Theoretical Investigation of Length-Dependent Flicker-Phase Noise in Opto-electronic Oscillators

Andrew Docherty,* Olukayode Okusaga,† Curtis R. Menyuk,* Weimin Zhou,† and Gary M. Carter*

*UMBC, 1000 Hilltop Circle, Baltimore, MD 21250
† Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783

6 May 2011
Opto-electronic oscillators (OEO) operate with low phase noise due to the large delay and low loss that is achievable in optical fibers.\(^1\)

Length-dependent flicker-phase noise

- Experimental evidence shows beyond around 6 km the phase noise does not improve\(^1\) due to length-dependent flicker noise.
- The source of this length-dependent flicker noise (LDFN) is still uncertain.
- Experiments to date have significantly constrained the possibilities\(^1,2\).

It is important to understand and overcome this limit in order to realize the full potential of OEOs

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\(^1\)O. Okusaga et al., Quantum Electronics, 3-4 (2009).
Experimental evidence

Length-dependent flicker noise is seen experimentally, where does it come from?

- Expected phase noise without flicker

- Frequency, kHz

- Phase noise, dBC/Hz

- 40 m
- 500 m
- 6 km
OEO: Noise sources

Figure: The OEO system showing the sources of noise and the harmonics of the RF signal at different points in the loop.
Laser noise

The likely source of significant length-dependent flicker phase noise comes from length-dependent conversion of laser noise.

The laser frequency noise and RIN measured by Volyanskiy et al. ³

The signal in the optical domain

The RF signal is modulated onto the laser carrier producing harmonics in the optical domain at the RF oscillator frequency:

\[ A_{\text{mod}}(t) = \sum_{m=-\infty}^{\infty} A_m(t) \exp[jm\omega_0 t + jm\phi(t)] \]

- \( \omega_0 \): the RF oscillator natural frequency
- \( A_m \): the amplitude of the harmonics
- \( \phi \): the input RF phase noise

The harmonics have the same laser noise:

- \( \alpha_{\text{RIN}} \): laser amplitude noise (RIN)
- \( \Delta\omega \): the laser frequency noise
Laser noise: where does it go?

The electric field in the optical domain:

\[ E(t) = A_{\text{mod}}(t)[1 + \alpha_{\text{RIN}}(t)] \exp \left[ j\omega_c t + j \int_0^t \Delta \omega(t') dt' \right] \]  

(1)

If optical fiber acts as a pure delay then after direct detection:

\[ V_{\text{RF}}(t) = |E(t)|^2 = |A_{\text{mod}}(t)|^2[1 + 2\alpha_{\text{RIN}}(t)] \]  

(2)

- Laser amplitude noise (RIN) is directly converted to RF amplitude noise
- Laser frequency noise vanishes with direct detection

The laser frequency noise vanishes only if it remains identical on all optical harmonics
Laser phase noise conversion: Dispersion

- Dispersion means different harmonics will travel through the fiber at different velocities.
- The signal on different harmonics will be delayed differently.
- This gives a conversion to RF phase noise given by:\(^3\)

\[
\phi_{RF}(t) \sim T_h \Delta \omega(t)
\]

\[
T_h \sim \beta_2 \omega_0 L = \text{relative time delay between harmonics}
\]

\(\beta_2\): the fiber dispersion
\(\omega_0\): the oscillator frequency
\(L\) the length of the optical fiber

Scattering from Rayleigh or fiber connectors and end-faces also causes a delayed signal to appear at the detector.

A double reflected signal from two planes of reflectivity $r$ adds to the main signal, giving a total signal of:

$$E_{\text{out}}(t) = E(t) + r^2 E(t - T_s)$$

$$T_s = \frac{2L_s}{v_g} = \text{time delay of scattered signal}$$
Scattering: two plane scattering

The delayed laser frequency noise converts to RF phase noise:

\[
\phi_{RF}(t) \approx r^2 \tan \theta \sin[T_s \Delta \omega(t)] = r^2 \tan \theta \sin[2\beta_1 L_s \Delta \omega(t)]
\]

\(\theta\): optical phase between carrier and harmonics

\(L_s\): spacing between scatter planes

Using a power scattering of \(-50\) dB there is significant conversion for \(L_s \approx 15\) m.
Scattering: multiple-plane scattering

- Scattering from connectors would increase with number of connectors, not length of fiber.
- Distributed scattering processes could give length-dependent flicker phase noise.
- We use a multi-plane model estimate the effect of distributed scattering:

\[
\phi_{\text{max}}(t) = \frac{2r^2L \tan \theta}{v_g} \Delta \omega(t)
\]
Scattering required for the same effect as dispersion: $-65 \text{ dB}$ for each plane of the multiple-plane model.
RIN conversion and Kerr nonlinearity

- RIN can be converted to phase noise by third-order dispersion and scattering.
- For typical RIN noise this is well below the white noise floor.
Conclusions

- We have investigated different possible sources of length dependent flicker noise in OEOs.
- Amplification and conversion due to the Kerr nonlinearity has been ruled out.
- Conversion of laser frequency noise to RF phase noise could be significant source of experimentally observed length-dependent flicker noise.
- This conversion can come from either fiber dispersion or double scattering.
- We are also investigating amplification processes in the fiber.