Study of dual-loop optoelectronic oscillators

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***Abstract*— Dual-loop optoelectronic oscillators are used to obtain high-frequency harmonic signal with a very low phase noise while maintaining very low spurs. However, the fundamental limits of these devices are not known. Therefore, it is essential to develop theoretical models to improve the performance of dual-loop optoelectronic oscillators (OEOs) and in particular the performance of the dual-injection-locked optoelectronic oscillator (DIL-OEO). In this work we use a multi-time scale approach to model dual-loop OEOs. The model enables calculating the phase noise and the spurs level for an arbitrary coupling strength between the two locked OEOs. A good quantitative agreement between theory and experiments is obtained for the DIL-OEO.**

I. Introduction

Optoelectronic oscillators are used to generate high-frequency harmonic signals with a very low phase noise [1]. Modeling optoelectronic oscillators is a challenging task since the frequency of the output signal is of the order of 10 GHz while the frequency range of the phase noise of interest is between 100 Hz to 10 KHz. However, since the bandwidth of the intracavity filter is about three orders of magnitude narrower than the carrier frequency we could efficiently applied a multiscale approach to model single-loop optoelectronic oscillators (OEOs) [2]. In our model we have calculated for each roundtrip the evolution of the phasor that represents the electrical signal. White noise was added to the signal in each roundtrip. In this work we extend our model to simulate the dual injection-locked optoelectronic oscillator (DIL-OEO). The model is especially important to analyze strongly coupled OEOs where the injected signals between the two OEOs are not small in comparison with the oscillating signal. A good quantitative agreement between theory and experiments is obtained for the phase noise spectrum and the spur level for both the slave and the master OEOs. The forward and backward injection reduces the spur level in the master OEO while maintaining a very low phase noise in the locking frequency range (below about 2 kHz) in the slave OEO.

II. Model description

In this section we shortly describe our model for studying dual-loop OEOs. The model is based on the single-loop OEO model which is described with details in [2]. We implement the dual-loop model to analyze the dual injection-locked OEO (DIL-OEO) with the configuration shown in Ref. [3] that is described schematically in Fig. 1. A long cavity OEO, called the master OEO, generates an RF signal with low phase noise. However, a long cavity implies a mode spacing that is too small for a single mode to be selected by an RF filter. Therefore, in addition to the oscillating signal strong spurs are generated in the uncoupled master OEO. In order to reduce the spur level, the master OEO is injection-locked to another short-cavity OEO, which we refer to as the slave OEO.

In our model we have calculated for each roundtrip the evolution of the phasor $V(T)$, that represents the electrical signal, where T is a time scale of the order of the OEO roundtrip. In each roundtrip we took into account the effect of all OEO components: an electro-optic modulator, a fiber delay, a photodiode, and a RF filter. Additive white Gaussian noise due to the amplifier, the detector, and the laser is included in the model and is added to the signal phasor at the input of the RF amplifier. To improve the agreement between theory and experiment, we added into the model described in [2], the gain saturation of the RF amplifiers and a flicker $1/f$ noise. In Ref. [2] the nonlinear transfer curve of the modulator determined the oscillation power. In our experiments the small signal gain of the RF amplifiers was about 60 dB while the signal gain in stationary condition was about 45 dB. Therefore, the oscillation power was determined by the gain saturation of the RF amplifiers rather by the electrooptic modulator.

Phase flicker noise is obtained near dc frequency in most electronic devices and especially in RF amplifiers. Due to nonlinearity in electronic devices, the flicker noise near dc frequencies is upconverted to the carrier frequency [4]. The phase flicker noise in our system is added by electronic amplifiers, laser, and by transmission through the optical fiber. The phase flicker is modeled in our system by multiplying the phasor of the oscillating signal by $\exp[i\theta(T)]$ at the output of the RF amplifier, where the spectral density of $\theta(T)$ is proportional to $1/f$. The flicker noise $\theta(T)$ is modeled using the method given in Ref. [5]. In another work, we have shown that in single-loop OEOs the power of the phase flicker noise depends on the loop length. Therefore, this noise source was found to limit the performance of long-cavity single-loop OEOs ($L > 4$ km) at frequencies below about 1 kHz.

