Suppression of Rayleigh-scattering-induced noise in OEOs

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Abstract: Optoelectronic oscillators (OEOs) are hybrid RF-photonic devices that promise to be environmentally robust high-frequency RF sources with very low phase noise. Previously, we showed that Rayleigh-scattering-induced noise in optical fibers coupled with amplitude-to-phase noise conversion in photodetectors and amplifiers leads to fiber-length-dependent noise in OEOs. In this work, we report on two methods for the suppression of this fiber-length-dependent noise: altering the amplitude-dependent phase delay of the OEO loops and suppressing the Rayleigh-scattering-induced noise in optical fibers. We report a 20 dB reduction in the flicker phase noise of a 6 km OEO via these suppression techniques.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (230.0250) Oscillators.

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1. Introduction

Optoelectronic oscillators (OEOs) are ring resonators that utilize the low loss-per-unit-length of optical fibers to generate ultra-high Q cavities [1]. The high Q of the OEO cavity results in low phase noise RF signals. Theoretical models of the OEO predict that the phase noise of the OEO at frequencies within 100 kHz of the nominal carrier frequency (hereafter referred to as the "close-in" phase noise) should decrease quadratically with fiber length [2]. However, this expected relationship between phase noise and fiber length has not been observed at low offset frequencies [3]. Figure 1 shows the phase noise of 10 GHz OEOs with various fiber lengths. The phase noise of the 6 km OEO is higher than what is predicted by the theory, which indicates that there is a fiber-length-dependent noise source in the OEO. Similar fiber-length-dependent noise has been observed in the duplex transfer of frequencies over optical fiber [4]. The low-offset-frequency phase noise is a critical measure of the stability of an oscillator; therefore, identifying and suppressing such flicker phase noise sources is a crucial step towards optimizing OEOs and other RF-photonic systems.

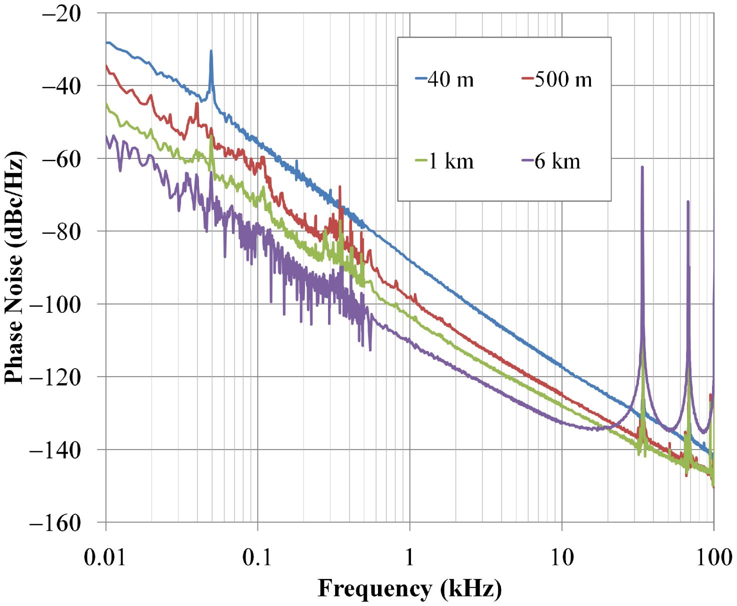

Fig. 1. Phase noise plots of 10 GHz single-loop OEOs with varying fiber lengths.

Sources of fiber-length-dependent phase noise in OEOs have been studied extensively [5, 6]. Volyanskiy et al. showed that in some configurations the OEO flicker phase noise is dominated by the combination of laser frequency noise and chromatic dispersion in optical fibers [5]. In our OEOs, however, the fiber-length-dependent noise is dominated instead by Rayleigh scattering in optical fibers [6]. Rayleigh scattering in the optical domain leads to intensity noise in the RF domain. We have also shown that the nonlinearities in the photodetectors and RF amplifiers convert amplitude noise in OEOs to phase noise [7]. It is this combination of Rayleigh scattering and amplitude-to-phase noise conversion that we will focus on in this work. In the rest of this work, we will refer to "our OEOs". We do so to distinguish between OEOs like ours where Rayleigh scattering coupled with amplitude-to-phase noise conversion are the dominant fiber length dependent noise mechanisms and OEOs like those of Volyanskiy et al. where laser frequency noise and chromatic dispersion dominate. For a given OEO, the dominant fiber-length-dependent noise source will depend on such parameters as: the laser frequency noise, laser power level, the OEO's oscillating frequency, and the amount of amplitude-to-phase noise conversion in the amplifiers and photodetectors.

