TuB5 (Contributed Oral)
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# Wafer-scale silica optomechanical oscillators with low threshold power and low phase noise for monolithic optical frequency references

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**ABSTRACT:** We present wafer-scale processed optomechanical oscillators with low threshold power (<120μW) owing to high $Q_{optical}$=5.3M, with phase noise of -110dBc/Hz (10kHz offset, 18.6MHz carrier). Phase noise is modeled, and measured vs. $Q_{optical}$ and $Q_{mechanical}$.

## INTRODUCTION

Optomechanical devices utilize radiation pressure inherent in photons to generate, or sense mechanical motion. Some applications include quantum limited displacement measurement [1], mechanical memory [2], and, the focus of this work, optomechanical oscillators (OMO) [3]. An OMO relies on light pressure to offset the intrinsic damping of a mechanical resonator mode and force it into regenerative oscillations. We aim to create an OMO for a low threshold, low noise, GHz monolithic frequency reference with optical carrier.

The importance of phase noise for OMOs as frequency references has spawned prior work that fitted the phase noise spectrum to Leeson's model [4], and demonstrated a zero flicker noise OMO [5]. This work demonstrates low phase noise OMO for carrier offsets > 1kHz and shows that a 2.5 times increase in mechanical quality factor improves phase noise by 20dBc/Hz in agreement with our model.

This work employs a novel wafer-scale annealing process that achieves spoke supported rings [6] with high intrinsic optical quality factors, $Q_o$ in excess of 5 million. With $Q_o$'s of this size, we attain low threshold power and observe phase noise degradation at high offsets but leveling of the spectrum at intermediate offsets. The fabrication process permits integration with on-chip grating couplers providing a scalable platform for high performance OMO's [7].

## FABRICATION PROCESS

The fabrication begins with an LPCVD deposition of 2μm phosphosilicate glass (PSG) on a silicon wafer. The PSG is then patterned, etched and reflowed in a furnace to minimize surface roughness. A timed release removes the silicon underneath except at anchors [7].

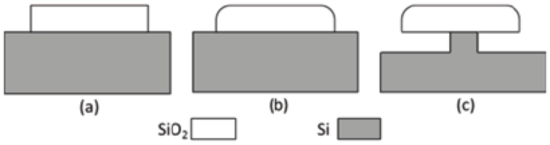

Figure 1: Fabrication process: (a) Patterning and RIE device etch. (b) PSG reflow in furnace, 2 hours at 1100°C. (c) Release in $XeF_2$.

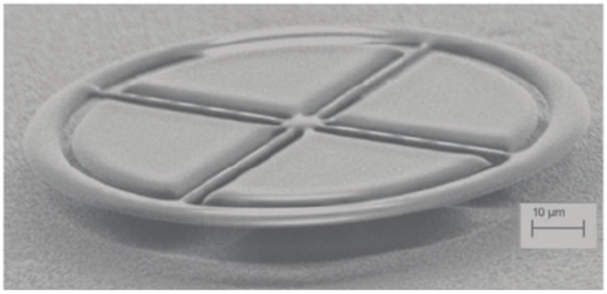

Figure 2: SEM image of a fabricated 52μm radius spoke-supported ring resonator OMO. The optical whispering gallery mode circulates along the ring periphery.

## PHASE NOISE MODEL

To predict phase noise in OMOs, the small signal model from [8] is utilized to find the noise spectrum in the output optical field amplitude, $\delta s_{out}(\Omega)$. Imprinted on $\delta s_{out}(\Omega)$ is noise in the radial displacement of the ring assumed to be dominated by thermal Brownian motion [9]. The output RF noise power after photodetection is $P_{noise}(\Omega) = I^2R \propto |\bar{s}^*_{out}\delta s_{out} + \bar{s}_{out}\delta s^*_{out}|^2$ where $\bar{s}_{out}$ is the mean output field amplitude. The measured phase noise spectrum is then [10]:

$$L(f') = 10Log_{10}\left(\frac{1}{2}\cdot\frac{P_{noise}(f')}{\Delta f \cdot P_{osc}}\right) \quad (1)$$

where $f'$ is the frequency offset from resonance, $P_{osc}$ the oscillating power, and $\Delta f$ the noise bandwidth.

## PHASE NOISE MEASUREMENT

In order to characterize our OMOs, light from a tunable laser is launched into a piezo-controlled tapered microfiber and evanescently coupled into the spoke supported optomechanical ring resonator. The first mechanical contour mode occurring at 18.6MHz for a 52μm radius is the focus here. We have measured self-oscillation up to $\Omega_m$=72MHz for 15μm OMOs [7].

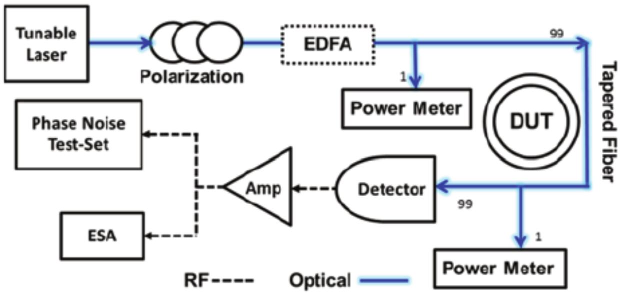

Figure 3: Characterization setup. EDFA=Erbium Doped Fiber Amplifier (only used for high threshold devices). ESA=Electrical Spectrum Analyzer. DUT=Device Under Test. Phase Noise Test Set: Agilent E5500 Phase Noise Measurement System.

