Contribution of Laser Frequency and Power Fluctuations to the Microwave Phase Noise of Optoelectronic Oscillators

Kirill Volyanskiy, Yanne K. Chembo, Laurent Larger, and Enrico Rubiola

***Abstract*—An opto-electronic oscillator is a microwave oscillator in which the resonator is replaced with an optical fiber delay-line carrying an intensity-modulated laser beam. We consider the frequency and power fluctuations of a standard DFB telecom laser, and we investigate their effect on the phase noise of microwaves generated with opto-electronic oscillators. We propose a theoretical study showing how these two laser fluctuations are converted into phase noise in the output microwave. This theory predicts that the power noise should have a minor contribution to microwave phase noise, while the wavelength fluctuations should strongly contribute to phase noise *via* the chromatic dispersion of the few kilometers long optical fiber delay line. We have experimentally confirmed the validity of this theory by measuring the relative intensity noise and the optical frequency noise of a semiconductor laser, which has later been used for microwave generation. We show that the use of a zero-dispersion fiber delay-line can lead to a 10 dB improvement of the phase noise performance, relatively to the case were a standard single mode fiber is used.**

***Index Terms*—Distributed feedback lasers, laser noise, microwaves, noise measurement, optoelectronic devices, phase noise, stochastic analysis, optoelectronic oscillator.**

I. Introduction

OPTO-ELECTRONIC OSCILLATORS (OEOs) are nowadays considered to be excellent ultra-pure microwave generators, and they are expected to play an important role in several applications where high spectral purity is required, such as in aerospace engineering, in lightwave communications, or in radar technology [1], [2]. The basic OEO architecture (see Fig. 1) relies on non-resonant optical storage of a microwave modulation carried by a laser in a long optical fiber. This approach is radically different from the standard principles typically involved in microwave oscillators, and making use of high-finesse microwave resonator. The main reasons to use an optical fiber to carry a modulated optical beam in order to implement the microwave delay are the long

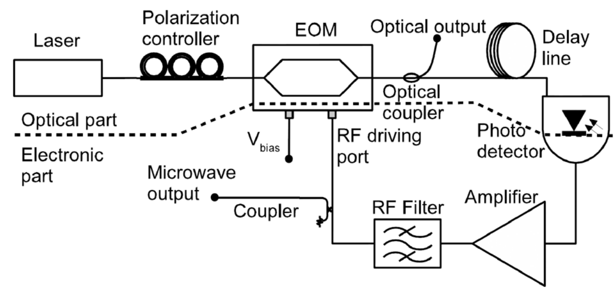

Fig. 1. Basic architecture of the optoelectronic oscillator. EOM: Electro-optic modulator; RF: Radio-frequency.

achievable delay, owing to the low loss of the fiber (0.15 dB/km, limited by Rayleigh scattering), the wide bandwidth of the delay (40 GHz, limited by the opto-electronic front-end), the low background noise, and the low thermal sensitivity of the fiber (typically 6.85×10^{-6}/K, 10 times better than the sapphire dielectric cavity). These features enable the implementation of high spectral purity oscillators and of high-sensitivity instruments for the measurements of phase noise. In both cases, the optical bandwidth turns into wide-range microwave tunability at virtually no cost in terms of phase noise.

It is self-evident that the highest spectral purity can only be achieved with ultra-low-noise opto-electronic components (laser, amplifier, photodiode, etc.) However, even in this optimal case, the interplay between the various elements of the oscillator results in additional composite noises.

