Parametric Study on the Phase Noise of an Optoelectronic Oscillator Submitted to Vibrations

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***Summary*—We present our recent investigations on the acceleration sensitivity of an ultra-low phase noise single loop optoelectronic oscillator (OEO) operating at 10 GHz. The OEO components are successively placed on a shaker in order to quantify the sensitivity of each component. The optical fiber coil is the bottleneck, with a 10^{-8} g^{-1} sensitivity. The other components exhibit sensitivities lower by at least one order of magnitude. We also measured the impact of vibration on the optical intensity noise in the optical components. With these measurements, we show that vibrations affect the OEO phase noise through intensity noise degradation in the intensity modulator.**

Keywords—Optoelectronic oscillator; Relative intensity noise; Vibration sensitivity

I. Introduction

Optoelectronic oscillators (OEO) [1] are competitive alternative solutions for low phase noise high frequency references, in lieu of traditional multiplied quartz oscillators. OEOs are delay-line oscillators, taking advantage of the low propagation losses of optical fibers: the equivalent quality factor of a resonator based on a 1 km optical fiber reaches 10^5 at 10 GHz. After optimization, OEO including such typical fiber length can exhibit ultra-low phase noise power spectral density (PSD), in compact form factors [2,3].

In order to deploy these devices on the field, OEOs must face potential harsh environmental conditions, in terms of temperature and vibrations. If the temperature impact can be managed [3], the vibration issue is more complex, and the OEO phase noise can be severely affected. This phase noise under vibration is usually quantified with the so-called acceleration sensitivity [4]. Because the OEO oscillation frequency strongly depends on the fiber length, the fiber coil has drawn important attention. Different approaches have been proposed to reduce the acceleration sensitivity, through spool geometries [5] or mechanical implementation [6], fiber coating selection [7], and even active cancellation [8]. However, the impact of the other components has been treated in a more superficial way, if treated. As a consequence, no convincing hypothesis on mechanisms from vibration to phase noise degradation has been proposed yet.

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We here present an analysis on the acceleration sensitivity of the different components constituting a single loop OEO. In a first section, we describe the OEO acceleration sensitivity measurements. Although the results highlight the role of the fiber, as already discussed in other papers, the other components show very interesting performances. In a second section, we focus on the optical intensity noise degradation associated to the optical components, giving insights of the possible coupling mechanisms from vibration to phase noise degradation for such components.

II. OEO Acceleration Sensitivity

A. Setup and protocole

The OEO setup is described in Fig. 1. It is composed of a high power distributed feedback (DFB) semiconductor laser with low intensity and frequency noise, a low half-wave voltage Mach-Zehnder modulator (MZM), a 1 km standard single mode optical fiber coil, a fast and high optical power handling PIN photodiode, two low phase noise RF amplifiers, a high-Q RF bandpass filter and a 10 dB RF coupler. The optical components are fibered and connected to each other using FC/APC connectors. The OEO oscillates at 10 GHz and the typical phase noise performance at rest is plot in Fig. 2. No modulation is applied on the laser to reduce the impact of the Rayleigh backscattering occurring in the optical fiber [2,9]. The MZM is biased at quadrature, without any stabilization scheme.

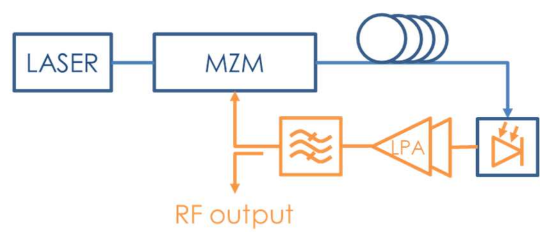

Fig. 1. OEO setup. MZM : Mach-Zehnder modulator. LPA: Low phase noise RF amplifier.

In order to conduct acceleration sensitivity measurements, we use a shaker (LabWorks ET-140) driven by an arbitrary waveform generator (Rohde & Schwarz HMF2525). The acceleration profile follows the VITA-47 class 3 standard for airborne vehicles [10]. The white noise level between 100 Hz and 1000 Hz can be as high as 0.04 g^2/Hz, corresponding to a RMS acceleration of 8 g in a [10;2000] Hz band. A typical profile is shown in see Fig. 2. Each component is successively fixed on the shaker, while the others are at rest. The vibration profile is monitored by an accelerometer placed close to the component under test (CUT), so that the vibration experienced by the CUT is as close as possible to the VITA-47 profile, without parasitic resonances related to the mechanical setup.