We have analyzed a dual OEO with the configuration described in Ref. [3]. A long-length master OEO with a loop delay $\tau_1 = 20\ \mu$s is coupled to a short-length slave OEO with a loop delay of $\tau_2 = 2\ \mu$s. The two OEOs are locked to each other by using forward injection from the master to the slave OEO and a back injection from the slave to the master OEO.

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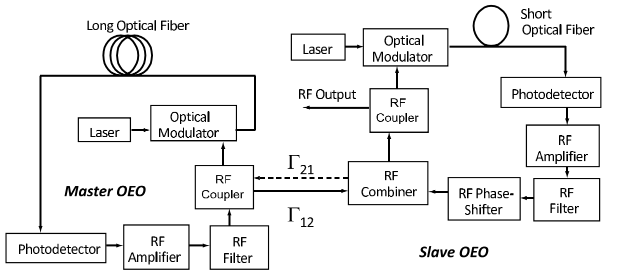

Fig. 1. Schematic description of the dual injection-locked OEO (DIL-OEO). The DIL-OEO consists of a master OEO with a long-length loop that is coupled to a slave OEO with a short-length loop. Part of the master signal, Γ_{12}, is injected into the slave OEO, as indicated schematically by the solid arrow. The dashed arrow indicates that part of the slave signal, Γ_{21}, is coupled back from the slave into the master OEO.

The coupling between the two OEOs is determined in the general case by four complex coefficients, $\gamma_{ij},\ i,j = 1,2$:

$$\begin{pmatrix} a_1^{`}(T) \\ a_2^{`}(T) \end{pmatrix} = \begin{pmatrix} \gamma_{11} & \gamma_{21} \\ \gamma_{12} & \gamma_{22} \end{pmatrix} \begin{pmatrix} a_1(T) \\ a_2(T) \end{pmatrix}. \qquad (1)$$

where $a_i(T)$ and $a_i^{`}(T)$ $(i = 1, 2)$ are the amplitudes before and after the coupling in the master $(i = 1)$ and in the slave OEO $(i = 2)$, respectively. The forward coefficient, $\Gamma_{12} = |\gamma_{12}|^2$, represents the power injection ratio from the master to the slave OEO and the backward injection coefficient, $\Gamma_{21} = |\gamma_{21}|^2$, represents the power injection ratio from the slave to the master OEO. We calculated iteratively in the master and in the slave OEO the evolution of the phasors $a_1(T)$ and $a_2(T)$, respectively, by taking into account the effect of all the cavity components.

III. Comparison between theory and experiments

In this section we present a comparison between the theoretical and the measured phase noise in DIL-OEO. First, we implemented the model to compare the results in case when the slave and the master OEOs are not locked. The total white noise were determined by fitting the theoretical and the experimental phase noise spectrum. The total white noise was equal to $\rho_{N,1} = 2.4 \cdot 10^{-20}$ W/Hz for the master OEO and to $\rho_{N,2} = 9 \cdot 10^{-21}$ W/Hz for the slave OEO. The amount of flicker noise that was used was also determined by fitting the theory with experiments. The flicker noise coefficient was equal to $b_{-1} = 10^{-11}$ rad^2/Hz for the master OEO that had a length of 4196 m, and to $b_{-1} = 10^{-12}$ rad^2/Hz for the slave OEO that had a length of 44 m. The value of the flicker noise in the slave is in consistent with the reported values in the literature for RF amplifiers [4]. However, the amount of flicker noise in the master OEO was considerably higher relative to that in the slave OEO. This result is in accordance with our previous results that showed that the amplitude of the flicker noise in a single loop OEO increases as the loop length becomes longer. The injection power coefficients were $\Gamma_{11} = -0.3$ dB, $\Gamma_{22} = -2.5$ dB, and $\Gamma_{12} = \Gamma_{21} = -20$ dB. An excellent quantitative agreement between theory and experiment was obtained for both the master and the slave OEOs in the free-running case, as shown in Fig. 2.

