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

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The Optoelectronic Oscillator

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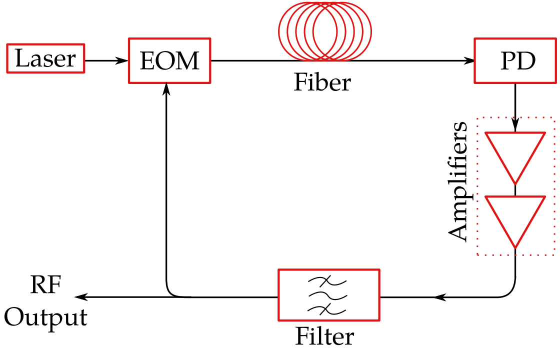
Opto-electronic oscillators (OEO) operate with low phase noise due to the large delay and low loss that is achievable in optical fibers.[1]



[1] X. S. Yao and L. Maleki, JOSA B, **8** 1725–35 (1996).

Length-dependent flicker-phase noise

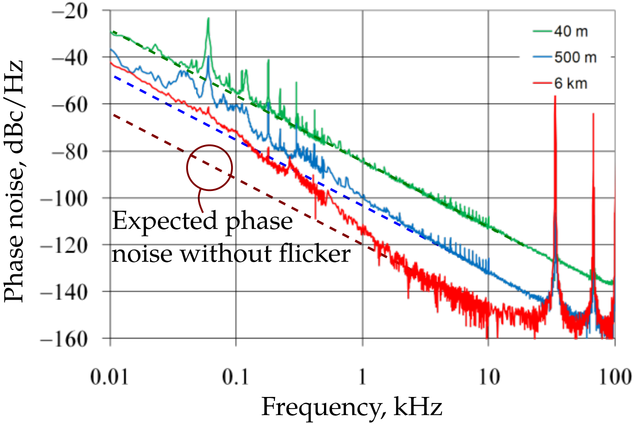
- Experimental evidence shows beyond around 6 km the phase noise does not improve [1] due to length-dependent flicker noise.
- The source of this length-dependent flicker noise (LDFN) is still uncertain.
- Experiments to date have significantly constrained the possibilities [1,2].

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

[1] O. Okusaga et al., Quantum Electronics, 3-4 (2009).

[2] D. Eliyahu et al., IEEE Trans. Microw. Theory Tech., **2** 449–56 (2008).

Experimental evidence



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

OEO: Noise sources

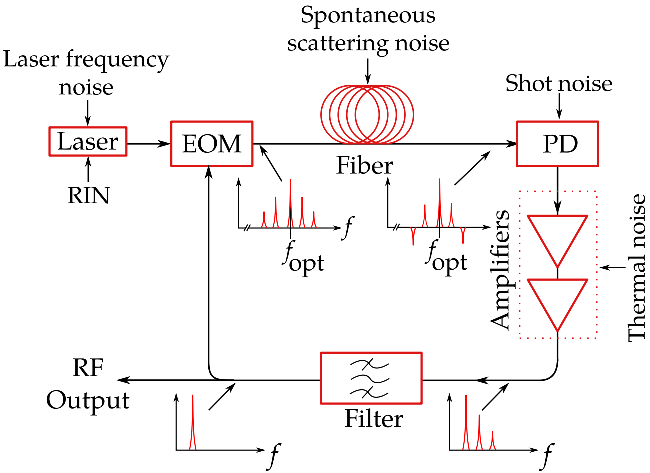
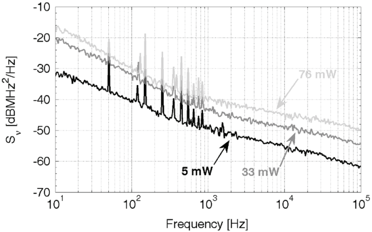
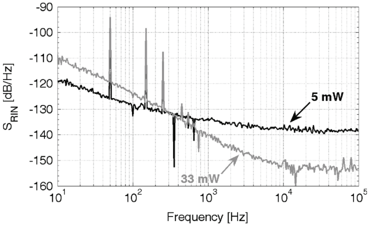


Figure: The OEO system showing the sources of noise and the harmonics of the RF signal at different points in the loop.

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]

[3] K. Volyanskiy et al. J. Lightwave Technology. **28** 2730–5 (2010).

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:

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

ω_0: the RF oscillator natural frequency
A_m: the amplitude the of harmonics
ϕ: the input RF phase noise

The harmonics have the same laser noise:

α_{RIN}: laser amplitude noise (RIN)
$\Delta\omega$: the laser frequency noise

Laser noise: where does it go?

