Towards Fully Integrated Optomechanical Clock

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***Abstract*—This report summarizes the research project supported by MTT-S Fellowship, focusing on the integration optomechanical resonator with standard CMOS fabrication process flow and its application in photonic microwave information processing, for example, high quality frequency references, frequency mixer and up/down converter. We also provide a brief perspective on potential directions in this newly emerged research field.**

***Index Terms*—optomechanics, frequency reference, photonic microwave information processing**

I. Introduction

HIGH-quality frequency references are the cornerstones in position, navigation and timing applications of both scientific and commercial domains. Optomechanical oscillators, with direct coupling to continuous-wave light and non-material-limited f*Q product, are long regarded as a potential platform for frequency reference in radio-frequency-photonic architectures. The direct coupling between continuous (CW) laser field and the mechanical oscillation allows us to use CW laser as both pumping source and signal probe. However, one major challenge is the compatibility with standard CMOS fabrication processes while maintaining optomechanical high quality performance. With part of the support from MTT-S Fellowship, we demonstrate the monolithic integration of photonic crystal optomechanical oscillators and on-chip high speed Ge detectors based on the silicon CMOS platform.

II. Summary of Main Results

We demonstrated for the first time the integration of mechanical RF oscillator of typical oscillation frequency ~100 MHz with high speed detector of typical bandwidth ~12 GHz on a monolithic silicon chip, using standard CMOS fabrication process flow. This integration is nontrivial as it requires both high quality of mechanical and optical cavity, together with some other metallization process for Ge detector. The latter is notoriously difficult as the optical quality of photonic crystal cavity is quite sensitive to the deviation from design. By carefully design fabrication process and rigorously model the etching process, we successfully fabricate optical cavities with quality factor ~70k. This allows us to drive the mechanical resonator into self-oscillation with a low threshold laser input power (~270 μW). The typical linewidth we measured is ~100 Hz. We also characterize our mechanical oscillator properties as a frequency reference, namely, we measured our oscillator's phase noise performance, the most important parameter for any frequency reference. We measured a free running phase noise level about -100 dBc/Hz which is only 20 dB higher than the best commercial silicon oscillator at same frequency. Note that our device operates at room temperature and in air. Most phase noise come from slow environmental fluctuations. We can introduce a clean master oscillator to inject locking our optomechanical oscillator. By doing this, we demonstrated about 20 dB reduction in phase noise near the carrier frequency.

With large mechanical oscillation amplitude, the variance in optical field due to moving boundary will not exactly follow the mechanical harmonic oscillation. Instead, it will follow the nonlinear Lorenztian shape of an optical cavity. This nonlinear transduction allows the generation of rich high order harmonics. In experiment, with 400 μW laser input power, we observed the generation of high order harmonics up to 7 GHz. This can be used to up convert source frequency to high order harmonics.

With high optical quality, we also observed rich nonlinear optical effects such as self-pulsation, which is generated by periodically shift in resonance frequency due to the completion of thermal effect and free carrier effect. However, the frequency of this nonlinear optical oscillation is typically low (~10 MHz) and the quality is low due to the thermal temperature fluctuations in this system. However, with high quality mechanical oscillation integrated with the optical cavity, we observed the automatically injection locking of these two oscillations. This allows us to down covert our mechanical frequency into its subharmonics. Experimentally, we observed the generation of from 1/5 to 1/2 subharmonics. As the frequency divided down, we also observed the reduction in phase noise.

III. Perspective

The integration of RF optomechanical resonator with a high speed detector is the first step towards functional microwave information processing device based on photonics. In the next step, there are several potential directions we are currently investigating.

First, we can further increase our frequency to GHz regime.

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This should be very promising as the LC circuit silicon oscillators current commercial available are all below 1 GHz due to the difficulty in reducing the size of inductance. Using optomechanical crystal, we already experimentally observed mechanical resonator with fundamental frequency ~ 6 GHz and drive it into self-oscillation (with linewidth ~ 1 kHz). Also, there are already some other techniques, such as Brillouin scattering of light and acoustic wave in a cavity which can generate frequencies up to 30 GHz.

Second, the narrow linewidth of a mechanical oscillator can be used as an ultranarrow band frequency filter if we use techniques like wavelength conversion in optomechanics. It can also works as a microwave amplifier or attenuator with possibility to close quantum limit. The optomechanical resonator can be scaled up by introducing photonic/phononic waveguide and forming a network. This will allow us to design different types of mechanical filters.

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References

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