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14. ABSTRACT

This research aims to quantify and control the dissipation dynamics of NEMS device in fluid and eventually recover the quality factor of NEMS device in fluid. Our approach bases upon innovative modeling of micromechanical damping dynamics and exploitation of anti-damping in optomechanical resonators parametrically coupled with the surrounding fluid. During this 9-month period, we have successfully fabricated devices that can be operated in fluid with ultrahigh optical quality factor and recovered mechanical quality factor. Our next steps are to

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|---|---|---|---|---|---|
| UU | UU | UU | UU | | Hongxing Tang |
| | | | | | 19b. TELEPHONE NUMBER: 203-432-4256 |

**Report Title**

Control of the dissipation dynamics of nanomechanical resonator in viscous media

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## Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

| Received | | Paper |
|---|---|---|
| 09/24/2013 | 1.00 | Xufeng Zhang, Carsten Schuck, Xiankai Sun, Hong X. Tang. Nonlinear optical effects of ultrahigh-Q silicon photonic nanocavities immersed in superfluid helium, Scientific Reports, (03 2013): 0. doi: 10.1038/srep01436 |

**TOTAL:** 1

**Number of Papers published in peer-reviewed journals:**

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### (b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

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### (c) Presentations

**Number of Presentations:** 0.00

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### Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

**TOTAL:**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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## Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

**TOTAL:**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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## (d) Manuscripts

Received Paper

**TOTAL:**

**Number of Manuscripts:**

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## Books

Received Paper

**TOTAL:**

## Patents Submitted

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## Patents Awarded

## Awards

Elected Member, Connecticut Academic of Science and Engineering (CASE), 2013
Editor Board, Advances in Optics, 2013-

## Graduate Students

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Kingyan Fong | 0.30 | |
| **FTE Equivalent:** | **0.30** | |
| **Total Number:** | **1** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| Xiankai Sun | 0.00 |
| **FTE Equivalent:** | **0.00** |
| **Total Number:** | **1** |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Hong X. Tang | 0.00 | |
| **FTE Equivalent:** | **0.00** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ...... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

## Names of Personnel receiving masters degrees

NAME

**Total Number:**

## Names of personnel receiving PHDs

NAME

**Total Number:**

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
| --- | --- |

**FTE Equivalent:**

**Total Number:**

## Sub Contractors (DD882)

## Inventions (DD882)

## Scientific Progress

## Technology Transfer

Project report for Award ARO-STIR W911NF1210490

Project title: Control of the dissipation dynamics of nanomechanical resonator in viscous media

Principle investigator: Dr. Hong Tang, Associate Professor,
Department of Electrical Engineering
Tel: 203-432-4256, Fax: 203-432-7769, email: hong.tang@yale.edu
Yale University, 15 Prospect St, New Haven, CT 06520

Other personnel involved: Xiankai Sun, Kingyan Fong

Duration of effort: Sept 14 2012-May 31 2013 for 9 months

This research aims to quantify and control the dissipation dynamics of NEMS device in fluid and eventually recover the quality factor of NEMS device in fluid. Our approach bases upon innovative modeling of micromechanical damping dynamics and exploitation of anti-damping in optomechanical resonators parametrically coupled with the surrounding fluid. During this 9-month period, we have successfully fabricated devices that can be operated in fluid with ultrahigh optical quality factor and recovered mechanical quality factor. Our next steps are to apply these devices in practical chemical and biological sensing applications.

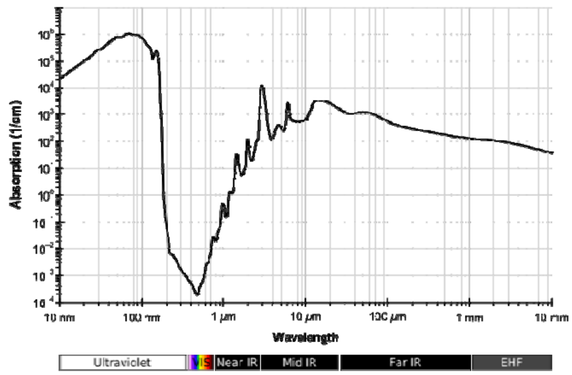
## 1. Introduction

Micro and nanomechanical devices are pushing towards smaller and smaller dimensions and start to find use in a range of biological and chemical sensing applications. As device dimensions become smaller we begin to interact with, manipulate, and sense physical systems at the stochastic limit given by the inherent thermal motion of matter. An understanding of this intrinsic dynamic process can yield deep physical insights. Our approach bases upon innovative modeling of micromechanical damping dynamics and exploitation of anti-damping in optomechanical resonators parametrically coupled with the surrounding fluid.