In the case of OEOs, some attention has been devoted in the past to the effect of the fiber delay line on phase noise spectrum. In fact, it has been understood very soon that this delay line plays a positive role in terms of optical storage since the global quality factor of the OEO linearly increases with L. Effectively, the equivalent quality factor of the OEO is $Q_{\mathrm{OEO}} = 2\pi f_0 L/v_g$, where f_0 is the microwave frequency, L is the fiber delay line length, and v_g is the group velocity of light in the fiber core medium. On the other hand, the delay line creates spurious microwave cavity modes, which are very detrimental for most potential applications. A noteworthy study on the effect of optical elements on OEO performance was proposed in [3], where optical photonic filters (either high-Q optical cavities or atomic cells) were used to stabilize OEOs. The authors analyzed in that article several interesting effects, such as the interaction of noise with various filter properties (bandwidth, phase shift, etc.). However, no attention has ever been paid to the effect of the fiber chromatic dispersion. Our aim in this paper is to show that group

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velocity dispersion plays a key role, as it directly converts the optical frequency noise of the laser (i.e., the wavelength fluctuations) into phase noise for the output microwave. Moreover, we will show that by canceling dispersion, we are able to improve significantly the phase noise performance of OEOs, by a factor that may be as high as ten.

This article is organized as follows. In Section II, we present the system under study, and we propose a model for the conversion of laser noise into phase noise. We experimentally measure in Section III the relative intensity noise (RIN) and the frequency noise of the laser that will later be used in the OEO. Then, we will discuss the effect of this laser noise on OEO performance in Section IV, and the last section will be devoted to concluding remarks.

II. Phase Noise Model for the OEO

The OEO under study is organized in a single-loop architecture as depicted in Fig. 1. The oscillation loop consists of: a Mach–Zehnder (MZ) modulator (half-wave voltage $V_\pi = 4$ V and bias voltage V_B), seeded by a continuous-wave semiconductor laser of optical power $P_{\rm opt}$ and wavelength $\lambda_0 = 1550$ nm; a thermalized optical fiber of length $L = 4$ km, performing a time delay of $T = 20$ μs on the microwave signal carried by the optical beam, corresponding to a free spectral range of $\omega_T/2\pi = 1/T = 50$ kHz; a fast photodiode with a conversion factor $\rho_{\rm ph} = 0.75$ A/W; a narrow band microwave radio-frequency (RF) filter, of central frequency $f_0 = \omega_0/2\pi = 10$ GHz, and -3 dB bandwidth of $\Delta f = \Delta\omega/2\pi = 50$ MHz; a microwave amplifier with gain $G = 22$ dB and noise figure $F = 6$ dB.

Owing to the RF filter inserted into the oscillation loop, the microwave signal $V(t)$ at the input of the MZ modulator is narrowband. Thus, it can be rewritten under the form

$$V(t) = \frac{1}{2}\mathcal{V}(t)e^{i\omega_0 t} + \frac{1}{2}\mathcal{V}^*(t)e^{-i\omega_0 t}, \qquad (1)$$

where $\mathcal{V}(t) = |\mathcal{V}(t)|e^{i\psi(t)}$ is the complex slowly-varying envelope of the microwave. The random phase fluctuation $\psi(t)$ is precisely the variable of interest for phase noise studies. It has been earlier demonstrated that when the OEO has a stable single-frequency output, its phase obeys the following stochastic differential delay equation [4]

$$\begin{aligned}\frac{d\psi}{dt} &= -\frac{\omega_0}{2Q_{\rm RF}}[\psi(t) - \psi(t-T)] \\ &\quad + \frac{\omega_0}{2Q_{\rm RF}}\left\{\chi_{\rm fn}(t) + \frac{\varrho_{\rm rin}(t)}{2Q_{\rm RF}} + \frac{\eta_m(t)}{2Q_{\rm RF}} + \frac{\xi_a(t)}{|\mathcal{V}_0|}\right\} \qquad (2)\end{aligned}$$