This paper is organized in the following fashion. In Section 2, we briefly review Rayleigh scattering noise in optical fibers and amplitude-to-phase noise conversion in photodetectors and amplifiers. In Section 3, we present the results of suppression experiments designed to reduce the amplitude-to-phase noise conversion and Rayleigh scattering in the OEO. Finally, in Section 4, we provide an analysis of our results and their potential applicability to other RF-photonic systems.

2. Fiber-length-dependent phase noise sources

In this section, we will briefly describe the combination of phenomena that leads to length-dependent noise in our OEOs. Together, amplitude noise induced by Rayleigh scattering in optical fibers and amplitude to phase noise conversion in nonlinear elements — in particular the amplifiers and photodetectors — cause length-dependent flicker phase noise in the OEO's microwave signal. In the following subsections, we will present experimental data demonstrating both phenomena.

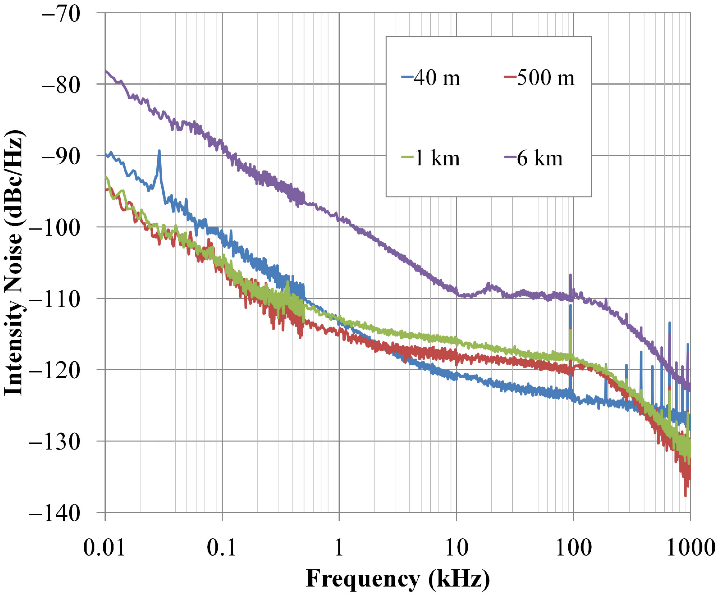

Fig. 2. Optical intensity noise plots of 1550 nm laser signals transmitted over various lengths of optical fiber.

2.1 Guided entropy mode Rayleigh scattering in optical fibers

The refractive index of a dielectric material such as fused silica depends, in part, on the density or strain of the dielectric [8]. Density or strain fluctuations lead to fluctuations of the dielectric susceptibility which cause optical scattering. Density or strain fluctuations caused by pressure or stress lead to Brillouin scattering while density or strain fluctuations due to

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temperature lead to Rayleigh scattering. We have shown previously that Guided Entropy Mode Rayleigh Scattering (GEMRS) – that is, scattering due to transverse temperature gradients in the fiber – leads to fiber-length-dependent intensity noise at offset frequencies below 100 kHz, which corresponds to the flicker noise region of the OEO [9]. We measured the GEMRS-induced intensity noise in our OEOs by employing the forward scattering measurement system used in ref. 9. Figure 2 shows plots of the forward-scattered optical intensity noise in various lengths of single-mode optical fiber. The data show that increasing the fiber length increases the intensity of the noise due to GEMRS in the relevant frequency range.

2.2 Amplitude-to-phase noise conversion

The GEMRS effect is not sufficient to explain the increased phase noise of the OEO. Intensity noise due to GEMRS will lead to optical intensity noise, yet, to first order, optical intensity noise has no effect on the RF phase noise of an amplitude-modulated OEO with direct detection [10]. A second mechanism is required to convert the optical intensity noise to RF phase noise. That mechanism is intensity-dependent phase delay in the nonlinear photodetectors and RF amplifiers in the OEO. Such AM-to-PM conversion has also been reported in mode-locked laser systems used to generate and transmit RF signals [11]. In order to measure the AM-to-PM conversion factor for each component, we connected an RF-photonic link to a network analyzer and varied the optical power into the photodetector. We then recorded the phase delay experienced by the RF signals at 10 GHz passed through the link.

