Generation of a compact oscillator using self-injected piezoelectric optomechanical crystal

Aude Martin[1], Inès Ghorbel[1,2], Maëlle Bénéfice[1], Rui Zhu[2], Sylvain Combrié[1], Rémy Braive[2,3], Alfredo De Rossi[1]

[1]*Thales Research and Technology, 1, avenue Augustin Fresnel, 91767 Palaiseau Cedex*
[2]*Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Sud, Université Paris-Saclay, C2N, 10, Boulevard Thomas Gobert, 91120 Palaiseau, France*
[3] *Université Paris Diderot, Sorbonne Paris Cité, 75207 Paris Cedex 13, France*

e-mail: aude.martin@thalesgroup.com

ABSTRACT

We report on the demonstration, in ambient atmospheric conditions, of an optomechanical oscillator made of InGaP. Self-sustained oscillations directly at 3 GHz are achieved with a low optical power of 47 muW and a linewidth narrowed down to 80 Hz. We report on injection locking experiments where the phase noise was reduced by 20 dB with 56 mV of input power. By introducing a delay, the phase noise could be also reduced by 20 dB via piezoelectric effect.

Keywords: Optomechanical oscillator, Photonic crystal cavity, Injection-locked oscillators, Phase noise

1 INTRODUCTION

Radar technologies rely on the development of ultra-stable oscillators to increase the sensitivity of detection systems. This sensitivity is linked to the phase noise of oscillators describing the spectral width of the modulated signal. A first challenge in this field lies in the direct generation of high-frequency microwave signals in the GHz domain and above, with ultralow phase noise. A second challenge lies in the implementation of miniaturized, compact, transportable and integrated oscillators, especially for potential on-board applications and on-chip signal processing.

In these applications, the frequency references are generally quartz oscillators. These provide an oscillation whose frequency can typically reach hundred megahertz with very good performance in terms of frequency stability and phase noise (-90 dBc/Hz for a carrier frequency of 100 MHz). To reach the gigahertz range, a crystal oscillator is followed by frequency multiplication steps that cause an intrinsic degradation of the noise performance of the synthesized oscillator. An alternative solution is to generate an oscillaton directly at high frequency based on optics. In fact, optics has several advantages: low transmission losses in the optical fiber, wide bandwidth of optoelectronic components, and high maturity of the components developed in the context of telecommunications. In this context, the optoelectronic oscillator was developed [1]. It relies on a long optical delay, giving high quality factors at high frequency and a phase noise of -100 dBc/Hz at 100 Hz for a carrier frequency of 10 GHz [2]. Although these types of oscillators have been integrated on-chip [3], losses limit the quality factor and strongly degrade the phase noise (-91 dBc/Hz at 1 MHz for a carrier frequency of 7 GHz). However, on-chip generation of temporal delays (up to several hundreds of ns)is required for the implementation of compact and efficient RF oscillators. Optomechanical crystals (OMC), which exploit the interaction between light and a moving cavity, and more specifically, phononic waveguides based on the slow propagation (3000m/s) of the RF signal in the acoustic domain should help build compact stable and high frequency oscillators.

2 FREE RUNNING OPTO-MECHANICAL OSCILLATOR

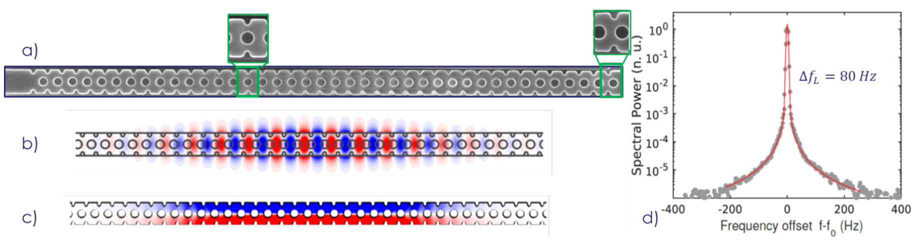

Figure 1. a) SEM picture of the fabricated structure in InGaP and modelling of the b) electromagnetic and c) displacement field of the bichromatic cavity. d) Fit of the normalized RF spectrum with the Voigt function.

The design of the one dimensional cavity (Figure 1a) is based on the concept of the bichromatic lattice [4]. It consists of a suspended beam made of GaInP, patterned with a line of holes with fixed period a and, on the sides, half-ellipses, with period $a' = 0.98a$. On one side, some holes and teeth are removed in order to couple light in the cavity and taper the loaded quality factor. This cavity sustains an optical mode (Figure 1b) and a high frequency mechanical breathing mode (Figure 1c) which are co-localized and are coupled together. The measured optical intrinsic quality factor, limited by fabrication disorder, is equal to 3.10^5 and the fundamental mechanical breathing mode ocillates at 2.93 GHz. By probing the optical resonance with a tunable laser and analyzing the light coming back from the cavity, a lecture of the mechanical movement of the cavity is achieved. Moreover, an exchange of energy between the mechanical mode and the optical mode can compensate the losses of the mechanical mode leading to self sustained oscillations [5]. To obtain a mechanical spectrum (Figure 1d), the light coming from the cavity is analyzed with a photodiode and the generated electrical signal is sent to an Electric Spectrum Analyzer. We observe self-sustained oscillations with a threashold optical on-chip power of 47 μW and a narrowing of the Lorentzian linewidth from 1.2 MHz to 80 Hz for an on-chip power of 53 μW (Figure 1d)[6].

