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Optomechanical microwave oscillators

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Abstract
Optomechanical interaction in optical dielectric cavities can be used to generate high-purity microwave tones, giving rise to optomechanical microwave oscillators. Here, we introduce the main properties of these devices, which can be implemented in photonic integrated chips, and envisage its deployment in the mid-term in microwave photonics applications.

Key terms
Cavity optomechanics; Microwave photonics; Microwave oscillators; Silicon photonics

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1. Introduction

Microwave oscillators displaying high-spectral purity as well as long-term stability are key building blocks in a number of applications, including radar, wireless networks, or satellite communications. Typically, low-noise microwave oscillators are built by applying frequency multiplication to an electronic source. This requires a cascade of frequency-doubling stages, which introduces noise and reduces the signal power at each multiplication stage. Recently, several techniques to produce microwave tones using optical technology have been proposed. The resulting device is termed an optoelectronic oscillator (OEO) [1, 2]. In an OEO, a pure microwave tone is overimposed on an optical carrier so that, after photodetection, we get a microwave tone, which can be further amplified to attain the desired signal level. An OEO has multiple advantages with respect to its electronic counterparts, such as immunity to electromagnetic interference, low weight, compactness, long-distance transport, and extremely-low noise.

First realizations of OEOs included long paths of optical fiber as a feedback mechanism to achieve oscillation. This resulted in bulky, heavy devices, not appropriate in applications requiring compactness and low-weight. An interesting alternative to generate microwave tones optically is via mechanical waves coexisting and interacting with optical waves in dielectric cavities. This approach would allow for extreme miniaturization of the OEO, since the wavelength of mechanical waves in solids is about five orders of magnitude smaller than in their electromagnetic counterparts.

2. Microwave oscillators from optomechanical interaction

The interaction between optical and mechanical waves in cavities, arising mainly from electrostriction and radiation pressure effects, is addressed by the field known as cavity optomechanics [3, 4]. When an optomechanical (OM) cavity - supporting an optical resonance at ω_o and a mechanical resonance at Ω_m - is driven by a blue-detuned laser (with frequency $\omega_L > \omega_o$) it can reach a regime characterized by self-sustained oscillations and usually termed phonon lasing, arising from dynamical back-action in the cavity [2, 4, 5]. In this regime, the cavity behaves as OM microwave oscillator (OMO) since at the output the optical laser signal is modulated by an ultranarrow tone at a frequency Ω_m (Fig. 1). In comparison with optical fiber schemes, no feedback loop is required since the gain is provided by the OM cavity itself.

First demonstrations of OMOs were performed using high-Q travelling-wave optical resonators (a silica microtoroid [7] or a suspended silicon nitride ring [8]) with radii of tens of microns, mechanical frequencies of tens of MHz and phase noise values as low as -120 dBc/Hz at a 100 KHz offset. OMOs in such resonators were also implemented separating the optical and mechanical oscillator, which was driven by electrical means instead of by a blue-detuned laser [9]. This approach, which is amenable for fabrication using standard silicon MEMS technology, was used to demonstrate a 2 GHz OMO with a phase noise $\approx -100 dBc/Hz$ at 100 kHz [10].

Reaching microwave frequencies requires further miniaturization of the OM cavity down to wavelength-scale sizes