## 2. Our experimental research and main findings

Our first task is to identify a suitable wavelength to operate optomechanical resonators in fluid. Figure 1 shows the absorption of light in water as a function of wavelength. It can be seen that in the most commonly used telecom band, water has very high absorption up to 34dB/cm. Fortunately, water has a transparent window in visible band (that is why this planet is blue).

Under separate effort, our lab has acquired a laser working in that wavelength regime (~775nm). Therefore we target to optimize our device at 770nm.




- n=1.318, k=9.86e-5, α=-34.7dB/cm @ 1550nm
- n=1.330, k=1.43e-7, α=-0.100dB/cm @ 780nm
- n=1.331, k=2.11e-8, α=-0.017dB/cm @ 670nm

Figure 1. Light absorption in pure water at different wavelengths. At telecom wavelengths, water significantly attenuates the light whereas there is very little absorption for light in visible regime.

However another arises: silicon – the most common materials to build photonic structure – is not transparent at 775nm. This steers us to fabricate resonant optomechanical structures out of stoichiometric SiN. In the past we have demonstrated that SiN has very low optical loss in both visible and NIR wavelengths. Very high optical Q is expected in devices patterned from SiN thin films.

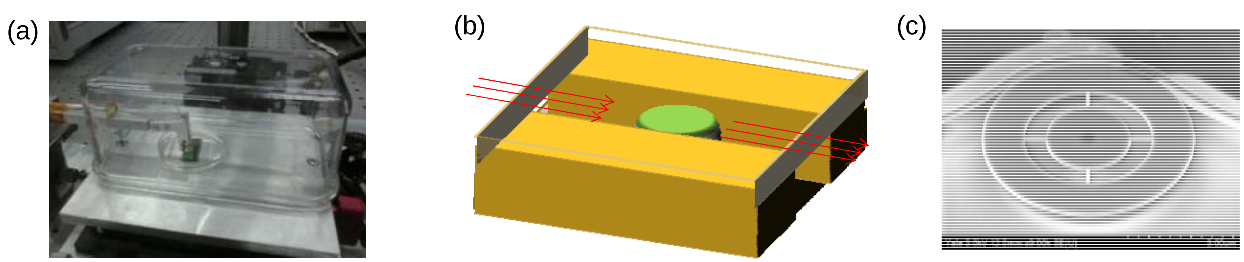



Figure 2. (a) Setup for measuring optomechanical response in fluid. (b) Schematic of microfabricated fluid channel enabling liquid-resonator coupling. (c) SiN microwheel resonator.

The fabricated first generation device is shown in Fig. 2c. Here the optomechanical resonators are patterned as microwheel of 6-8um in diameter. The mechanical modes are radial contour mode therefore operates at very high frequencies. The optical modes are whisper gallery modes. To allow for fluid coupling with the resonator, we embed the microwheel resonator inside a microfluidic channel (Fig. 2b) etched into the silica-on-silicon substrate. Grating couplers are utilized to access to the waveguide within a vapor saturation chamber. (Fig. 2a).