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The electric field in the optical domain:

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

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

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

- 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

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- 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]

$$\phi_{\mathrm{RF}}(t) \simeq T_h \Delta\omega(t)$$

$$T_h \simeq \beta_2 \omega_0 L = \text{relative time delay between harmonics}$$

β_2: the fiber dispersion
ω_0: the oscillator frequency
L the length of the optical fiber

[3] K. Volyanskiy et al. J. Lightwave Technology. **28** 2730–5 (2010).

Laser phase noise conversion: Scattering

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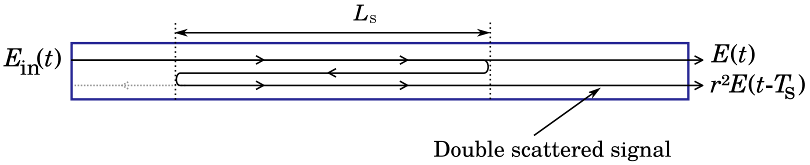
- Scattering from Rayleigh or fiber connectors and end-faces also causes a delayed signal to appear at the detector.
- A double reflected signal from two planes of reflectivity r adds to the main signal, giving a total signal of:

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

$$T_s = \frac{2L_s}{v_g} = \text{time delay of scattered signal}$$

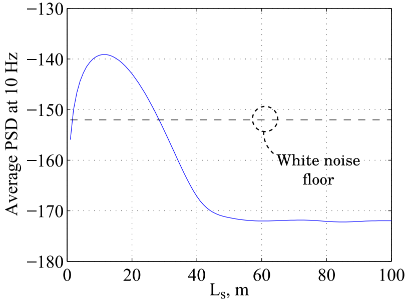


Scattering: two plane scattering

The delayed laser frequency noise converts to RF phase noise:

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

θ: 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

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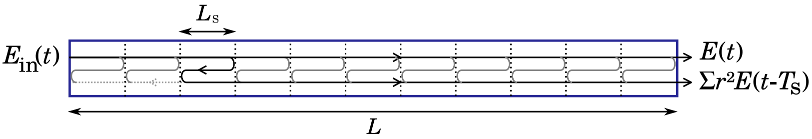
- Scattering from connectors would increase with number of connectors, not length of fiber.
- Distributed scattering processes could give length-dependent flicker phase noise.
- We use a multi-plane model estimate the effect of distributed scattering:



- The approximate maximum scattering is given by:

$$\phi_{\max}(t) = \frac{2r^2 L \tan\theta}{v_g}\Delta\omega(t)$$

Laser frequency noise conversion

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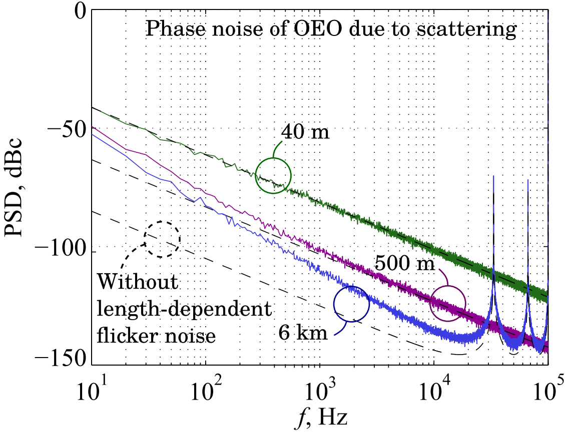
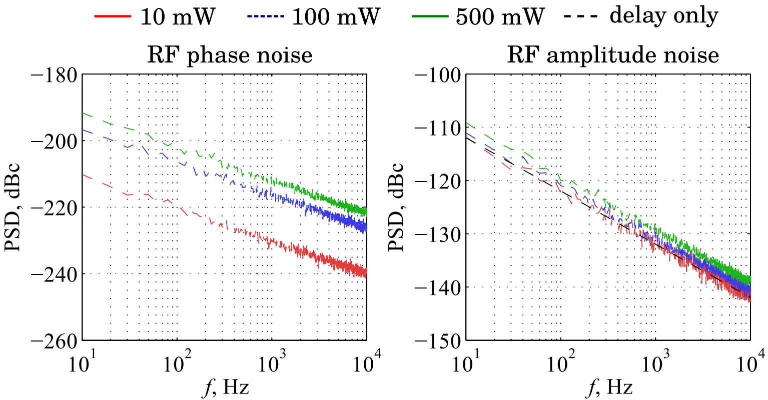


Scattering required for the same effect as dispersion: −65 dB for each plane of the multiple-plane model.

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.