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Exploiting Repulsive and Attractive Optical Forces in Advanced Nanophotonic Systems

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REGENTS OF THE UNIVERSITY OF MINNESOTA MINNEAPOLIS

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The objective of the project is to investigate optical forces and optomechanical effects in various integrated nanophotonic systems and develop their applications for RF photonics, reconfiguration photonics and optical sensing. During the period of the project, integrated optomechanical devices based on three types of nanophotonic systems have been investigated. Those are silicon photonic devices, metal-dielectric hybrid plasmonic devices and piezoelectric acousto-optic devices. The research results has been reported in six papers published in renowned journals such as Nature Nanotechnology, Nature Communications and Optica, and been presented at numerous conferences by the PI and the students.

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Final Project Report

AFOSR Young Investigator Program

Exploiting Repulsive and Attractive Optical Forces in Advanced Nanophotonic Systems

PI: Mo Li, University of Minnesota

Overview

The objective of the project is to investigate optical forces and optomechanical effects in various integrated nanophotonic systems and develop their applications for RF photonics, reconfiguration photonics and optical sensing. During the period of the project, integrated optomechanical devices based on three types of nanophotonic systems have been investigated. Those are silicon photonic devices, metal-dielectric hybrid plasmonic devices and piezoelectric acousto-optic devices. The research results has been reported in six papers published in renowned journals such as **Nature Nanotechnology**, **Nature Communications** and **Optica**, and been presented at numerous conferences.

In the following, research results obtained during this project are summarized briefly.

1. Silicon Cavity Optomechanics

Optomechanical effects in photonic devices can be utilized as a new means for optical signals to directly interact in order to achieve optical signal processing. One optical signal can generate optical force to induce mechanical motion in the optomechanical devices which can modulate the phase or intensity of another optical signal coupled in the same device. Such all-optical interaction is achieved without involving any optoelectronic interaction or nonlinear optical effect and thus is move efficient. In particular, since the optomechanical motion is typically in the radio-frequency to microwave frequency range, those optomechanical devices can be applied for optical signal processing of RF and microwave signals. To further enhance the effects, optomechanical effects can be enhanced in photonic cavities by optical resonance. These devices can be readily fabricated on silicon photonics platform with high performance for near-infrared band operation because silicon provide both excellent optical and mechanical properties.

In 2012 we demonstrated a silicon photonic cavity optomechanical device with multiple optical channels (i.e. waveguides) and capable of optomechanical amplification of radio-frequency signals. In this device (Fig. 1), two optical waveguides are coupled to a micro-disk optical cavity, which resonantly amplifies the optical force generated by the optical signal coupled from one of the waveguide to displace the other movable waveguide. We demonstrated the device could be operated as an optomechanical relay with which a low-power control channel was able to modulate

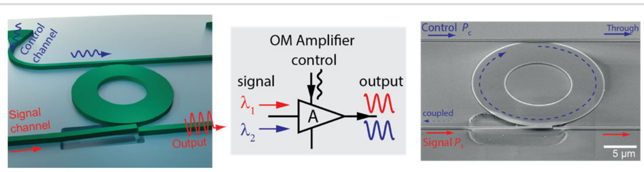

Figure 1 A multichannel cavity optomechanical relay that can amplify radio-frequency signal.

a high-power signal channel and thus to achieve signal amplification with a gain factor of more than three. Since the signal channel is not coupled with the cavity which has a narrow resonance band, this optomechancial relay can be used to amply and convert the control channel to a broad optical band of the signal channel and thus enabling wavelength multiplexing. Furthermore, the device shows strong but tunable optomechancal nonlinearity that can overwhelm the intrinsic nonlinearity to compesate it and to improve the device's dynamic range.

In a more recent work, we demonstrated a new paradigm of cavity optomechanics in which the mechanical mode is "bigger" than the optical modes, and even extends over multiple cavities to couple them strongly. The device is a dual-cavity torsional optomechanical resonator, which we name as a "photon see-saw" (Fig. 2). The coupling between two photonic crystal nanocavities, one on each side of the see-saw, is modulated by the rotational motion in a unique anti-symmetrical way. We show that the photons in one cavity can "outweigh" the photons in the other cavity and tilt the see-saw, causing detuning of both cavities but in opposite directions. Furthermore, the see-saw oscillation can "shuttle" photons from a filled cavity to an empty cavity in an amount that can be controlled with an achieved minimum of ~1000 photons per mechanical cycle. This demonstration can be extended to other forms of mechanical modes, such as flexural plate waves and acoustic waves, to enable nonlocal coupling between multiple photonic cavities at even higher rates. It provides a way to transmit photonic states via mechanical states over a long range. I envision ultimately, in strongly coupled systems, coupling between single photon states can be modulated by a single phonon for quantum regime photonic information processing.