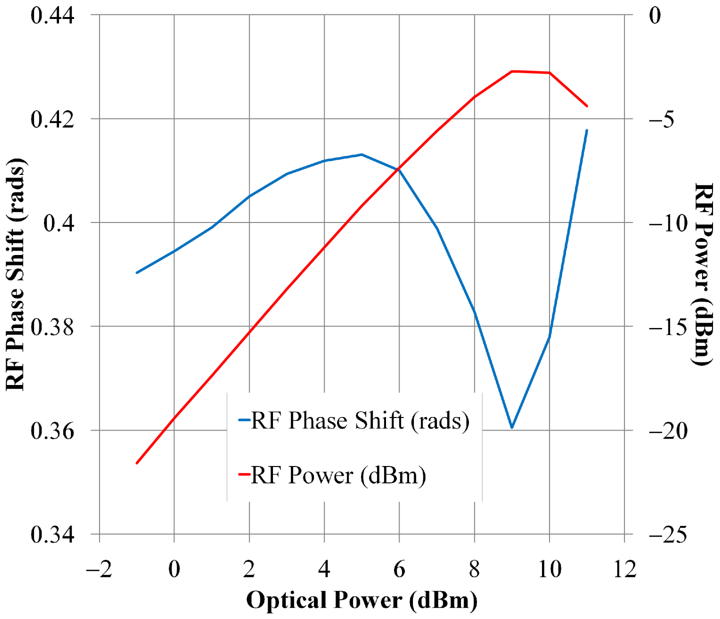

Fig. 3. RF gain and phase shift for a 10 GHz RF signal transmitted through a photodetector.

Figure 3 shows the plots of the phase delay and output intensity versus input optical power for the photodetector used in our OEOs. Our data show that the phase delay is a nonlinear function of the input optical power. Therefore, fluctuations in the optical intensity will lead to fluctuations in the RF phase of the OEO signal. The magnitude of the AM-to-PM conversion factor is proportional to the slope of the phase curve in Fig. 3 at the mean optical power level into the photodetector of the OEO.

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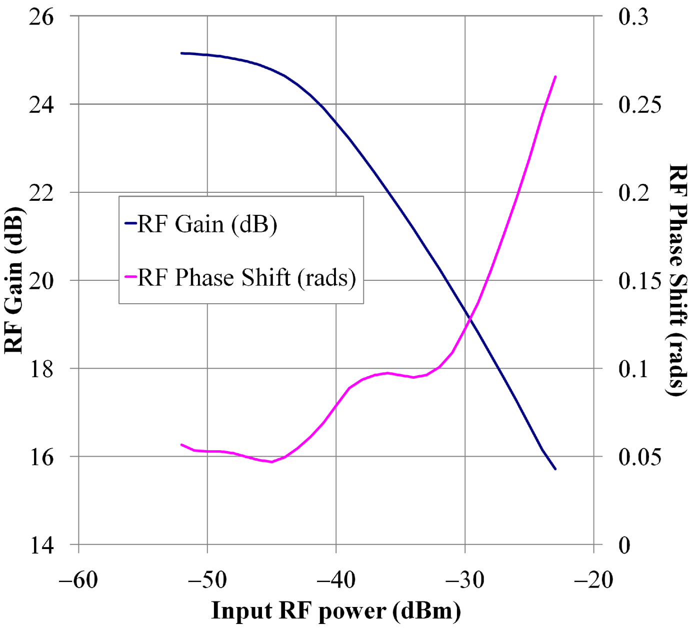

Fig. 4. RF gain and phase shift for a 10 GHz RF signal transmitted through an amplifier block.

We used a similar experiment to measure the intensity-dependent phase delay of the amplifiers in the OEO. Figure 4 shows the resulting phase-delay and output intensity plots versus input RF power to the amplifier block. Again, we note that the magnitude of the AM-to-PM conversion factor is given by the slope of the phase curve at the steady-state mean RF power level into the amplifier block of the OEO.

3. Noise suppression techniques

In the following subsections, we present data from experiments designed to verify our theories about the two phenomena responsible for the fiber-length-dependent phase noise in OEOs. This verification is a necessary step towards our long-term goal of counter-acting the Rayleigh noise effect in OEOs and other RF-photonic systems.

3.1 Suppression of AM-to-PM conversion

From the phase plots in Figs. 3 and 4, we can see that the magnitude of the AM-to-PM conversion terms depend on the input powers into the nonlinear components (photodiodes and RF amplifiers) of the OEO. We showed previously that by introducing a nonlinear gain element with the proper phase relationship, we could eliminate the AM-to-PM effect [7]. In lieu of using such a device, we instead attenuated the optical power into the photodetector and the RF power into the final stage of the amplifier block in the OEO to alter the magnitude of the AM-to-PM conversion in these devices. We note that we attenuated the optical power after the fiber spool so as not to change the GEMRS induced in the fiber. In addition, we placed the RF attenuator after the first stage RF amplifier so as not to change the amount of additive noise generated by the amplifiers; this additive noise is dominated by the first amplifier stage.

