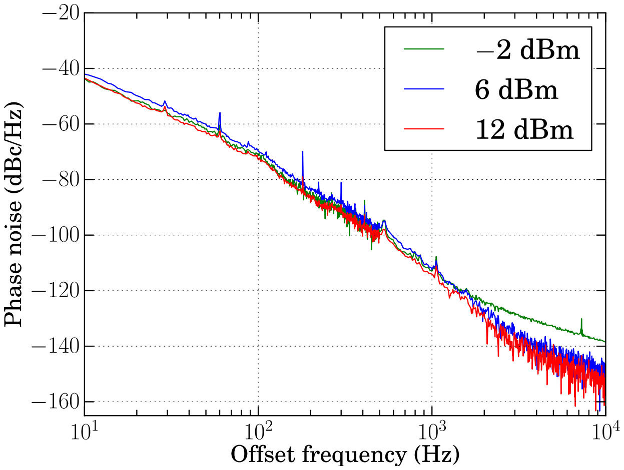

Fig. 5. Phase noise of a 6 km OEO. We varied the laser driver current to set the optical power into the fiber delay line to –2 dBm (green), 6 dBm (blue) and 12 dBm (red).

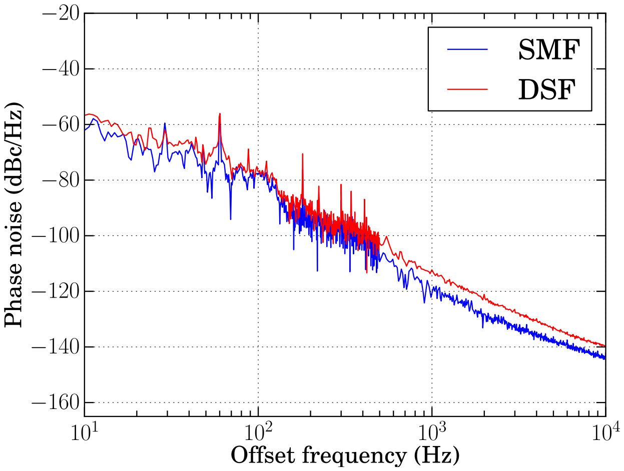

Fig. 6. Phase noise of a 6 km OEO with an SMF (blue) and DSF (red) delay line. We used an optical attenuator to set the optical power into the delay line to 6 dBm.

IV. CONCLUSION

We have investigated optically-induced length-dependent sources of phase noise in OEOs. We have shown that the close-in phase of the OEO is dependent on fiber length, optical power and laser noise. This dependence is consistent with the conversion of laser noise into phase noise via the Kerr effect. For the optical powers that we used, we showed that our OEO operates below the SBS threshold. Also, chromatic dispersion is not a dominant source of length-dependent phase noise. These results do not rule out other length-dependent mechanisms such as thermal and vibration effects.

ACKNOWLEDGMENT

This work was supported by DARPA under the SILO program.

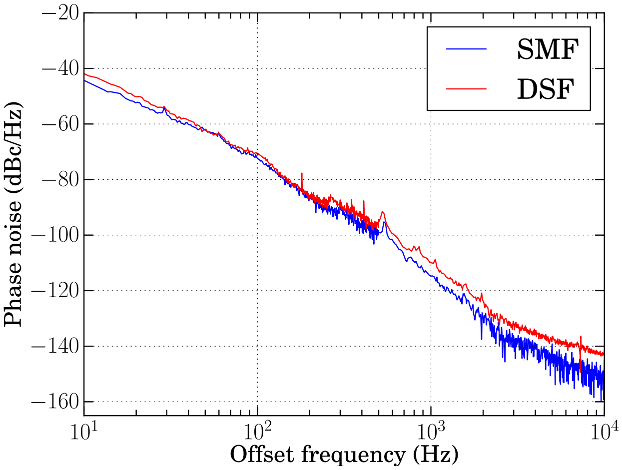

Fig. 7. Phase noise of a 6 km OEO with an SMF (blue) and DSF (red) delay line. We used an optical attenuator to set the optical power into the delay line to 12 dBm.

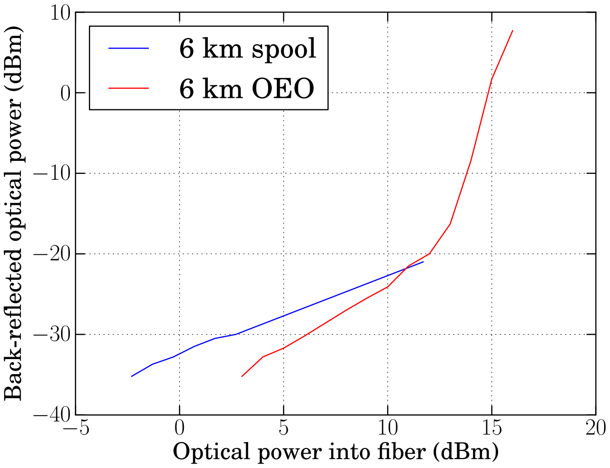

Fig. 8. Back reflected optical power vs injected optical power for a 6 km spool (blue) and 6 km OEO (red).

REFERENCES

[1] X. S. Yao and L. Maleki, “Optoelectronic oscillator for photonic systems,” IEEE J. Quant. Elect, vol. 32, no. 7, pp. 1141 –1149, Jul 1996.

[2] X. S. Yao and L. Maleki, “Optoelectronic microwave oscillator,” J. Opt. Soc. Am. B, vol. 13, no. 8, pp. 1725–1735, Aug 1996.

[3] W. Zhou and G. Blasche, “Injection-locked dual opto-electronic oscillator with ultra-low phase noise and ultra-low spurious level,” IEEE Trans. Microw. Theory and Techniques, vol. 53, no. 3, pp. 929 – 933, March 2005.

[4] O. Okusaga, E. Adles, W. Zhou, E. Levy, M. Horowitz, G. Carter, and C. Menyuk, “Spurious mode suppression in dual-injection-locked optoelectronic oscillators,” unpublished.

[5] O. Okusaga, W. Zhou, E. Levy, M. Horowitz, G. Carter, and C. Menyuk, “Non-ideal loop-length-dependence of phase noise in oeos,” Conf. Lasers Electro-Optics, 2-4 2009, pp. 1–2.

[6] O. Okusaga, W. Zhou, E. Levy, M. Horowitz, G. Carter and C. Menyuk, “Experimental and simulation study of dual injection-locked oeos,” in IEEE Freq. Cont. Symp., 20-24 2009, pp. 875 –879.

[7] E. Salik, N. Yu, L. Maleki, and E. Rubiola, “Dual photonic-delay line cross correlation method for phase noise measurement,” Int. Freq. Cont. Symp., 23-27 2004, pp. 303 – 306.