Nanoscale optomechanical sensors: split-beam photonic crystal nanocavities

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***Abstract*—Optomechanical nanocavities allow nanomechanical resonances to be measured optically with high sensitivity. We have created a new type of photonic crystal nanocavity optomechanical sensor optimized for detecting sources of torque and other forces which can deflect nanoscale cantilevers. This nanocavity consists of two precisely engineered photonic Bragg mirrors patterned in silicon cantilevers and separated by a $50 - 100$ nm wide gap. Simulations of the optical and mechanical modes predict that mechanical displacements of the sub-picogram cantilevers will shift the optical nanocavity resonance frequency at a rate exceeding 20 GHz / nm, and that the nanocavity optical mode may have a quality factor $Q_o > 10^6$ in optimized devices.**

I. Introduction

In recent years, optomechanical nanocavities have enabled detection of sub-pm motion of micro- and nano-scale objects, allowing the realization of force sensors with record sensitivity [1], [2], [3] and studies of the quantum properties of mechanical objects [4]. These devices consist of nanostructures which support optical and mechanical resonances which overlap in space. The optical nanocavity can be formed from dielectric materials patterned with a variety of geometries, including photonic crystal and whispering gallery mode optical resonators, and typically support optical modes with frequencies in the $200 - 600$ THz range (wavelengths from visible to near-IR), high optical quality factor, Q_o, and wavelength-scale optical mode volumes. Mechanical resonances of these nanocavities, or of mechanical structures placed in the optical nanocavity near-field, can be engineered to have frequencies ranging from kHz - GHz, and effective mass below a fg. Here we analyze a new type of optomechanical nanocavity called a "split-beam" photonic crystal nanocavity, which combines strong optomechanical coupling with high sensitivity detection of a variety of torsional and cantilever mechanical modes.

II. Design Rationale

Motion of mechanical resonances within optomechanical nanocavities is readout by monitoring changes in the optical response of the nanocavity to which they are coupled. Transduction of mechanical motion onto a change in the optical nanocavity response results from modification of the dielectric environment of the optical nanocavity field as a function of mechanical resonator position. This transduction can be understood by considering the frequency dependent transmission of an optical waveguide coupled to a nanocavity:

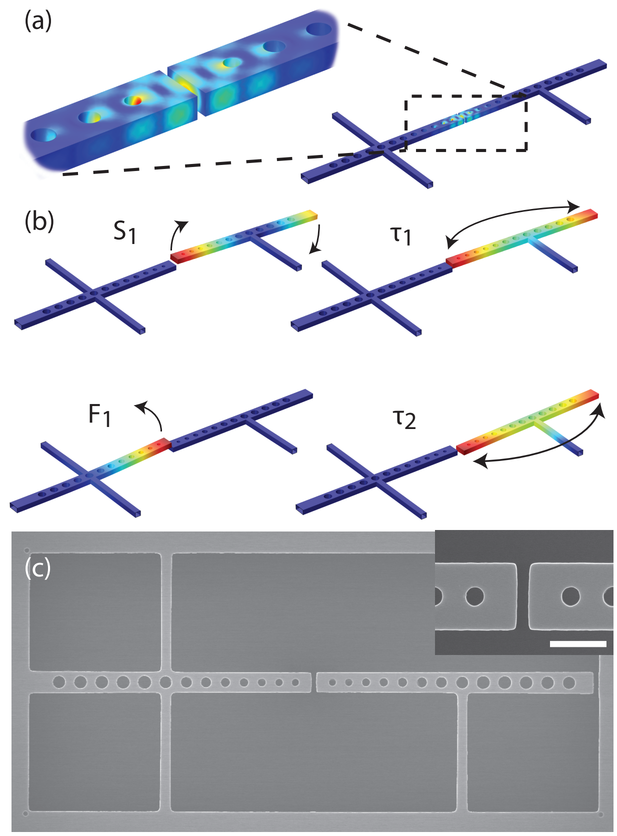

Fig. 1. a) Finite element (FEM) simulation of the TE-like optical field inside the nanocavity. Warmer colors correspond to stronger electric field intensity. b) Mechanical mode shapes as determined by FEM simulations: out-of-plane "see saw" S_1 = 5.12 MHz, in-plane first torsional τ_1 = 5.28 MHz, out-of-plane flexural F_1 = 9.89 MHz and in-plane second torsional τ_2 = 18.72 MHz. τ_1 flexes on the side of the support while τ_2 has its pivot point in the half-nanobeam. The support is 3 μm long and 250 nm wide. Warmer colors signify larger displacement which was exaggerated to demonstrate mechanical motion. c) a) Scanning electron micrograph of the fabricated split-beam nanocavity. The inset shows the 80 nm split with the scale bar indicating 500 nm.