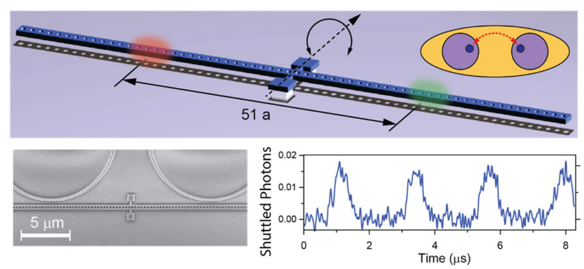

Figure 2 A cavity optomechanical photon "see-saw". Photon shuttling between two photonic crystal cavities was demonstrated. The trace in the lower-right panel shows photons being mechanically shuttled from one cavity to the other.

Reference:

1. Huan Li, Yu Chen, Jong Noh, Semere Tadesse, Mo Li "Multichannel cavity optomechanics for all-optical amplification of radio frequency signals", Nature Communications, 3, 1091 (2012).
2. Huan Li, Mo Li, "Optomechanical photon shuttling between photonic cavities",Nature Nanotechnology, 9, 913 (2014)

2. <u>Plasmonic enhanced optical force</u>

Optomechanical effects in integrated photonic devices is dominated by the gradient optical force which is proportional to the spatial gradience of the optical field. Therefore, to obtain even stronger optical forces, the optical field needs to be more tightly confined. To this end, we explored metallic plasmonic devices which can provide higher spatial confinement of light than dielectric photonic devices such as silicon photonics. However, metal based plasmonic devices suffers high optical loss due to absorption of metal. To mitigate the loss in all-metal plasmonic devices, we investigated silicon-gold hybrid plasmonic waveguide in which the optical mode is confined within a nanogag between a gold plate and a silicon waveguide.

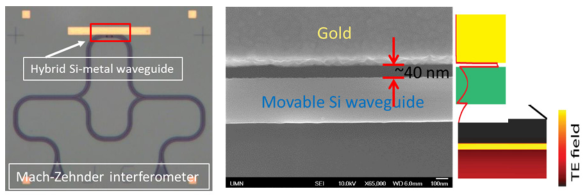

Figure 3 Hybride plasmonic waveguide device to study plasmonic enahnced optical force.

We fabricated the hybrid waveguide on standard SOI substrates. A Mach-Zehnder interferometer was integrated to tranduce the optical force exicted mechanical motion. We employed advance ebeam lithography process (low temperature resist development) to achieve a nanogap between the silicon waveguide and the gold slab. The smallest gap obtained was 20 nm with edge roughness of less than 5nm (r.m.s. value). By measuring the calibrated vibration amplitude of the suspended silicon waveguide, which was actuated by the optical force, the force magnitude was accurately determined. We obtain a peak force of 100 picoNewtwon/micron for Si-Au gap of 20 nm. The total optical force obtained is undermined by the excessive optical loss in the waveguide, which can be improved further by reducing the edge roughness. Nevertheless, the value of gradient optical force obtained in this hybrid plasmonic waveguide is already two orders of magnitude than that in all-dielectric devices and thus is promising to achieve tunable, plasmonic opto-mechanical systems.

Reference:

1. Huan Li, J. Noh, Yu Chen, Mo Li,"Enhanced optical forces in integrated hybrid plasmonic waveguides", Optics Express, 21, 11839 (2013).

3. <u>Gigahertz Acousto-optic Devices</u>

To achieve even higher mechanical frequency, we subsequently studied the optomechanical effects of propagating acoustic waves. As stand-alone components, acousto-optic devices are indispensable in many optical applications but conventional devices are rather bulky and difficult to be miniaturized and integrated. Their operation frequency has been limited to a few hundred megahertz at most which is insufficient for the need of high speed optical communication. On the other hand, various acoustic wave devices, including surface acoustic wave (SAW), bulk acoustic wave (BAW) and flexural plate wave (FPW) devices, have been operating in the gigahertz range with wide spread applications as front-end filters and delay lines in wireless communications.

We realized that at multi-gigahertz frequencies, the acoustic wavelength is approaching the optical wavelength in the same material, such as silicon and aluminum nitride. Therefore, an unprecedented regime of strong acousto-optic interaction can be reached because of the very high modal overlap and phase matching conditions that can be obtained. Employing advanced fabrication techniques, we pushed the operation frequency of surface acoustic transducers to above 10 GHz, and significantly, reached an unprecedented regime of acousto-optics in which the

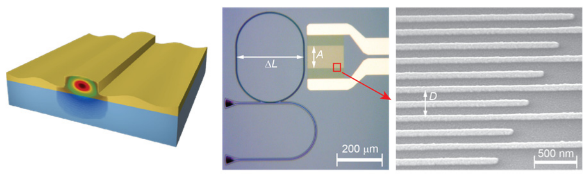

Figure 4 Integration of sub-optical wavelength surface acoustic wave transducers on AlN and strong acousto-optical modulation of an optical resonator at >10GHz frequency.

acoustic wavelength (as low as 500 nm) was less than the optical wavelength (around 750 nm) and demonstrated broadband acousto-optic modulation. This demonstration establishes a powerful platform for exploiting light-sound interaction with much improved strength and expanded parameter space. Novel optical phenomenon predicted previously by theory but not yet viable for experiments will become possible on this platform. Those include non-reciprocal light propagation induced by forward Brillouin scattering by actively excited acoustic phonons, optical generation of coherent phonons and optical-to-microwave signal conversion. With further improvement in fabrication, the operation frequency of the acoustic transducers can reach above 20 GHz and the quality factor of the nanophotonic cavities can be significantly improved. Then the sideband resolved regime of cavity optomechanics can be reached with propagating phononic modes, rather than confined phononic modes as in conventional cavity optomechanics, to strongly couple multiple photonic cavities. In such a regime, we aim to achieving nonlocal modulation and shuttling of photons between distant cavities for applications in quantum photonics and optomechanics. For technical applications, because the strong acousto-optic interaction directly links microwave signals with optical signals, the new platform will enable a wide range of applications in microwave photonics and optical signal processing.