where $\chi_{\rm fn}(t)$ is the phase noise excitation originating from laser frequency noise, $\varrho_{\rm rin}(t)$ is the contribution from RIN, $\eta_m(t)$ is a multiplicative noise corresponding to relative gain fluctuations, $\xi_a(t)$ is an additive noise corresponding to the fluctuations uncorrelated to microwave oscillations, $\mathcal{V}_0$ is the steady-state complex amplitude of the microwave, and $Q_{\rm RF} = \omega_0/\Delta\omega$ is the quality factor of the RF-filter. The noise term $\xi_a(t)$ can be considered as a Gaussian white noise of correlation $\langle\xi_a(t)\xi_a(t')\rangle = 2\Gamma_a\delta(t-t')$, where Γ_a is the related power spectral density. On the other hand, $\eta_m(t)$ is spectrally and statistically more complex, as it includes for example the $1/f$ noise close to the microwave carrier [4]. From a mathematical point of view, $\xi_a(t)$ and $\chi_{\rm fn}(t)$ appear as additive noise terms in the stochastic equation ruling the complex envelope $\mathcal{V}(t)$, while $\eta_m(t)$ and $\varrho_{\rm rin}(t)$ arise as multiplicative noise terms.

After (2), the Fourier spectrum $\psi(t)$ is

$$\tilde{\psi}(\omega) = \frac{\omega_0}{2Q_{\rm RF}}\frac{\tilde{\chi}_{\rm fn}(\omega) + \frac{\tilde{\varrho}_{\rm rin}(\omega)+\tilde{\eta}_m(\omega)}{2Q_{\rm RF}} + \frac{\tilde{\xi}_a(\omega)}{|\mathcal{V}_0|}}{i\omega + \frac{\omega_0}{2Q_{\rm RF}}[1-e^{-i\omega T}]}, \qquad (3)$$

where the overtilde denotes the Fourier transform. Since all the noise terms are supposed to be independent, the power density spectrum (PSD) of the phase noise is determined as $S_\psi(\omega) = |\Psi(\omega)|^2$, that is

$$S_\psi(\omega) = \frac{\omega_0^2}{4Q_{\rm RF}^2}\frac{|\tilde{\chi}(\omega)|^2 + \frac{|\tilde{\varrho}_{\rm rin}(\omega)|^2+|\tilde{\eta}_m(\omega)|^2}{4Q_{\rm RF}^2} + \frac{2\Gamma_a}{|\mathcal{V}_0|^2}}{\left|i\omega + \frac{\omega_0}{2Q_{\rm RF}}[1-e^{-i\omega T}]\right|^2}. \qquad (4)$$

The power spectral density Γ_a can be calculated using the characteristics of OEO components. The noise power at the amplifier output is caused by laser RIN, thermal noise, and shot noise; it can be expressed as:

$$P_n = [N_{\rm rin}I^2R + FkT_0 + 2eIR]\frac{Gf_0}{2Q_{\rm RF}}, \qquad (5)$$

where G is the amplifier gain, F is the noise figure of amplifier, $T_0 = 295$ K is the room temperature, k is the Boltzmann constant, e is the electron charge, $N_{\rm rin}$ is the RIN power density spectrum, I is the photodiode current, and R is the equivalent load of the photodiode. The power Γ_a of additive noise can be then calculated as

$$\Gamma_a = \frac{P_n R_{\rm out} Q_{\rm RF}}{\pi f_0}, \qquad (6)$$

where $R_{\rm out}$ is the output impedance ($= 50\ \Omega$ in our case) in the open loop configuration [4]. In the next section, we are going to measure experimentally the RIN and the optical frequency noise of the laser in order to evaluate its contribution to the phase noise of the output microwave.

III. Measurement of the DFB Laser Noise

The laser used for the OEO is a EM253-050-YYY InGaAsP/InP multi-quantum well (MQW) distributed feedback (DFB) laser diode that delivers up to 50 mW at 450 mA. This enables to scan a wide range of pumping currents and output optical powers. Laser cooling and bias stability are ensured by commercial controllers suited for butterfly lasers (no customized feedback control circuits). We will first measure the RIN, and then the optical frequency noise.

