1.12GHZ OPTO-ACOUSTIC OSCILLATOR

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ABSTRACT

We report on the development of a GHz Opto-Acoustic Oscillator (OAO) using an air gap capacitively actuated silicon optomechanical resonator. An optical sensing technique using optomechanical ring resonators in silicon allows for observation of the mechanical resonances of electrostatically excited resonators up to 3.5GHz. Using amplifiers to compensate for losses, we demonstrate an oscillator operating at 1.12GHz with 8.8dBm output RF power and a phase noise of -85 dBc/Hz at 10 kHz offset.

INTRODUCTION

Oscillators based on electrostatically actuated MEMS resonators have been demonstrated in the few MHz range [1,2]. These oscillators offer phase noise performance comparable to quartz oscillators while reducing size and allowing for easier integration with circuits. Direct conversion radio architectures require oscillators to operate at higher frequencies with good phase noise performance. To meet these requirements there is a need for high frequency resonators with high quality factors (Q). MEMS resonators up to a few GHz have been demonstrated in silicon with very high quality factors close to the f-Q product of silicon [3,4] using electrostatic transduction. However, at high frequencies, the motional impedance of electrostatically transduced resonators is very large. This makes it harder to sense the mechanical resonance and to provide enough gain to close the loop to obtain an oscillator.

In previous work, we have demonstrated an alternate displacement measurement technique for electrostatically actuated mechanical resonators using optical sensing. The optical displacement sensing was demonstrated at a frequency of 236MHz using coupled disk geometry [5]. The structure was fabricated on 220nm thick silicon device layer of 3µm thick buried oxide silicon on insulator wafer. The radial vibrational modes of one of the disk is excited using electrodes spaced 150nm from the resonators. These vibrations couple to the second optomechanical resonator which supports both optical and mechanical modes. When the optomehcanical resonator is interrogated using waveguides, the light at the output of the waveguides show modulation at the mechanical frequencies due to the excited vibrations. The depth of the optical modulation is proportional to the amplitude of radial displacement in the optomechanical resonator. This technique allows for the detection of displacement amplitudes much smaller than that observable with typical air gap electrostatic sensing.

The electrostatically actuated optomechanical resonator combines the frequency filtering response of a mechanical resonator with the optical amplitude modulation obtained from an optical modulator thereby creating an integrated narrowband optical modulator. One application of such a narrow band optical modulator is in the opto-electronic oscillator (OEO), which is the current state-of-art oscillator in the few GHz regimes that uses optical feedback in the oscillation loop [6]. To convert the narrow band optical modulator into an oscillator, the optical output from the modulator is converted back to the electrical domain using a high speed optical detector. The electrical signal from the detector is then amplified and fed back into the modulator along with an appropriate phase shift. Employing this technique, an opto-acoustic oscillator (OAO) has been previously demonstrated at the mechanical frequency of 236MHz [7].

Traditional quartz oscillators offer very good phase noise performance albeit at relatively low frequencies of a few MHz. For practical applications, higher frequencies in the GHz range are required and this is obtained by multiplying the oscillator output. This multiplication degrades the phase noise at the required frequency. A potential advantage of using micromechanical resonators, on the other hand, is the promise of directly obtaining high quality factor resonators and oscillators at the required higher frequency of operation. This paper studies two approaches for scaling the previously demonstrated opto-acoustic oscillator to the GHz range. The first approach is to scale the frequency of the fundamental radial mode of the disk by scaling the radius of the disks to smaller dimensions. The second approach considered is the use of alternate resonator geometry such as ring resonators.

SCALING RESONATORS TO HIGHER FREQUENCIES

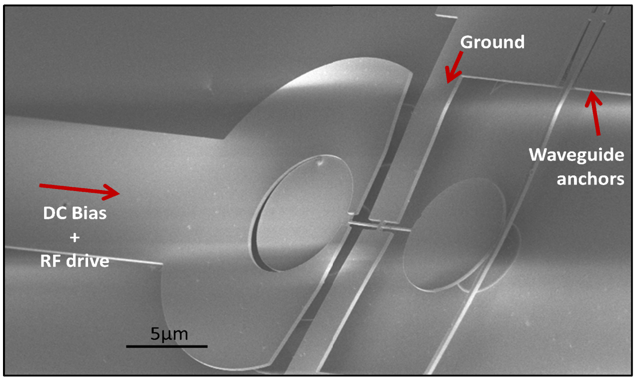

Figure 1. SEM image of disk based optical modulator fabricated on 220nm thick Si on 3µm thick buried oxide SOI wafer. The electrodes are spaced 150nm away from the 3.8 µm radius resonators.