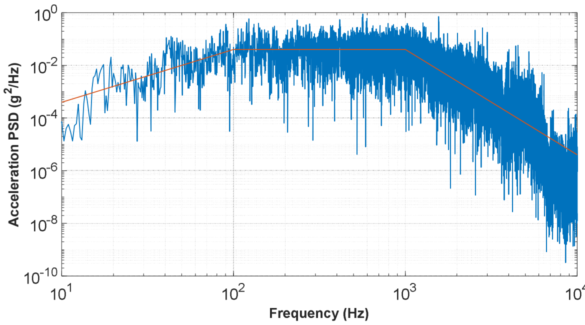

Fig. 2. Blue line : typical acceleration profile applied to the shaker. Red line : target profile.

We record the OEO output phase noise PSD and the acceleration PSD while the CUT is mechanically excited. The phase noise PSD is measured by a Rohde&Schwarz FSWP-26 signal source analyzer. We can he compute the acceleration sensitivity $\Gamma(f_v)$ of the CUT using [4]:

$$\Gamma(f_v) = \frac{f_v}{f_0}\sqrt{\frac{S_{\varphi_{OEO}}(f_v)}{A(f_v)}} \quad (1)$$

where f_v is the vibration frequency, f_0 the OEO oscillation frequency, $S_{\varphi_{OEO}}(f_v)$ the OEO phase noise PSD (in rad^2/Hz) and $A(f_v)$ is the acceleration PSD (in g^2/Hz). By definition, Γ corresponds to the relative frequency variations per acceleration unit. It equivalently represents the phase noise PSD under a given vibration profile, but not the phase noise PSD *degradation* from rest. Using (1), one can also determine the lowest acceleration sensitivity achievable using the OEO phase PSD at rest and the applied vibration profile.

B. Phase noise and acceleration sensitivy

Fig. 3 shows the phase noise PSD recorded for all the OEO components, and the acceleration sensitivities computed when the VITA-47 acceleration profile is applied by the shaker with a white noise level of 0.04 g^2/Hz. The frequency range is limited to [10;5000] Hz. Although not shown here, the computed Γ values for each component are constant with acceleration levels ranging from 0.001 to 0.04 g^2/Hz. This means that the phase noise PSD degradation scales linearly with the acceleration level.

One can see that the optical fiber is the most sensitive component to vibrations, with a Γ of 10^{-8} g^{-1}, in agreement with previously reported values [8]. The phase noise PSD degradation is as high as 70 dB at 1 kHz from rest. The other components exhibit Γ values ranging between 10^{-10} g^{-1} and 10^{-9} g^{-1}. It is also worth noting that the overall OEO acceleration sensitivity cannot be lower than few 10^{-12} g^{-1} in the [100;1000] Hz band, as shown in Fig. 2(b).

Experimentally, we noticed different biases. First, the RF cable must be correctly tightened using torque wrenches, in order to avoid large impact on the phase noise, especially at high frequencies. Second, the relative position between the accelerometer and the CUT is also important, as the CUT packaging can exhibit eigenfrequencies in the vibration band. This is for instance the case for the laser, as the acceleration sensitivity exhibits a resonance at 750 Hz, likely coming from the DFB+driver assembly. One can also observe frequency dependent acceleration sensitivities at offset frequencies below 100 Hz for some components (MZM, photodiode and RF amplifier). As, these components handle the RF signal, RF power fluctuations may be the reason, although we did not measure the AM noise. This hypothesis remains to be confirmed.