Figure 4 shows data from a low phase noise 18.6MHz carrier OMO (-110dBc/Hz at 10kHz offset) fitted with the aforementioned small signal model. Nearly ideal behavior is exhibited for $f'$ >10kHz. At lower frequencies, *1/f* noise sources dominate, which appears as a $1/f^3$ dependence in the measured spectrum.

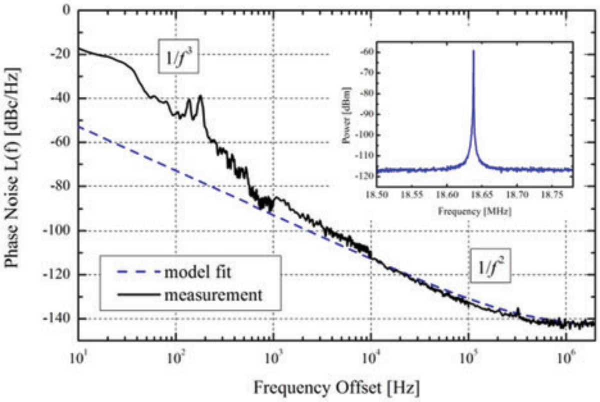

Figure 4: First contour mode phase noise spectrum. $\Omega_m$ =18.6MHz, $Q_o$=520k and $Q_m$=1160. Inset: RF spectrum of measured resonance.

## OPTICAL QUALITY FACTOR

To study phase noise dependence on $Q_o$, three resonances within a free spectral range of the same resonator were measured. Each optical mode circulates at a slightly different radial location on the ring interacting differently with the sloped edges and thus has a different $Q_o$. This method ensures, that the mechanical quality factor, $Q_m$ is conserved.

Our measurements (Figure 5) show, that a higher optical quality factor has an adverse effect on phase noise for $f' > 10kHz$. For 1kHz< $f'$ <30kHz, high $Q_o$ resonances have a slope less than 20dBc/decade. The $Q_o$=5.3 million resonance exhibits leveling of the slope at 20kHz. *1/f* noise is not observed for the $Q_o$=5.3 million resonance, even down to a 10Hz offset.

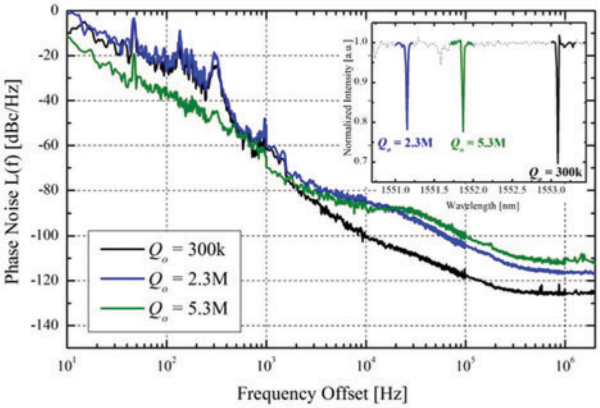

Figure 5: Phase noise for three optical resonances showing, that high $Q_o$ increases phase noise at $f'$>10kHz. Inset: Optical spectra of measured resonances.

The threshold laser power to induce self-oscillation in the unresolved sideband regime varies as $Q_o^{-3}$. For our optical quality factor of 5.3 million we have measured $P_{thresh}$=120$\mu W$.

## MECHANICAL QUALITY FACTOR

In order to investigate the dependence of phase noise on $Q_m$, we deliberately reduced the mechanical quality factor by placing epoxy on one of the spoke supports. This left $Q_o$ unchanged, but $Q_m$ degraded from 1160 to 440. This reduction of 2.5 times in $Q_m$ caused 20dBc/Hz degradation in phase noise at 100kHz offset matching our model expectations. Additionally, since the threshold power scales with $Q_m^{-1}$, we conclude, that realizing low threshold *and* low phase noise OMOs requires high $Q_m$.

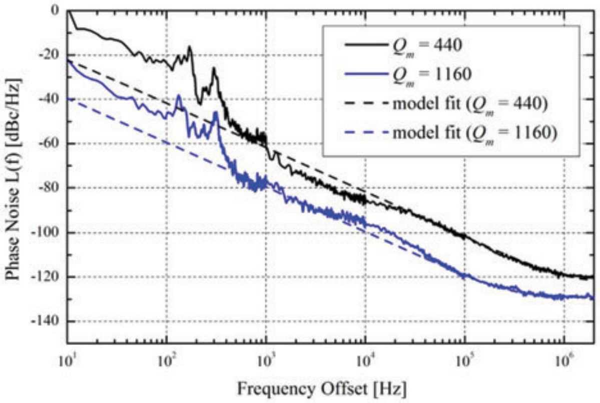

Figure 6: Phase noise measurements of the same OMO, with two different mechanical quality factors. A 2.5 times increase in $Q_m$ shows a 20dBc/Hz improvement in phase noise at 100kHz offset.

## CONCLUSION

Optomechanical oscillators with high $Q_o$ (up to 5.3 million) and low phase noise have been fabricated using a silica based wafer-scale fabrication process. For higher $Q_o$, phase noise was observed to degrade for $f'$>10kHz. An increase of 2.5 times in $Q_m$ was observed to improve phase noise up to 20dBc/Hz at 100kHz offset in agreement with our phase noise model.

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