Disk Resonator based modulator

To obtain higher mechanical frequencies close to a GHz, the disk resonators are scaled to a smaller radius of 3.8µm compared to the 10 µm radius used for the 236MHz

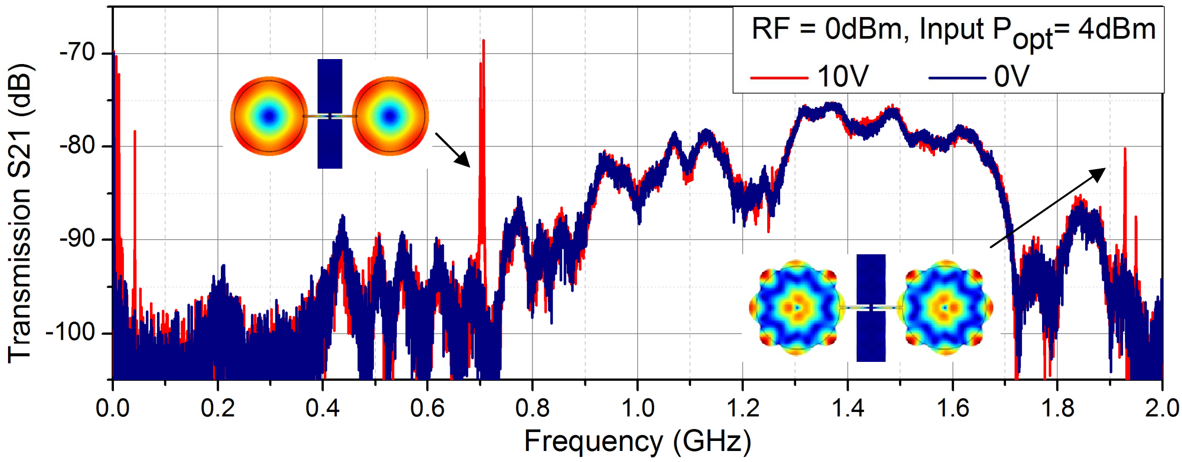

Figure 2. Transmission of 3.8µm radius disk based optical modulator measured on the network analyzer for RF input power of 0 dBm for DC bias of 0 V (blue) and 10V (red). (inset) Fundamental radial mode shape at 706MHz and the second order radial mode at 1.93GHz.

demonstration. Figure 1 shows a Scanning Electron Microscope (SEM) image of the smaller disk based optical modulator.

The vibrational motion in the mechanical resonator is driven by the air gap capacitive actuators surrounding the disk and the optomechanical disk resonator converts these vibrations to an optical intensity modulation at the output of the waveguide. In order to reduce anchor loss and obtain high mechanical quality factors, a balanced anchor scheme is used [8]. In this scheme, the anchor is connected at the nodal point of the coupling beam. On observing the optical transmission spectrum through the waveguides, an optical resonance with an optical quality factor of 5,500 is obtained. Light from a tunable laser with wavelength corresponding to the half maximum point of the optical resonance is input to the waveguide to measure the electro optic response. The light at the output of the waveguide is sent to a photodiode whose electrical output is connected to port 2 of a network analyzer. RF output from port 1 along with a DC bias is applied to the electrodes surrounding the mechanical resonator. The electro optic response (Figure 2) measured as the transmission spectrum (S21) on the network analyzer shows the fundamental mode at a frequency of 706MHz with a mechanical quality factor in air of 2,600 and the second order radial mode at 1.93GHz. The insertion losses obtained are too high to obtain an oscillator by closing the loop. The high insertion loss is due to two reasons, the first being small capacitive actuator area of the small disk. The mechanical force applied by the electrostatic actuator for a given potential is proportional to the capacitor area. This implies that a smaller area corresponds to smaller displacement amplitude. The second factor is reduced displacement sensitivity due to low optical quality factor of 5,500. The low optical quality factor can be attributed to increased optical radiation losses as the light travels around the smaller optomechanical disk resonator. Additionally, the coupling beam width between the resonators is comparable to the disk dimensions and has an adverse effect on the optical mode quality factor.