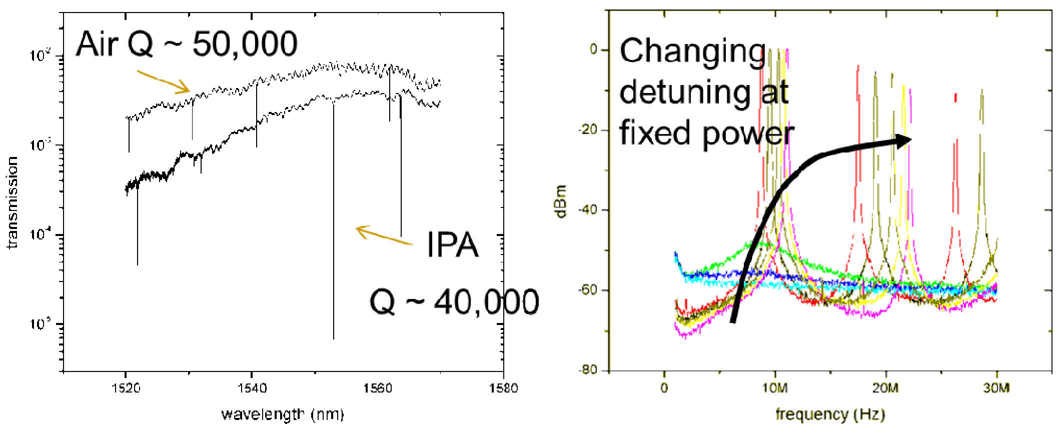



Figure 3. (a) Observed high Q optical resonances (Q~50,000) when optomechanical oscillator operated in air and in IPA at 1550nm. Since IPA is not absorbing at this wavelength, we did not find significant quality factor degradation when the device was submerged in IPA. (b) When immersed in IPA, the device displays spontaneous oscillations as a result of fluid-opto-mechanical interactions.

Before characterizing the device in fluid, we first investigate our device operating in air and in non-absorbing viscous media such as IPA. Figure 3a shows high Q optical resonators when optomechanical oscillator operated in different environments. In our first group of devices, we observed quality factor as high as 50,000 in air. Since IPA is not absorbing at this wavelength, we did not observe significant quality factor degradation when the device was submerged in IPA. In IPA, we found that when we increase the optical power, regenerative oscillations appear. Meanwhile we found that the device optical performances are modified significantly. The higher harmonics shown in Figure 3b are also unexpected. We conclude that these oscillations arise from thermal optical effect instead of radiation pressure effect.

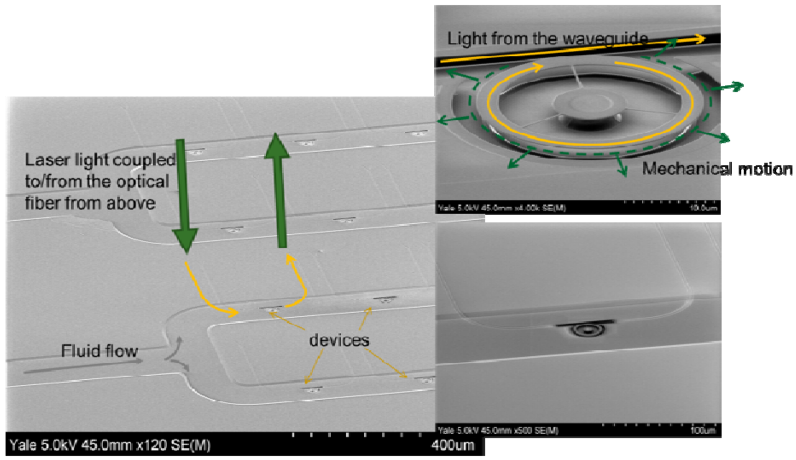



Figure 4. Our new generation of fluidic coupled optomechanical resonator working at 775nm. Also shown are grating couplers, the microfluidic flow channel and the optomechanical resonator.

In order to observe true radiation pressure effect, we need to improve the optical Q of our optomechanical oscillators. Figure 4 displays our optimized device design. The devices are designed for operation at ~775nm. To facilitate heat dissipation, we incorporated large cross section microfluidic channels so that a large volume of fluid can flow through the resonator and carries away possible heat generated in the micro-resonator. The figure also illustrates how light is coupled in and out of the chip through grating couplers.