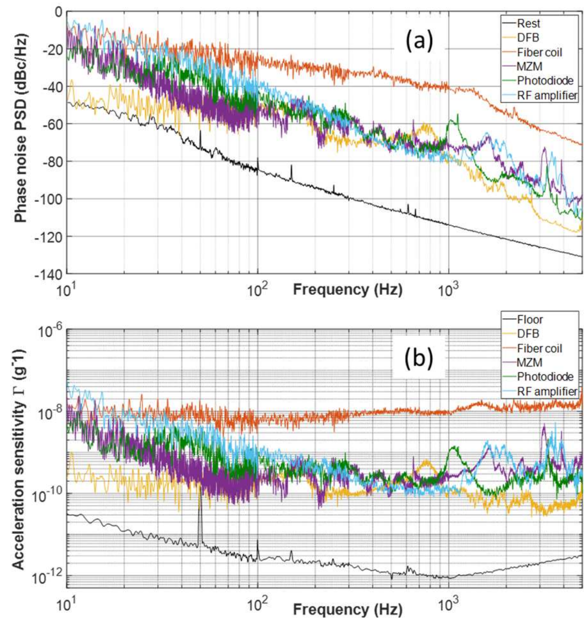

Fig. 3. OEO phase noise PSD (a) and acceleration sensitivities (b) for different components under vibrations. Yellow : DFB laser ; red : 1 km fiber coil; purple : Mach-Zehnder modulator; green : photodiode; blue : RF amplifier. The solid black line respectively corresponds to the OEO at rest (no vibration) in (a), and to the lowest acceleration sensitivity achievable given the OEO phase noise at rest and the acceleration profile in (b).

The high sensitivity of the fiber is obviously related to the long fiber length implemented in the OEO (here 1 km). Indeed, the oscillation frequency of an OEO f_0 corresponds to the resonator mode selected by the RF filter. The modes are separated by the inverse of the propagation time of the RF circulating signal, which is mainly set by the fiber length. One can consequently assume that f_0 is inversely proportional to the fiber length. Therefore, small fiber length variations induce small oscillation frequency variations. Such fiber length fluctuations are supposed to occur when the fiber is mechanically stressed by vibrations [11]. As already mentioned, Γ corresponds the relative frequency variations per acceleration unit. In the case of an OEO, it can be related to the relative fiber length variations per acceleration unit. The measured acceleration sensitivity of 10^{-8} g^{-1} leads to residual fiber length fluctuations of 10 µm/g for the 1 km fiber coil or our OEO.

III. Optical relative intensity noise

A. Setup and protocole

In an OEO, a potential contribution to RF phase noise is the baseband optical intensity noise, which is converted into phase by nonlinearities at the photodetection stage [9]. This contribution can be marginal using a laser with low relative intensity noise (RIN) and/or photodiode with low AM/PM conversion. This is the case of our setup when the OEO is at rest [2]. However, when the OEO is submitted to vibrations, this contribution may become significant. Indeed, optical components such as the DFB or the MZM include an optical waveguide whose mode is coupled to the mode of the interface fiber. Any mechanical vibration can induce small displacement between the component and the fiber, which can affect the coupling efficiency, and eventually the transmitted optical power. Such fluctuations can be considered as optical intensity noise. A possible coupling mechanism between vibrations and RF phase noise may lie in this optical intensity noise degradation. Evaluating the veracity of this coupling can be performed as follows. On the one hand, we know the OEO phase noise degradation when one optical component is submitted to vibration (from Fig. 3(a)). On the other hand, we can measure the intensity noise degradation when the same optical component is submitted to vibrations, feed a phase noise model with this equivalent RIN, and compare this simulated phase noise with the experimental trace. If the intensity noise coupling is important, the simulation should match the experimental phase noise PSD. If not, the simulated phase PSD result should be lower than the experimental phase noise PSD.

The baseband RIN measurement setup is described in Fig. 4. The MZM is biased at quadrature without stabilization scheme, and no RF signal is applied. An optical attenuator is inserted before the photodiode so that the optical power incident on the photodiode is adjusted to 15 mW. As for the acceleration sensitivity measurement, we apply a VITA-47 class 3 standard acceleration profile with the shaker. Each component is successively fixed on the shaker, while the others are at rest. The vibration profile is monitored by an accelerometer placed close to the CUT. The photodiode output is connected to the baseband input of the signal source analyzer. The recorded voltage noise PSD at the photodiode output is further converted into an equivalent RIN induced by vibrations. Results are shown in Fig. 5(a) for the maximum acceleration level (0.04 g^2/Hz). We also plot the RIN of the link at rest.