A. Measurement of Relative Intensity Noise

The experimental setup for the measurement of low frequency RIN is presented in Fig. 2. This scheme uses two independent channels to reject the instrument background noise (mainly originating from the photodiodes and amplifiers), thanks to correlation and averaging on a suitable number of

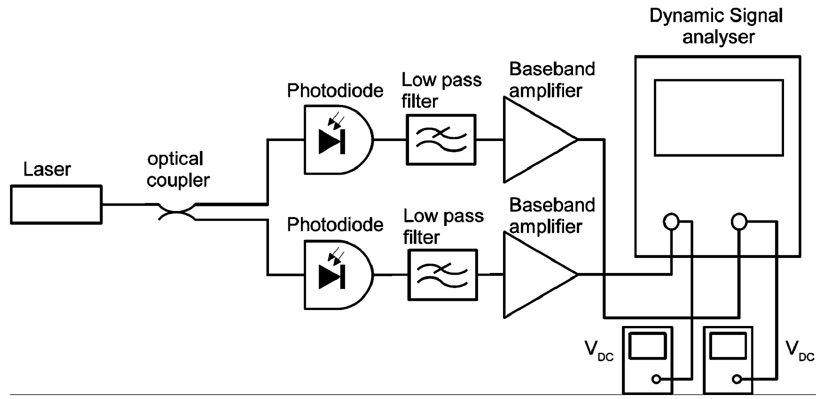

Fig. 2. Dual channel measurement bench for the laser RIN spectrum.

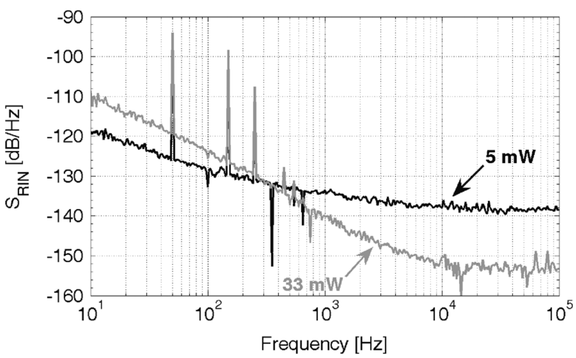

Fig. 3. Experimental measurements for the laser RIN for two output optical powers (5 mW and 33 mW). The peaks at 50 Hz and its harmonics are induced by the power supply.

spectra [5]–[8]. The upper frequency is limited to 100 kHz by the FFT analyzer. It is important to note that we measure the low frequency RIN and frequency noise of the laser as components of the multiplicative noise.

Looking at the RIN spectrum (Fig. 3), at 5 mW optical power the spectrum has a quite usual shape, with $1/f$ (or "flicker") noise at low frequencies and a white noise floor beyond 2 kHz. At higher optical power the low-frequency noise becomes steeper, approximately proportional to $f^{-1.5}$. This type of spectrum deserves further attention. Nonetheless, for the generation of highly pure microwaves we have no choice other than operating the laser at high power because a higher signal-to-noise ratio can be achieved in this way, ideally limited by shot noise in the photodetector. After analyzing the laser frequency noise, further discussed in this article, it turns out that the low-frequency RIN that goes with this choice is not the dominant noise effect. It may also be interesting to note that the high frequency RIN for the laser at 10 GHz is -158 dB/Hz according to its datasheet.

B. Measurement of Optical Frequency Noise

The experimental scheme shown in Fig. 4 makes use of a fiber based imbalanced passive Mach–Zehnder interferometer (typically used in optical differential phase shift keying -DPSK- demodulation). The device is used here to convert the optical frequency noise into intensity fluctuations, at the two complentary optical outputs. Each output is advantageously used to seed the same dual-channel method already discussed in the previous sub-section for RIN measurement. The interferometer is a commercial DPSK modulator with a differential delay $\tau = 402.68$ ps.