Ring Resonator Based Modulator

An alternate scheme for obtaining high frequency resonators without reducing the size of resonators is to use higher order mode ring resonators. The second order radial mode of a ring resonator is set mainly by the width of the ring with little dependence on the radius of the ring. This allows access to GHz frequencies using the second order modes without a need for scaling the radius. A SEM image of the ring resonator modulator structure is shown in figure 3. The inner radius of the ring resonator is 5.7µm and the width of the ring is 3.8µm.

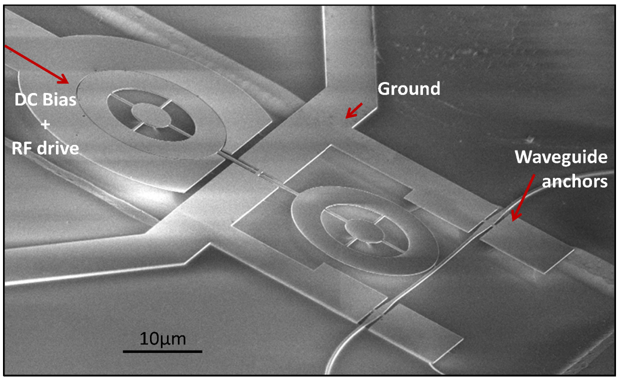

Figure 3. SEM image of ring based optical modulator. The inner radius of the ring is 5.7µm and 3.8µm wide. The 350nm wide waveguides are suspended 150nm from the ring resonator.

The optical resonance observed for the rings have a quality factor of ~45,000 due to the relatively larger radius. The larger size also ensures a large capacitive actuation area which gives rise to a larger force, larger displacements and thereby higher optical modulation at the output. Figure 4 shows the electro optic response obtained for the ring resonator based modulator. Multiple mechanical resonances up to 3.5GHz are observed in the electro optic response of the device as shown in figure 4. The first order radial mode is at 176MHz while the second order radial mode is obtained around 1.12GHz. The mechanical quality factor of the mode at 176MHz in

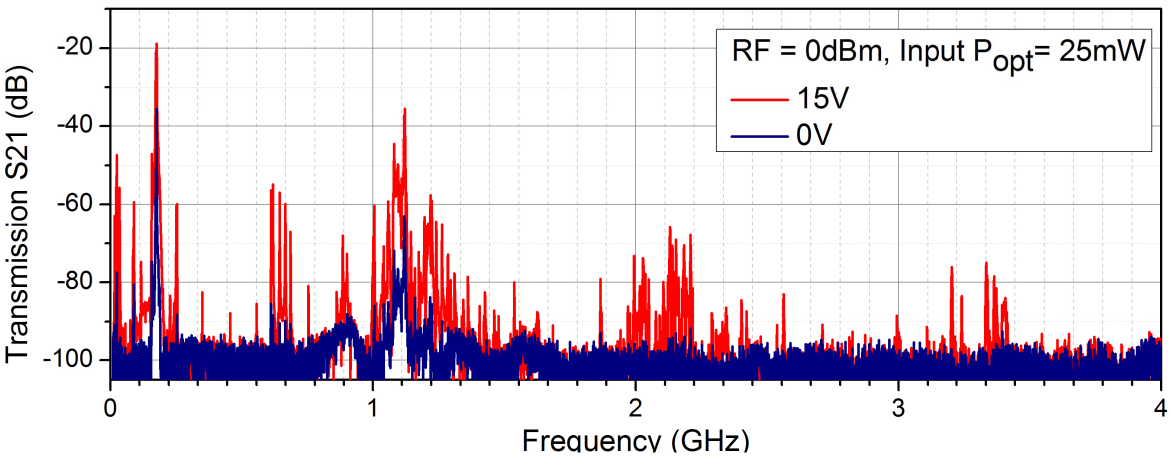

Figure 4. Transmission of ring based optical modulator measured on the network analyzer for DC bias of 0 V (blue) and 15V (red) showing multiple mechanical resonance modes.

air is 1,000 while the second order mode at 1.12GHz has a quality factor of 2,500 in air.