3 INJECTION LOCKING EXPERIMENT WITH LOW AC POWER

In the following work, the design of the OMC is slightly different and inspired from [7]. Light is injected in the sample via a taper and the OMC can be actuated thanks to capacitive gold electrodes (3a). The fundamental optical mode is at 1593.12 nm and its quality factor is equal to 160 000. The mechanical mode of interest is a beam wave mode (inset of Figure 3a) which frequency is equal to 21.5 MHz. The quality factor at room temperature and atmospheric pressure is equal to 1316 ± 153 (corresponding linewidth : 15 ± 2 kHz) .

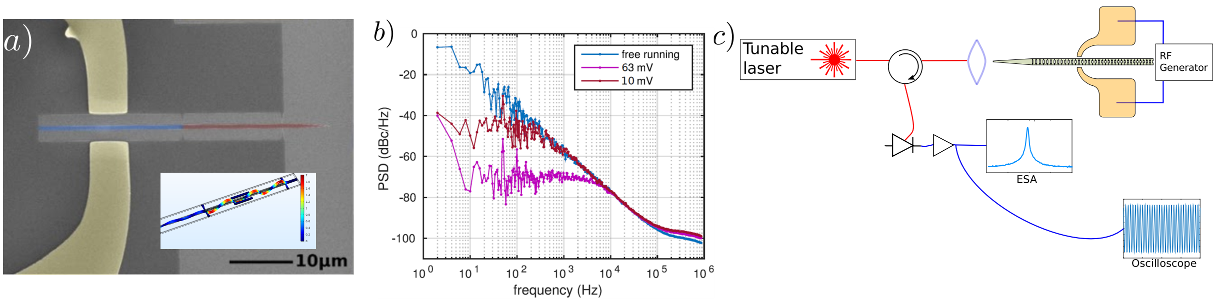

Figure 2. a) SEM image in false colors of the sample (OMC in blue, injection taper in red, gold electrodes in yellow with simulated displacement of the mode of interest with Finite Element Method implemented in Comsol (inset). b) Phase noise spectral density in a free running configuration or with injected RF signal at various input AC powers.

In the experiment shown in Figure 2c), we inject an AC voltage on the electrodes at a frequency of 21.5 MHz $\pm$ 10 kHz and analyze the short-term stability of the locked oscillator by measuring the phase noise. The phase noise is the power spectral density of the fluctuations of the phase of the RF signal. To compute it, the RF signal generated by the photodiode is transfered to the time domain with an oscilloscope and the time trace is numerically processed. In a similar experiment in [8], an improvement of the phase noise of 20 dB was obtained for a DC voltage of 50V and an AC voltage of 400 mV generated by a RF generator. Here, for a frequency offset ranging between -5 kHz and 5 kHz, the OMC is locked to the RF trigger and the mechanical frequency is tuned over 10 kHz. In this region, the phase noise is also locked to the phase noise of the RF generator and experiences an improvement of 20 dB with 53 mV and no DC input.

4 STABILIZATION OF THE OSCILLATION USING A FEEDBACK LOOP

The set-up used here is shown in Figure 3b). The back reflected light from this sample is injected into a fiber delay line of a few kilometers. The signal detected by the photodiode (PD) is injected on the electrodes to provide a feedback on the OMC. A feedback loop on a free running optomechanical oscillator was already proposed in the literature [9]. Here, we introduce a fiber delay which acts as a filter and decreases noise in the oscillator. The phase noise (Figure 3c) is measured and experiences an improvement of 20 dBc/Hz at 1kHz as the delay in the loop is increased compared to the case where there is no fiber delay in the feedback loop.

5 CONCLUSION

In this work, we have proposed a new design for optomechanical crystals and shown that this device can go into mechanical self-sustained oscillations. We have also achieved locking of an optomechanical oscillator to an external RF generator via the piezoelectric effect. Finally, we made a feedback loop on an optomechanical oscillator including a fiber delay and shown that a decrease of the phase noise of 20dB was possible. Future work is aimed at repeating this feedback loop experiment in the GHz range, integrating the delay thanks to a phononic waveguide and synchornizing several oscillators.

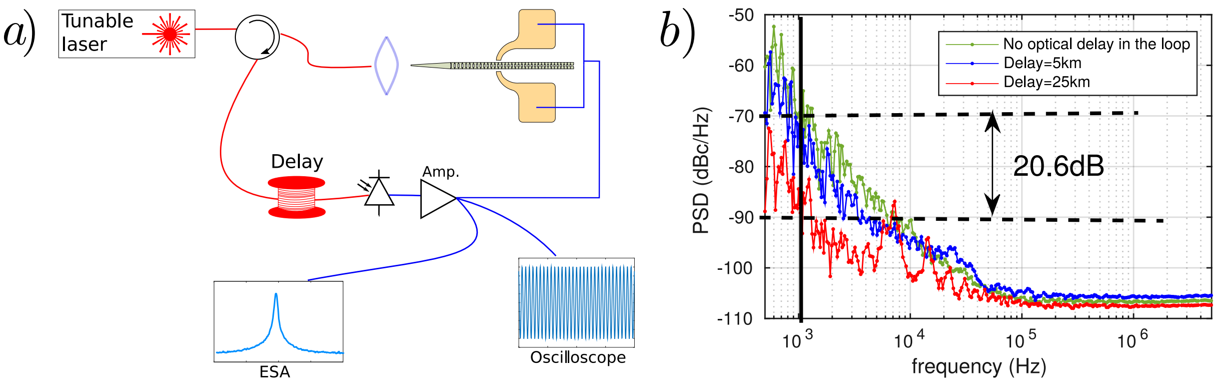

Figure 3. a) Set-up b) Phase noise measurements for different delay lengths.

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