The optical-power transfer function $K(\nu) = P_{\mathrm{out}}/P_{\mathrm{in}}$ of the interferometer is

$$K(\nu) = \frac{1}{2}[1 + \cos(2\pi\nu\tau)], \quad (7)$$

where $\nu = c/\lambda$ is the optical frequency. The sensitivity of this interferometer is the partial derivative

$$\frac{\partial K(\nu)}{\partial \nu} = -\pi\tau \sin(2\pi\nu\tau). \quad (8)$$

For a given frequency ν_0, the interferometer can be operated as a linear transducer, with $|\sin(2\pi\nu_0\tau)| \simeq 1$. This can be done by finely tuning the device temperature or the laser wavelength. In this case the transfer function reads

$$\begin{aligned} K(\nu) &\simeq K(\nu_0) + \left[\frac{\partial K(\nu)}{\partial \nu}\right]_{\nu_0} \delta\nu \\ &\simeq \frac{1}{2} \pm \pi\tau\delta\nu. \end{aligned}$$

Accordingly, the conversion factor $C_\nu = \delta\nu/\delta V$ relating the voltage fluctuation V at the photodiode output to the laser-frequency fluctuation $\delta\nu$ is

$$\begin{aligned} C_\nu &= \frac{1}{\left[\frac{\partial K(\nu)}{\partial \nu}\right]_{\nu_0} P_{\mathrm{opt}}\rho_{\mathrm{ph}} R G} \\ &= \frac{1}{\pi\tau P_{\mathrm{opt}}\rho_{\mathrm{ph}} R G}, \end{aligned} \quad (9)$$

where P_{opt} is the laser power at the photodetector input, ρ_{ph} is the photodiode responsivity, R is the resistive load at the photodiode output, and G is the voltage gain of the amplifier. Since the DC voltage at the amplifier output is

$$V_{\mathrm{DC}} = \frac{1}{2} P_{\mathrm{opt}}\rho_{\mathrm{ph}} R G, \quad (10)$$

C_ν simplifies as

$$C_\nu = \frac{1}{2\pi\tau V_{\mathrm{DC}}}. \quad (11)$$

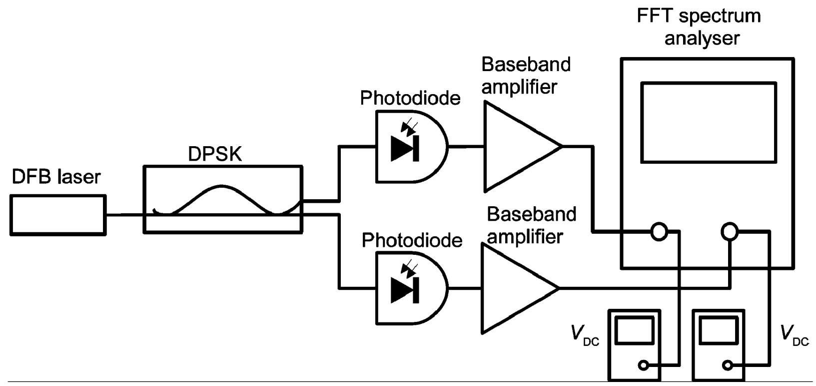

Fig. 4. Frequency noise measurement bench. The differential phase shift keying (DPSK) modulator plays the role of a frequency/amplitude converter.

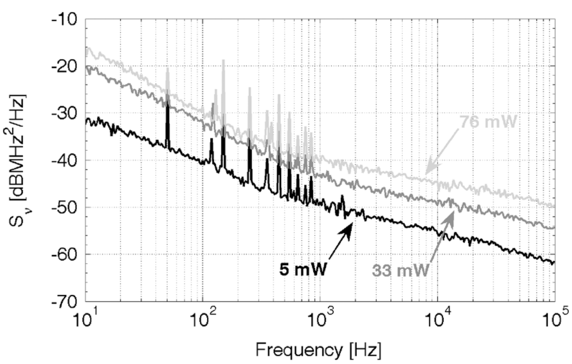

Fig. 5. Experimental measurements for the laser optical frequency noise, and for three output optical powers (5 mW, 33 mW, and 76 mW). The peaks at 50 Hz and its harmonics are induced by the power supply.