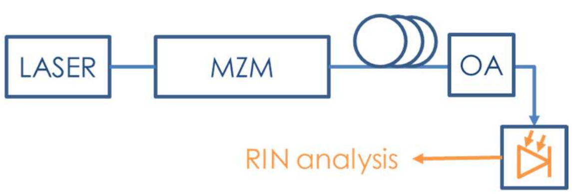

Fig. 4. RIN measurement setup. MZM : Mach-Zehnder modulator. OA: optical attenuator

These equivalent RIN spectra are further fed to a phase model of the OEO [2]. The AM/PM coupling coefficient of the photodiode has been characterized apart. Fig. 5(b) shows the comparison between the phase noise PSD from Fig. 2 (dashed lines) and the simulated OEO phase noise PSD including the degraded RIN from Fig. 5(a) (solid lines).

For the laser, one can see that the simulated phase noise is 20 dB lower than the measured phase noise. This means that the RIN degradation induced by vibrations has minor impact on the phase noise. Other coupling mechanisms should be considered. The discrepancy between simulation and measurement is even larger for the fiber (almost 60 dB). In this case, mechanical solicitations affect the fiber more in length fluctuation than in transmission fluctuation [11]. Finally, one can observe good agreement between the OEO phase noise measured when the MZM is placed on the shaker and the simulated phase noise induced by RIN degradation. This suggests that the phase noise degradation induced by the MZM likely comes from such an indirect coupling with intensity fluctuations.

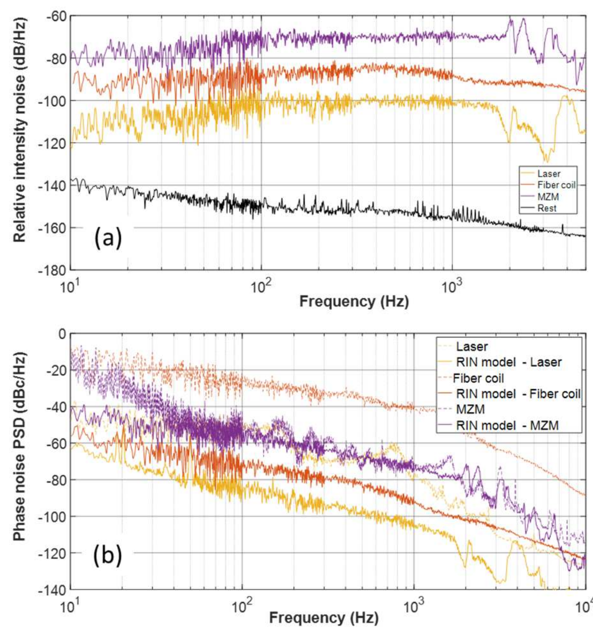

Fig. 5. (a) Equivalent baseband relative intentisy noise for different components submitted to vibrations. (b) Dashed lines : OEO phase noise PSDs for different components under vibrations. Solid lines : simulated phase noise PSDs including optical intensity noise degradation. Yellow : DFB laser; red : 1 km fiber coil; purple : Mach-Zehnder modulator. In (a) the solid black line corresponds to the optical link laser at rest (no vibration).

IV. Conclusions

We presented here our investigations on the acceleration sensitivity of an ultra-low phase noise single loop 10 GHz OEO, with a detailed analysis of the different components contribution. The fiber coil exhibits the largest sensitivity (10^{-8} g^{-1}), while the other components are less sensitive by one or two orders of magnitude. The other components exhibit sensitivities lower by at least one order of magnitude.

We also conducted experimental measurements on the intensity noise degradation when optical components are submitted to vibrations. The MZM is the most sensitive components. Simulating the OEO phase noise with this intensity noise degradation, we compared the simulated PSD with experimental phase noise PSD. We showed that the MZM under vibration affects the OEO phase noise due to this intensity noise degradation. This contribution is however marginal in the case of the DFB. Further investigations are required to identify the coupling mechanism for this device.

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