$$T(\omega) = S\left|1 - \frac{\gamma_e}{i(\omega - \omega_o) + \gamma_t/2}\right|^2 \quad (1)$$

where S is the power input to the waveguide, γ_e is the rate of optical coupling between the optical waveguide and

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nanocavity, γ_t is the total energy decay rate of the nanocavity, and ω_o is the optical nanocavity resonance frequency. In optomechanical nanocavities, ω_o, γ_e and γ_t may each depend on the displacement, x, of a mechanical resonator interacting with the optical nanocavity field. In general, x describes the displacement amplitude of a specific mode of the mechanical resonator. To quantify the optomechanical coupling, it is necessary to calculate the rate of change in optical nanocavity parameters as a function of mechanical displacement. For example, in the case of purely dispersive coupling ($\omega_o = \omega_o(x), \gamma_{e,t}$ independent of x), a small displacement dx of the mechanical resonator will induce the following change in waveguide transmitted power:

$$dT = \frac{dT}{d\omega_o}\frac{d\omega_o}{dx}dx = \frac{dT}{d\omega_o}g_{\text{om}}dx \qquad (2)$$

where g_{om} is the optomechanical coupling coefficient. The above equation assumes that the mechanical frequency is small compared to the nanocavity photon decay rate, $\omega_m \ll \gamma_t$, so that backaction related to the delay in nanocavity response to mechanical displacement can be neglected. In the more general case, coupling between the mechanical and optical equations of motion must be analyzed [5]. In order to maximize dT/dx, it is necessary to simultaneously maximize the optomechanical couping, g_{om}, by ensuring that the optical and mechanical modes have strong spatial overlap and appropriate symmetries [6], and minimize γ_t by creating an optical nanocavity with high optical quality factor $Q_o = omega_o/\gamma_t$. If the device is to be used as a force sensor, it is also necessary to consider the mechanical susceptibility of the mechanical resonator, which describes the coupling between dx and an external force. Typically, it is desirable to minimize the mass of the resonator, maximize its mechanical quality factor Q_m, and engineer ω_m to be resonant with the driving force.

III. Photonic crystal split-beam optomechanical nanocavity design

With the above criteria in mind, we have recently designed a novel optomechanical nanocavity, consisting of two precisely engineered photonic Bragg mirrors patterned in silicon cantilevers and separated by a $50 - 100$ nm wide gap. This optomechanical nanocavity is called a photonic crystal "split-beam" nanocavity, and is illustrated in Fig. 1. Despite the large perturbation introduced by the gap in the center of the nanocavity to the refractive index profile of the nanobeam, a high Q_o optical mode can be supported by careful design of the hole dimensions through band-gap matching [7]. In this design, an optical potential is smoothly varied from the outer "Bragg mirror" region to the central gap region, allowing a localized optical mode to be tightly confined to the center of the nanocavity. The spatially varying optical potential can be calculated from the bandedge of each unit cell of the nanocavity, assuming that the unit cell is repeated periodically. In the design shown here, $Q_o > 10^4$, while in further optimized designs, $Q_o > 10^6$ is possible [7]. The optical field distribution of the high Q_o mode for the device considered here is shown in Fig. 1(a), and is predicted to exist at a wavelength $\lambda_o \sim 1550\text{nm} = 2\pi c/\omega_o$. As discussed below, small changes in the gap width dramatically shift the optical frequency of this mode, resulting in strong optomechanical coupling.

The central gap, combined with a supporting structure in which one of the nanobeams is only suspended by a single support connecting it to the surrounding device layer, opens up mechanical degrees of freedom such as those shown in Fig. 1(b). This mechanical design allows the device to be efficiently actuated by external sources of torque, and the mechanical resonant frequencies can be easily tailored for an application of interest by modifying the dimensions of the supporting structure. For the design presented here, assuming the source of torsional motion produces a torque vector pointing out of the plane of the device, this motion will couple favorably to in-plane mechanical modes such as the torsional modes at 5 MHz (τ_1) and 19 MHz (τ_2). Using perturbation theory [6], these in-plane modes are predicted to have $g_{\text{om}} \sim 20$ GHz/nm, allowing efficient optomechanical detection. Due to the symmetry of the optical field, vertical cantilever modes such as S_1 and F_1 have zero optomechanical coupling. However, the presence of an optical fiber in the nanocavity near-field can break this symmetry and induce a significant g_{om}, allowing observation of optomechanical coupling to these modes even in the limit of thermal Brownian motion. An example of a fabricated device is shown in Fig. 1(c). Measurements of the optomechanical properties of this device is on-going, and will be presented in future work.

IV. Conclusion

We have designed and fabricated a new type of optomechanical nanocavity which is expected to be a sensitive detector of external force and torque. The optical and mechanical modes of this structure overlap spatially, resulting in large optomechanical coupling. Small displacements of the mechanical resonator actuate large shifts in the optical nanocavity frequency, which can be sensitively measured in the nanocavity Q_o is sufficiently high.

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