The results are shown in Fig. 5, where we can see that the laser frequency noise steadily increases with the output power. It is experimentally clear that increasing the optical power induces increased frequency instability through different types of noise. It also appears that beyond 1 kHz, the frequency noise is not directly related to RIN because the RIN decreases at higher power (see Fig. 3), while the frequency noise increases.

In time and frequency literature, the spectra are generally fitted with integer-exponent polynomials (power laws). Conversely, the spectrum of Fig. 5 has f^{-1} to $f^{-1.5}$ behavior below 1 kHz, depending on power, and $f^{-0.5}$ behavior beyond. A verification is therefore mandatory. After checking on the good practice of electronics we have only to make sure that no experimental mistake can come from the laser RIN. In fact, the scheme of Fig. 4 differs from the RIN measurement (see Fig. 2) only in the presence of the DPSK, which acts as a frequency-dependent 'power splitter' [see (7)]. The operating point, set at half-power in each output, is the same. Thus, we replace the DPSK with a 3-dB power splitter and we measured the spectrum in the same conditions. We observe that the effect of the RIN on the frequency measurement is of 30–50 dB (25 dB worst case) lower than the measured spectrum. This guarantees that the experiment is free from mistakes.

IV. Contribution of Laser Noise to Microwave Phase Noise

In classical phase noise theory, the $1/f$ phase noise of a stand-alone amplifier involved in the oscillator loop, becomes a major concern in the closed loop phase noise performance. Through the feedback mechanism of the closed loop, it is converted into a $1/f^3$ contribution to the oscillator phase noise. This can be seen from (4), and has been widely discussed in simpler terms in [5]. For this reason we chose a SiGe amplifier that exhibits a flicker of 8×10^{-13} rad^2/Hz at 1 Hz (specified as -154 dBc at 1 kHz), and a gain of 22 dB. Since the loop gain is proportional to the optical power, at low power we need two cascaded amplifiers to sustain the oscillation. The typical flicker coefficient of an InGaAs p-i-n photodetector is -120 dBrad^2/Hz [9]–[11]. General experience indicates that the other components have lower phase noise. So, we focus on the laser contribution to the phase noise. We will consider in the following the laser contribution to the phase noise of an OEO of the architecture in Fig. 1.

The optical delay line has an optical length that is defined by its physical length $L = 4$ km and its refractive index $n_g = 1.46$, which depends on optical frequency. In the classical OEO, the oscillating microwave frequency $f_0 = \omega_0/(2\pi)$ is ruled by a very sensitive in-phase condition, due to the strong phase shifting resulting from a long delay $T = n_g L/c$, and it explicitly reads $\Delta\psi = -2\pi f_0 T$. Any fluctuation of the delay is thus converted through this in-phase condition, into a microwave phase noise. The chromatic dispersion of the fiber is defined by the expression

$$D_\lambda = \frac{2\pi c}{\lambda_0^2 v_g^2}\frac{dv_g}{d\omega}, \tag{12}$$

with $D_\lambda = 17$ ps/nm/km for SMF28e fibers at 1550 nm. From the above equation, we can deduce that laser frequency fluctuations are converted into delay fluctuations according to

$$\delta T \simeq -\lambda_0^2 D_\lambda \frac{L}{c}\delta\nu. \tag{13}$$

The corresponding phase fluctuation therefore reads

$$\delta\psi = -2\pi f_0 \delta T = 2\pi f_0 \lambda_0^2 D_\lambda \frac{L}{c}\delta\nu. \tag{14}$$