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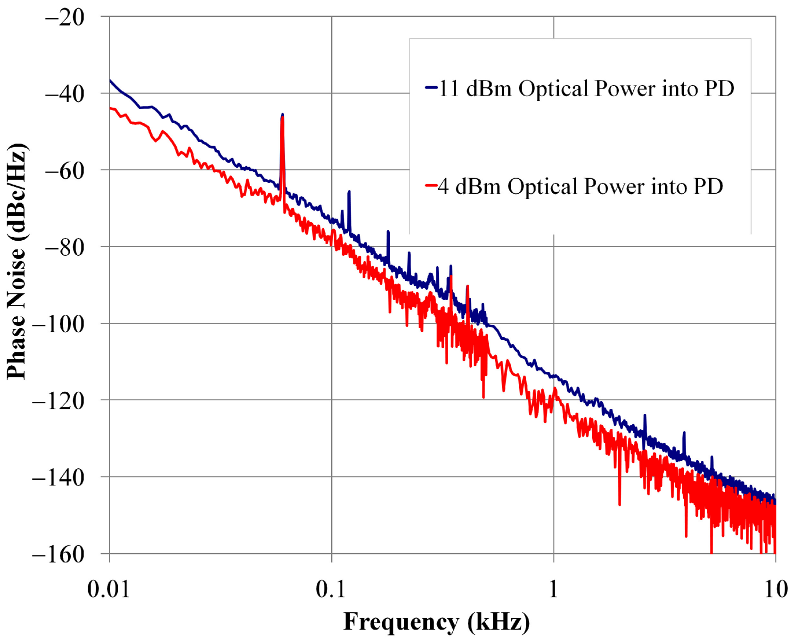

Fig. 5. Phase noise plots from a 10 GHz OEO with a 6 km fiber delay with and without optical attenuation before the photodetector.

Figure 5 shows the phase noise of a 6 km OEO with and without optical attenuation before the photodetector. The unattenuated optical power level into the photodetector was 11 dBm. After attenuation, the optical power was 4 dBm. The AM-to-PM conversion factor in the photodetector is proportional to the slope of the amplitude-dependent phase shift shown in Fig. 3. From Fig. 3, we see that changing the input optical power from 11 dBm to 4 dBm decreases the AM-to-PM conversion factor in the photodetector. We observe a commensurate 7 dB reduction in the relative flicker noise at offset frequencies below 10 kHz. Note that if the flicker noise were due to an additive noise source such as shot noise in the photodetectors, then attenuating the optical power would have increased the relative flicker noise level. Therefore, the observed reduction in flicker noise indicates that the induced noise was due to the nonlinear AM-to-PM effect shown in Fig. 3.

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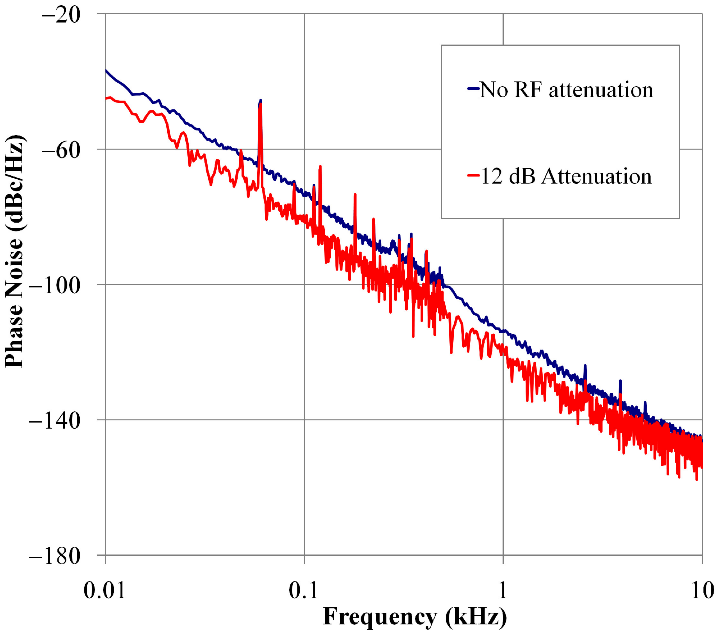

Fig. 6. Phase noise plots from a 10 GHz OEO with a 6 km fiber delay with and without optical attenuation before the second stage amplifier.