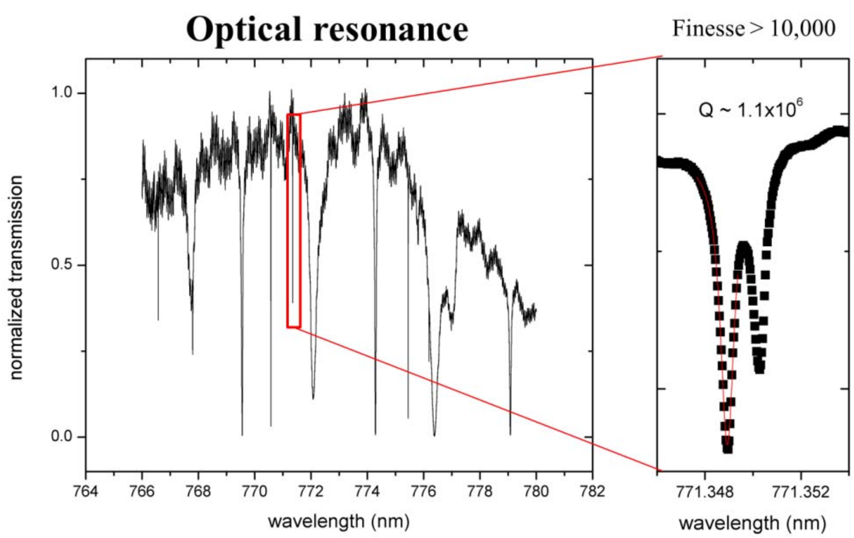



Figure 5. High Q (> 1,000,000) optical resonances observed in optimized SiN optomechanical resonators.

To further reduce the optical loss, we apply resist reflow process after ebeam exposure. This reflow removes the edge roughness in the resist pattern hence reduces light scattering. As expected, we observed very high quality factor after releasing the optomechanical structure, both in air and in water. Figure 5 shows the optical resonances we observed in our optomechanical structures. Quality factor as high as 1.1 million is measured in water (similar value is observed in air). The high Q also allows resonant peaks of the clockwise and counter-clockwise propagating modes become separable.

With all these improved outlined above, we finally are able to detect mechanical resonators in water. The first radial-contour mode in our device is ~180MHz in air with quality factor of 1300. After fluid immersion, we found the resonance shift to about 160MHz and its quality factor drops to 12. Interestingly there is another mode show about at around 180MHz. This mode is found to correspond to the 190MHz mode when measured in air. The shift in resonance frequency and observed damping rate are consistent with Sadre's model (J. Appl. Phys. 84, 64 1998).

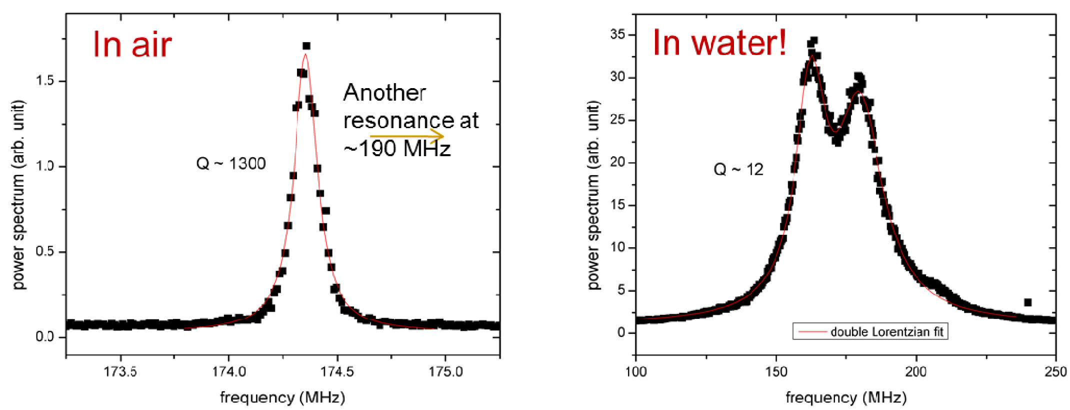



Figure 6. Mechanical resonances observed in air and in water. Although the quality factor is degraded when immersed in water (down to 12), the resonances are clearly observable with very high signal to noise ratio.

### 3. Prospect and future plans

Our technique of coupling optomechanical oscillators in fluid opens new possibilities for sensing applications. For the first time we are able to perform dual modal sensing in optical domain and mechanical domain with nanoscale sensors. With its ultra-high optical quality factor and recovered mechanical quality factor in fluid, our devices should offer very high sensitivity for biological and chemical sensing in viscous environment. We are in the process of functionalizing our devices for proof of principle demonstration of DNA detection. These new devices should be capable of recognizing targets with high speed and high specificity.

**Paper published:**

X. Sun, X. Zhang, C. Schuck, H. Tang, “Nonlinear optical effects of ultrahihg-Q silicon photonic nanocavities immersed in superfluid helium”, **Scientific Reports** 3, 1436 (2013)