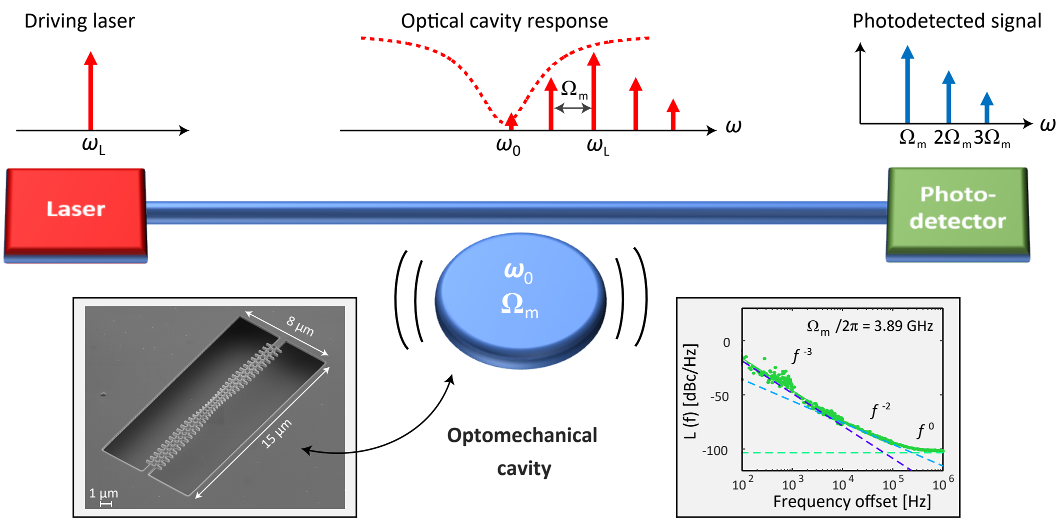

Figure 1: Conceptual scheme of an OMO. A laser, which generates coherent light at ω_L, drives an OM cavity to the phonon lasing regime, which modulates the light exiting the cavity with tones at frequencies $\omega_L \pm m \times \Omega_m$. Upon photodetection, a low-noise signal at Ω_m, as well as at integer multiples of it, is obtained. Left-side inset: scanning electron image of the silicon OM crystal cavity used in [13]. Right-side inset: phase noise of the cavity in [13] operating as an on-chip OMO. Green dots correspond to experimental data and dashed lines to fits to the different expected noise contributions: flicker white phase noise in light-green (f^0), random walk of phase in light-blue (f^{-2}) and flicker frequency noise in dark-blue (f^{-3}).

for both optical and mechanical waves. This can be achieved using the so-called OM crystals [5], which are artificial crystals tailored with periodic lattices which exhibit photonic and phononic forbidden bands [11]. As a result, optical and mechanical waves can be strongly localized in point-like defects which sizes around half a wavelength, which usually results in mechanical resonances of several GHz for optical resonances in the telecom band. Recently, demonstrations of GHz-scale OMOs implemented in OM crystal cavities in released semiconductor films have been reported [12, 13]. Whilst in [12] a InGaP OMO at $\Omega_m/2\pi \approx 3$ GHz is demonstrated to operate under very low input powers (< 0.1 mW), in [13] a silicon OMO operating at $\Omega_m/2\pi \approx 4$ GHz is shown to reach phase noise values below -100 dBc/Hz at 100 kHz. The phase noise may be further improved if operating at low temperatures as a result of the increase of the mechanical Q factor of the cavity by eliminating material absorption of phonons.

Two-dimensional OM crystal cavities have pushed mechanical resonances up at frequencies around 10 GHz [14], thus reaching the technologically relevant X band. However, achieving even higher frequencies seems challenging using OM crystal cavities. One possible choice to go beyond 10 GHz is to use higher-order harmonics, which arise naturally due to the nonlinear response of the cavity (as long as its optical linewidth is broad enough) in the form of OM combs [15] (see Fig. 1). This would also open the door to the synthesis of complex microwave waveforms, beyond simple high-purity tones. For instance, using the 6th harmonic of the OMO reported in [13], microwave tones above 20 GHz have been observed. However, the harmonic mixing process in OM cavities results in an added phase noise of $20 \times \log(m)$ for the m-th harmonic, which seriously impairs the purity of the generated tone. This impairment can be suppressed in travelling-wave OM systems displaying Brillouin gain, where the mechanical dissipation is larger than the optical dissipation. In this case, cascaded Brillouin lasing becomes feasible, getting multiple harmonics of the Brillouin resonance [16]. This results in a spectral purification of the driving laser, leading to highly-coherent microwave signals at the output. This approach was used in [17] to synthesize a 21 GHz microwave tone (third harmonic of the mechanical resonance) with a phase noise of –110 dBc/Hz at 100 kHz in a high-Q silica wedge cavity.

3. Vision and conclusion

Although OM cavities display remarkable features to be used as OMOs, this is still a nascent field with a lot of room for further progress. For instance, other photonic integrated approaches such as Kerr-induced combs in silicon nitride rings can get phase noise values around -140 dBc/Hz at 100 kHz for a 14 GHz tone [18], which is smaller than the values reported in OMOs so far [12, 13]. However, recent experiments suggest that the phase noise can be well improved in OMOs, for example by locking the cavity to an external radiofrecuency source that modulates the laser [19]. Moreover, the demonstration of multimode phonon lasing phase-locked to a low-frequency radiofrequency signal not only shows how to improve the long-term stability of the OMO but also enables the generation of multitone microwave signals in a single cavity [20]. Other benefits of OMOs in comparison with combs in integrated ring resonators would be a much smaller foot-print and a higher output power of the microwave signal. The latter can be attained using a cavity with a linewidth approaching Ω_m so that a single harmonic of the mechanical resonance carries all the power.

Importantly, OMOs can be implemented on-chip using different technological platforms. The use of III/V semiconductors allows to tune the electronic bandgap so that two-photon absorption inside the cavity is avoided and more optical power can be handled [12]. In contrast, implementation in silicon-on-insulator wafers allows for large-volume fabrication at low-cost by using CMOS processes [21], as well as coexistence with other photonic, electronic or MEMS components on a chip. With all these features, we can envision the use of on-chip OMOs for different applications in microwave photonics, in particular in environments requiring low weight and small energy consumption, such as in aircraft and satellite communications.

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