1.12GHz OSCILLATOR

The electrical output from the photodiode is fed back as the electrical input into the mechanical resonator to obtain an oscillator [7]. For oscillations to start, the unity gain condition is met by using amplifiers to compensate for the losses in the loop. A phase shifter is used to ensure that the phase around the loop is a multiple of 2π. From the electro optic response, it is seen that the insertion loss is lower for the fundamental mode at 175.76MHz. On using a broadband amplifier, the gain condition is satisfied first at the fundamental resonance frequency of 175.76MHz. This oscillator output as seen on the spectrum analyzer is shown in figure 5 along with the expected mode shape obtained from COMSOL FEM simulations.

To get the loop to oscillate at the frequency of the second order mode at 1.12GHz where the insertion loss is higher, a setup as shown in figure 6 is used. A combination of available amplifiers and attenuator is used to obtain the required narrowband response with the necessary gain. An attenuator is used to limit the gain as the combination of the amplifiers can provide excess RF power which could damage the modulator. The bandwidth of the amplifiers used is such that the gain condition is satisfied at 1.12GHz before the fundamental frequency. The oscillator output observed on the spectrum analyzer is shown in figure 7. The RF power at the oscillator output can be varied by using the optical input power and the DC bias and is found to vary between 5dBm and 15dBm.

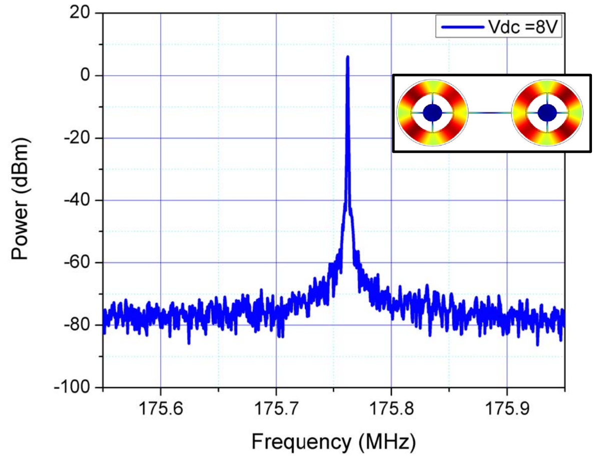

Figure 5. Output of OAO with ring based optical modulator operating at the fundamental frequency of 175.76MHz (inset) mode shape of the fundamental ring mode showing radial expansion of the entire resonator.

Phase Noise

The phase noise of the oscillator at 1.12 GHz is measured using an Agilent 5052B Signal source analyzer. The measured phase noise of the 1.12GHz oscillator at an oscillation power of 8.8dBm is shown in figure 8. The phase noise is modeled by looking at the noise added in the loop by the different components as shown in figure 6. As the resonator is the only frequency selection element, the oscillator can be modeled using the Leeson's noise

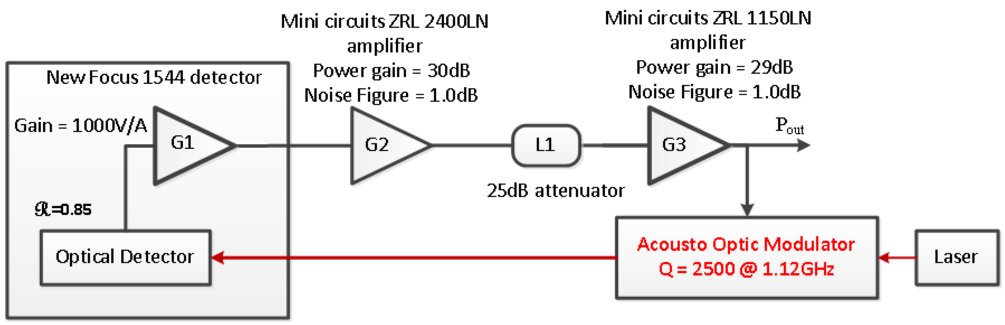

Figure 6. Schematic of the 1.12 GHz oscillator loop with the gain components and the noise they add to the oscillator.