Along this direction, we first demonstrated co-integration of ultrahigh frequency SAW devices with nanophotonic devices on piezoelectric aluminum nitride (AlN) thin film (*Tadesse, S., et al. Nat. Comm. (2014)*). In this configuration, both the acoustic wave and the optical field are simultaneously confined within a thin layer of piezoelectric material so that very strong interaction between the two waves and thus efficient acousto-optic modulation are attained. We achieved acousto-optic modulation of high-Q ring resonator at frequency up to 10 GHz. Later, we demonstrated modulation of a photonic crystal nanobeam cavities at even higher frequency of 12 GHz (*Li, H., et al. Optica (2015)*). Significantly, the photonic cavity has a high Q factor and narrow optical linewidth of less than 4 GHz. Therefore, this device reaches the side-band resolved regime of cavity optomechanics. This allows us to demonstrate acoustic wave induced transparency and opacity. We also demonstrated an acoustic cavity with a photonic cavity embedded inside to achieve a complete acoustic cavity optomechanical systems.

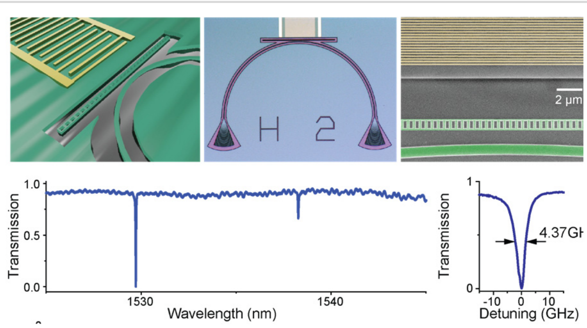

Figure 5 High-Q phhotonic crystal cavity integrated with surface acoustic wave device with frequency up to 12 GHz.

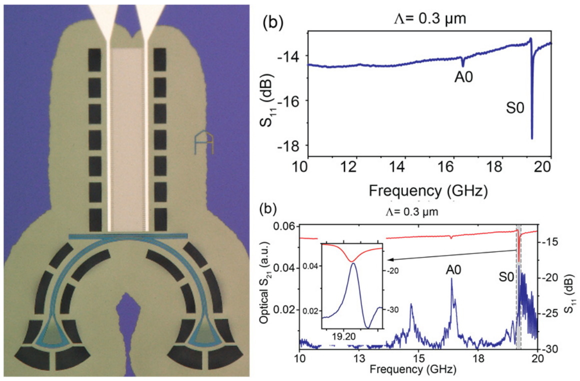

Figure 6 Lamb wave modulation of photonic crystal cavity at frequency up to 19GHz in the microwave K band.

To further increase the acoustic frequency, the AlN layer can be suspended so that the acoustic wave is confined in the active layer and decoupled from the inactive substrate (SiO_2). With this configuration, the acoustic wave is in the mode name as Lamb waves. In a paper that is currently under review, we demonstrate Lamb wave modulation of photonic crystal cavity at frequency up to 19 GHz reaching the microwave K band, for the first time and setting a record. We plan to continue increasing the modulation frequency and efficiency. Such systems can find important application in microwave photonics as frequency-agile filters and delay lines.

Reference:

1. Semere A. Tadesse, Mo Li, "Sub-optical wavelength acoustic wave modulation of integrated photonic resonators at microwave frequencies", Nature Communications, 5, 5402 (2014)
2. Huan Li, Semere A. Tadesse, Qiyu Liu, and Mo Li, "Nanophotonic cavity optomechanics with travelling surface acoustic waves at frequencies up to 12 GHz", Optica, 2, 826-831 (2015)
3. Semere A. Tadesse, Huan Li, Qiyu Liu, Mo Li, "Acousto-optic modulation of a photonic crystal nanocavity with Lamb waves in microwave K band", submitted to Applied Physics Letters (2015)

4. Summary

For summary, during this Young Investigator Program, we have explored optical forces and optomechanical effects in various advanced photonic systems, including silicon disk resonators, hybrid plasmonic waveguides and photonic crystal nanobeam cavities. We successfully demonstrated optically induced and coupled mechanical motions with frequency spanning a very wide range from kHz to multiple GHz. Our research has opened up a new field of piezoelectric acoustic-optics and demonstrated many "first-time". The results will not only impact the field of cavity optomechanics for fundamental interest, it will also lead to applications in microwave photonics. The research has yielded 6 publications in high impact journals and numerous conference presentations by the PI and the participating students.