Figure 6 shows the phase noise of a 6 km OEO with and without RF attenuation before the second stage of the amplifier block. Without RF attenuation, the input power into the amplifier block is approximately –30 dBm. Again, the amplitude-dependent phase curve in Fig. 4 shows that by reducing the input RF power by 12 dB, we reduced the AM-to-PM conversion factor in the RF amplifiers. As shown in Fig. 6, we observe a commensurate reduction in the OEO phase noise. Both attenuation methods reduced the flicker noise by approximately 7 dB. Constructing a nonlinear gain element with the precise optimal phase slope may have an even greater effect on the OEO’s flicker noise.

3.2 Suppression of Rayleigh scattering

In this subsection, we present the effect of GEMRS suppression on the OEO phase noise. Previously, we showed that laser frequency modulation suppresses GEMRS-induced intensity noise in optical fibers [12]. The GEMRS effect has a gain bandwidth between 10 and 100 kHz in single-mode optical fibers at 1550 nm. By modulating the laser frequency at frequencies between 10 and 100 kHz, we demonstrated up to 30 dB suppression of the GEMRS-induced intensity noise in the optical domain. We now present experimental data showing that laser frequency modulation also reduces the flicker phase noise of the OEO. Figure 7 shows the phase noise of a 6 km OEO with and without laser frequency modulation. The data show that the phase noise of the OEO was reduced by up to 20 dB. In particular, the phase noise reduction was greatest at offset frequencies where the GEMRS-induced intensity noise shown in Fig. 2 was greatest. We note that the effectiveness of laser-frequency-modulation diminishes at frequencies below 100 Hz. The structure of the noise in this frequency range suggests vibrational effects are the principle noise source in this region. The noise spikes in the red curve in Fig. 7 match typical vibration frequencies of various fans in our laboratory.

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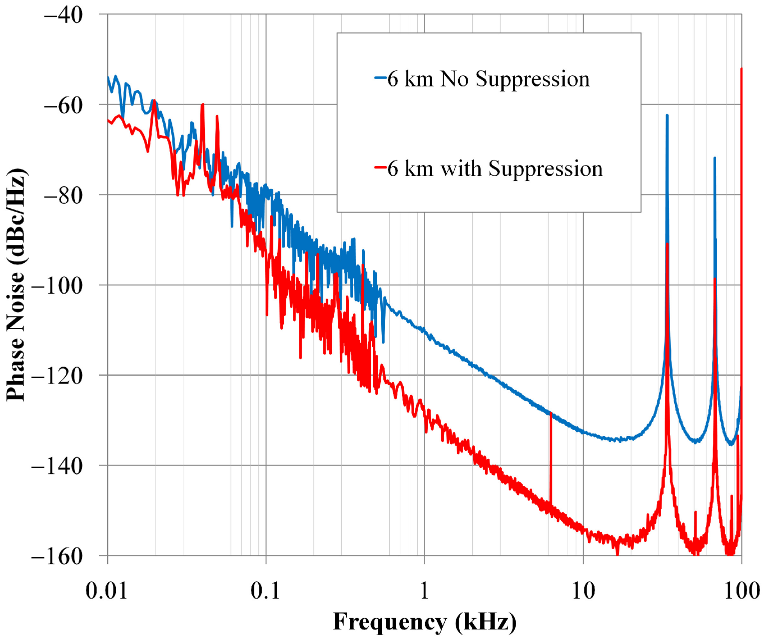

Fig. 7. Phase noise plots from a 10 GHz OEO with a 6 km fiber delay with and without GEMRS suppression via laser frequency modulation.

4. Conclusion

In this work, we demonstrated that together GEMRS-induced optical intensity noise and AM-to-PM conversion in photodetectors and RF amplifiers comprise the dominant source of fiber-length-dependent flicker phase noise in our OEOs. We demonstrated that suppressing either effect reduced the flicker phase noise of the OEO. Suppressing GEMRS via laser frequency modulation was the most effective means of flicker noise suppression. We observed up to 20 dB reduction of the flicker phase noise at 1 kHz by laser frequency modulation.

We note that these noise phenomena are not unique to OEOs. We expect similar flicker noise in any RF-photonic system with high-*Q* resonators or long waveguides with significant transverse gradients and nonlinear elements with amplitude-dependent phase such as photodetectors and amplifiers. Systems that include this combination of elements include: mode-locked laser-based RF sources such as coupled OEOs and carrier envelope phase locked lasers [13, 14]; whispering gallery mode optical resonators [15]; and time and frequency transfer systems that utilize optical fibers. For any of the above systems, the noise suppression techniques presented in this work may prove valuable.

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