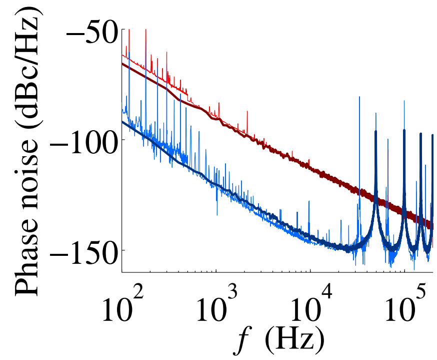

Fig. 2. Phase noise of the master OEO (blue) and the slave OEO (red) when the two OEOs are unlocked (free running case). A good agreement is achieved between the experimental results (thin lines or light colors) and the theoretical results (thick lines or dark colors). The measured data is used to extract the phase flickering noise and the white additive noise. The phase flickering noise coefficient in the slave and the master OEOs are equal to $b_{-1} = 10^{-12}$ rad^2/Hz and $b_{-1} = 10^{-11}$ rad^2/Hz, respectively.

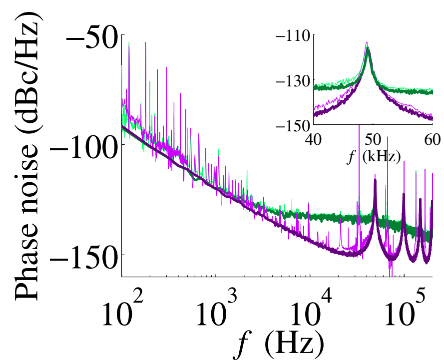

Fig. 3. Phase noise of the master OEO (magenta) and the slave OEO (green) in case when the two OEOs are injection-locked. A good agreement is achieved between the experimental results (thin lines or light colors) and the theoretical results (thick lines or dark colors). The backward and forward coupling coefficients equal -20 dB. The parameters of the two OEOs are the same as used in the uncoupled OEOs. The theoretical results show that inside the locking range the phase noise in the slave OEO becomes equal to the low phase noise of the uncoupled master OEO. The first spur level in the master OEO is decreased by about 20 dB compared to that in the unlocked master OEO.

The same loop and noise parameters that were extracted from each of the free-running OEOs were used to model DIL-OEO. A good quantitative agreement between theory and experiments was obtained for the phase noise spectrum and the spurs level in both OEOs as shown in Fig. 3. The results show that in the locking range ($f < 4$ kHz), the phase noise of the slave is approximately equal to that of the uncoupled master OEO. The coupling between the OEOs does not change significantly the phase noise of the master OEO; however it reduces the first spur level in the master OEO by more than 20 dB. The reduce in the spur level is obtained due to the enhancement of a common mode in both OEOs at the expense of other modes. The spur level is mainly determined by the phase noise of the uncoupled slave OEO and the injection parameters. Thus, it is possible to decrease the spur level in the master OEO by increasing the slave OEO loop-length and by increasing the injection power. Indeed, preliminary results show that it is possible to further decrease the first spur level of the master OEO by more than 20 dB in compare to that shown in Fig. 3, by increasing the slave loop-length by a factor of 10 and by increasing the injection power ratio to be -6 dB with respect to the oscillating signal $\Gamma_{12}/\Gamma_{22} = \Gamma_{21}/\Gamma_{11} = 0.25$. The increase in the slave OEO length and the increase in the injection ratio contribute about 10 dB each to the decrease in the spur level.

IV. Conclusion

We have presented a general model to study injected-locked OEOs. The model does not assume a weak-coupling between the two OEOs and therefore the injected signal can be of the order of the oscillating signal power. A good agreement between the model results and experiments was obtained for the phase noise, the locking range, and the spur level in a dual injection-locked OEO (DIL-OEO). The model can be used in order to improve the performance of injection-locked OEOs as well as to study physical effects obtained when coupling two oscillators.

Acknowledgment

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