Numerical study of a COEO device versus loop chromatic dispersion and detuning

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***Summary* — Numerical results on a COEO device providing a better understanding of its phase-noise behavior are presented. A special focus is made on the quality factor dependence on the chromatic dispersion and detuning, completing previously published models.**

Keywords— COEO; optoelectronic oscillator; microwave oscillator; mode locked laser; phase noise; optical fiber

I. INTRODUCTION

The Coupled Opto-Electronic Oscillator (COEO) is a self-sustained oscillator which enhance the quality factor of an Opto-Electronic Oscillator (OEO) through the coupling with a Mode-Locked Laser (MLL) [1]. This is a convenient way to reduce the fiber spool length of the OEO for the same quality factor, thus making a compact device. As the MLL features the highest quality factor of the two coupled oscillators, optical loop parameters can be used to optimize the RF phase noise. In this paper, we propose a numerical integration of the system partial differential equations to model the COEO device and leading to the deterministic behavior of the oscillator, including its phase noise properties, with no specific assumption on the optical pulse shape [1, 2]. The RF quality factor of the system is also simulated and a strong dependence of this parameter on the optical cavity dispersion and oscillators detuning can be observed.

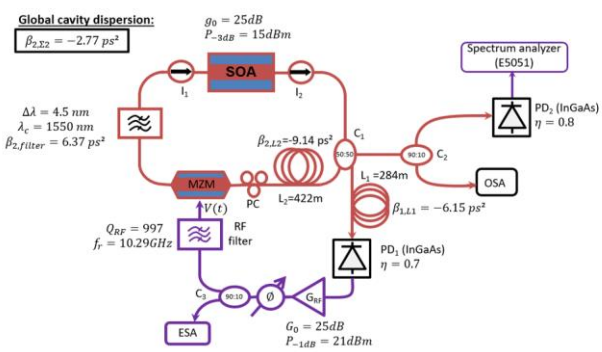

Fig. 1. COEO experimental setup. The MLL is composed of a SOA (20 dB gain), followed by a 400 m SMF28 fiber spool with 6.8 ps/m total dispersion ($\beta_2 = -0.25\ ps^2$), a Mach Zehnder Modulator (MZM) biased at $V_{\pi/2}$ and a Chirped Fiber Bragg Grating (CFBG) filter centered at 1550 nm with a -3dB bandwidth of 4.5nm and providing a chirp of -7 ps/nm. The RF feedback contains a global gain of about 35 dB and a microwave cavity centered at 10 GHz with a quality factor of 3380.

II. NUMERICAL MODEL

The COEO is modelled as a Regenerative Mode Locked Laser (RMLL) and the MLL is represented by a partial differential equation (1) taking into account the average chromatic dispersion ($\beta_{2\Sigma,2}$), the filter bandwidth (Ω_f), the self-phase modulation provided by Kerr effect (γ), the phase modulation due to the dynamic saturation of the optical amplifier (α_h) and the amplitude modulation (T_{MZM}) by which the coupling between the Opto-Electronic Oscillator (OEO) and the MLL can be obtained. This coupling also depends on the detuning (β_1) between the two oscillators. Equation (3), coupled to (1), provides the dynamic saturation of the SOA effect on the optical signal. Finally, the RF feedback (2) is stimulated by the current photogenerated which is then filtered by the dielectric resonator ($\widehat{M}_{rf}$) and amplified ($\widehat{G}_{rf}$) before being used as a parameter for the MZM modulation signal.

$$T_R \frac{\partial A(T,t)}{\partial T} = -\beta_1 \frac{\partial A}{\partial t} - \frac{i}{2}\left(\beta_{2\Sigma,2} + \frac{i}{\Omega_f^2}\right)\frac{\partial^2 A}{\partial t^2} + i\gamma|A|^2 A + \frac{1}{2}\left(g(1 - i\alpha_h) - \alpha\right)A - T_{MZM}(u_{rf})A \quad (1)$$

$$T_R \frac{\partial u_{rf}(T,t)}{\partial T} = \widehat{G}_{rf}.\widehat{M}_{rf}.i_{pd} \quad (2)$$

$$\frac{\partial g}{\partial t} = \frac{(g_0 - g)}{\tau_c} - g\frac{P_{opt}}{E_{sat}} \quad (3)$$

Regarding the noise treatment of the COEO, we consider optical white noise but also the additive phase noise of the RF amplifier (including 1/f noise) and RF thermal and shot noise sources [2,3,4]. The eigenvalues of the system formed by the small signal derivation of (1), (2), (3) provide the RF quality factor and the phase noise of the oscillator.

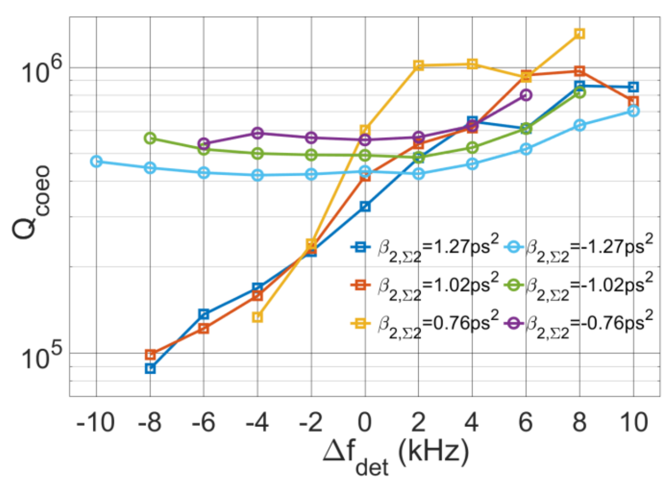

Fig. 2. COEO RF quality factor dependence on the oscillators detuning and on the optical loop total chromatic dispersion

III. NUMERICAL AND EXPERIMENTAL RESULTS

Following this formalism, simulations have been performed to investigate the impact of the chromatic dispersion and detuning on the quality factor the COEO and on its phase noise performances. The dependence of the quality factor on the chromatic dispersion is presented in Fig. 2. For each value of chromatic dispersion, an optimal detuning maximizing the Q factor can be found. This optimum is different in location and shape whether the total dispersion is positive or negative. Both parameters can be used to improve the oscillator phase noise.