model [9]. The phase noise of the oscillator is given by

$$S_{\Phi}(f) = \left(1 + \frac{1}{f^2}\left(\frac{\nu_0}{2Q_{mech}}\right)^2\right) S_{\psi}(f)$$

where $S_{\Phi}(f)$ is the phase noise power spectral density at the oscillator output, f is the frequency offset from the oscillator frequency ν_0 , $S_{\psi}(f)$ is the phase noise power spectral density of the components forming the oscillator loop and Q_{mech} is the mechanical quality factor. $S_{\psi}(f)$ includes the white noise at the detector, white noise and flicker noise of the amplifier. The Leeson frequency is specified by ($\nu_0/2Q_{mech}$) and represents the offset frequency beyond which the phase noise power spectral density shows white noise behavior. The expected Leeson frequency for the 1.12 GHz oscillator with a mechanical quality factor of 2,500 is 224MHz. This predicted value corresponds well with the measured phase noise corner frequency as shown in figure 8. For offset frequencies below the Leeson frequency, the measured phase noise shows a $1/f^{\,3}$ behavior which suggests that the flicker phase noise corner frequency of the amplifier is close to the Leeson frequency.

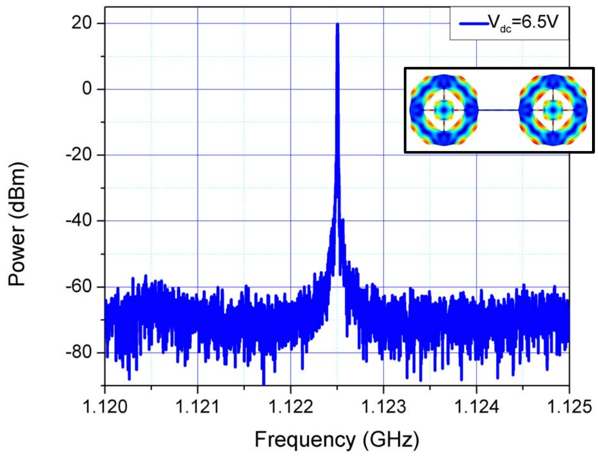

Figure 7. Output of OAO with ring based optical modulator operating at the second order radial mode frequency of 1.12GHz (inset) mode shape of the second order width extensional mode of the ring.

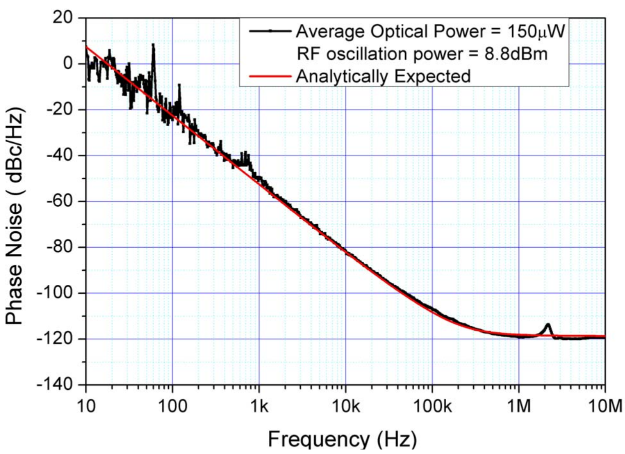

Figure 8. Measured and analytically expected phase noise of 1.12GHz oscillator using an Agilent Signal Source Analyzer 5052B.

CONCLUSION

Using a highly sensitive optical displacement sensing technique that overcomes the drawbacks of electrostatic displacement sense we observe mechanical resonances of a ring resonator up to 3.5GHz. Using amplifiers in feedback to compensate for losses in the loop, we demonstrate an opto-acoustic oscillator operating at the second order radial mode of the ring resonator at 1.12GHz with 8.8dBm output RF power and a phase noise of -85 dBc/Hz at 10 kHz offset.

ACKNOWLEDGEMENTS

The authors would like to thank David Hutchison for his assistance in the design of the experimental setup. This work was supported by the DARPA/MTO's ORCHID program and Intel. This work was performed in part at the Cornell NanoScale Facility, which is supported by the National Science Foundation (Grant ECS-0335765).

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