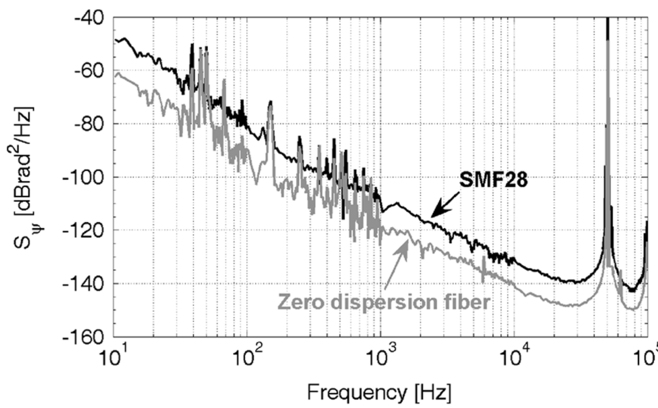

Fig. 6. The phase noise of OEO with the EM4 laser at laser power 78 mW, with a standard (black line) and zero-dispersion (grey line) optical fiber delay line. The gain of the microwave amplifier is $G = 22$ dB. The peak at 50 kHz is a typical spurious ring cavity peak.

Finally, if we consider S_ν to be the PSD of the laser frequency noise measured in Fig. 5, then its corresponding PSD phase noise contribution reads $|\tilde{\chi}_{\mathrm{fn}}|^2 = C_\psi^2 S_\nu$ with

$$C_\psi = 2\pi f_0 \lambda_0^2 D_\lambda \frac{L}{c}. \tag{15}$$

Equation (4) was used to estimate the OEO phase noise, taking into account the laser RIN at 10 GHz, its optical frequency noise, the thermal white noise, and the photodiode shot noise. Considering the above given numerical values, the laser frequency noise contribution through chromatic dispersion is found to be by 15 dB stronger than any other contribution.

The oscillator phase noise is measured with the instrument thoroughly discussed in [12]. In short, we measure the microwave frequency noise through the phase noise measurement of the oscillator output compared to a delayed (thus de-correlated) version of the same signal. The delay line is implemented with an optical fiber as in our oscillator. Correlation and averaging of the output of two equal channels reduces the instrument noise, so that the measurement is possible with the same technology used for the oscillator. The results are displayed in Fig. 6.

The most important fact of Fig. 6 is that the phase noise spectrum has the same shape of the laser frequency noise (Fig. 5), but multiplied by $1/f^2$. This is the signature of the conversion phenomenon stated by (14). This reveals that the OEO noise is limited by the laser frequency noise through the dispersion mechanism, and that a significant improvement can be obtained by stabilizing the laser or by nulling C_ψ. This can be accomplished with a zero-dispersion fiber or by compensating the dispersion with a section of negative-D_λ fiber of appropriate length. We can observe in Fig. 6 that the use of a dispersion shifted fiber globally enables a 10 dB decrease in the phase noise spectrum, thereby confirming that dispersion conversion of laser frequency noise may be strongly detrimental to phase noise performance. It is also noteworthy that the phase noise contribution of laser frequency noise is proportional to the product $D_\lambda L$ [see (15)], so that the equivalent power density contribution is proportional to $(D_\lambda L)^2$.

V. Conclusion

This article has presented a joint theoretical and experimental study of the influence of fiber induced dispersion on the phase noise of OEOs. We have found a good agreement between the main predictions of the model and the experimental results. In particular, we have explicitly calculated the conversion factor between laser frequency noise and the corresponding phase noise contribution, and it was found that the detrimental effect of wavelength fluctuations on phase noise increases with the chromatic dispersion D_λ, the length L of the fiber delay line, and the frequency f_0 of the generated microwave. On the other hand, we have also shown that low frequency laser RIN has only a minor influence on phase noise, that is typically inversely proportional to the Q-factor of the microwave RF filter.

This work suggests that wavelength-stabilized lasers should preferably be used in OEOs in order to reduce the laser frequency noise. Along the same line, the optical fiber delay lines should ideally have a (near) zero-dispersion at the operating wavelength, as this configuration eliminates a key source of phase noise for the generated microwave. Another equivalent alternative would be to use lasers whose wavelength is near the zero-dispersion point of a standard single-mode fiber (near 1300 nm). However, other effects may become predominant at zero-dispersion wavelength, particularly nonlinear effects (at high powers [13]). Future investigations will be devoted to the pathways to decrease to the theoretical limit the phase noise of this system.

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