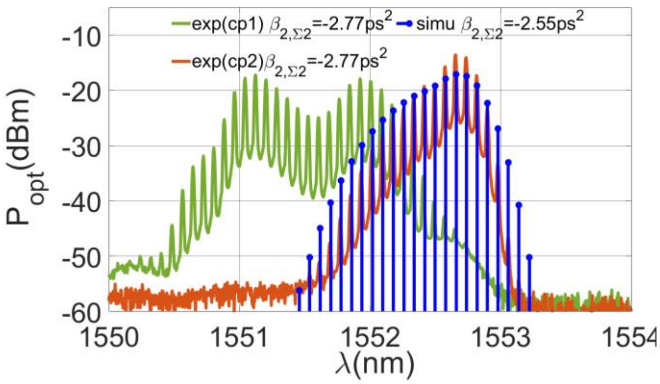

Fig. 3. Simulated optical spectrum (blue) compared to measured ones (green and red) for two different state of polarization at the polarization controller output.

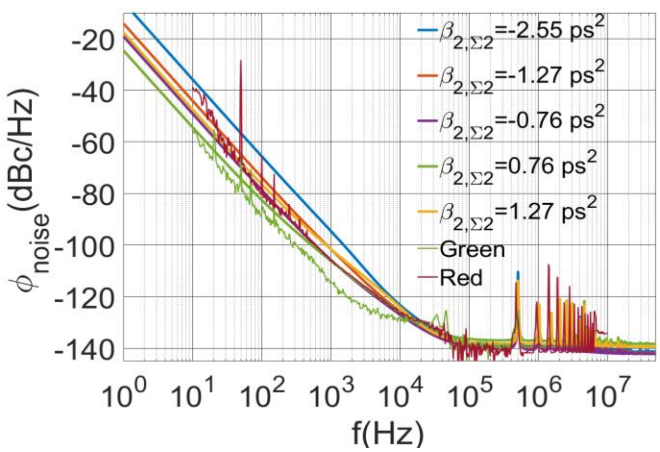

Fig. 4. Simulated phase noise for different chromatic dispersion values and a detuning of 10 kHz (full lines). Measured phase noise (green and red dotted lines) for the two optical spectra given in Fig. 3 (same colors) and an estimated chromatic dispersion of 0.25 ps^2 (-0.2ps/nm).

The optical spectrum is localized at the red border of the optical filter which provides stability to the optical spectrum. Nevertheless, the variation of the chromatic dispersion at the bandwidth border makes its value ambiguous. Simulations results indicates a global optical cavity dispersion of $\beta_{2\Sigma,2}$ =-2.55 ps² which leads to a CFBG chromatic dispersion of D = -5.17 ps/nm. This is in accordance with the measured chromatic dispersion (Fig.5) at the red spectrum location (Fig.3). By using the polarization controller inside the MLL, we are able to share the optical power between the oscillating state of polarization (in our case, a linear state aligned along the slow

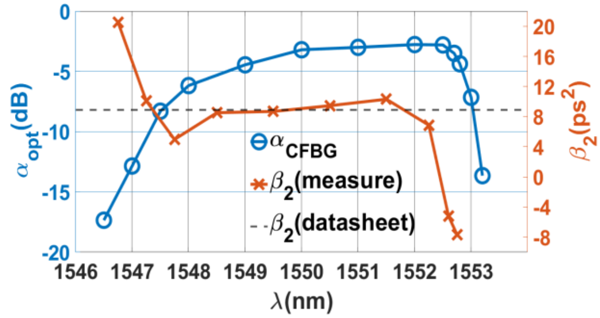

Fig. 5. Measured of the bandpass (blue) and the chromatic dispersion (orange) of the CFBG. The dotted black line indicates the datasheet chromatic dispersion value.

axis of the MLL) and the non-oscillating one. The optical losses can be slightly adjusted this way. The mechanical birefringence induced by our manual polarization controller also impose an additional delay on the slow axis, so that detuning and losses are changed. The green spectrum was obtained by adjusting the polarization controller and as a consequence those two parameters. A broader and symmetric spectrum can be recognized here characterizing a detuned MLL. The interference figure observed can be caused by the SPM provided by the SOA or by adding higher chromatic dispersion order due to the variation of the CFBG chromatic dispersion at the border. Surprisingly, this detuned configuration leads to a phase noise reduction of almost 10 dB at 100 Hz (Fig.4). Our model needs to be completed by adding higher chromatic dispersion order coefficients to adequately model this specific spectrum, of prior importance regarding the oscillator phase noise performance.

IV. CONCLUSION

We present a numerical approach for the simulation of a COEO device which provides the deterministic behavior of the COEO and its phase noise spectrum, without any initial assumption on the steady-state pulse shape. The present model has been used to investigate on the chromatic dispersion and detuning effect on the quality factor and phase noise performance of the oscillator. Numerical results are qualitatively coherent with the experimental ones and open new paths for phase noise optimization.

ACKNOWLEDGMENT

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