Strong quadratic coupling in slotted photonic crystal pair

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We present the design of a slotted photonic crystal compatible with CMOS fabrication techniques that is capable of state of the art position squared coupling. The confinement of the light into the slot together with the low weight, low frequency mechanical mode, Ω=1.4 MHz/2π gives a strong linear vacuum coupling rate g_0=1.47 MHz/2π. The design allows us to choose the optical splitting by means of the distance between the cavities and of an electro statically tunable slot width and gives a square vacuum coupling rate of g_0'=33 kHz. This is interesting because a strong square coupling enables quantum non-demolition measurements of phonon numbers or squeezing the mechanical motion.

Introduction

Cavity-optomechanics is about how a vibrational mode influence the resonance frequency of an optical mode and how the optical mode in turn influence the vibrations. When the optical resonance frequency changes it detunes the cavity compared to the optical pump affecting the photon population of the cavity. This in turn affects the radiation pressure acting on the vibration. This coupling has been shown in a wide variety of systems, from atomic gases [1] to the kilogram mirrors of the LIGO interferometers [2]. Relying on this principle it is possible to e.g. cool a mechanical mode to the ground state or to demonstrate optomechanical transparency.

In most of these systems it has been convenient to view the mechanical coupling to the optical resonance frequency as linear since the vibrational amplitudes have been low and the higher order components weak. It has been suggested that with a strong second order coupling it would be possible to perform quantum non-demolition measurements of phonon numbers[3] or to measure phonon shot noise[4]. As shown earlier by J. D. Thompson et al.[5] it is possible to generate a strong non-linear component by exploiting the avoided that appears when two similar optical resonators couple, see figure 2a. We suggest using a optomechanical crystal pair but to forgo the photonic crystal structure in-between the two cavities, suggested in [6], and instead use a tuning fork structure for mechanical coupling. This way you can design for an arbitrary cavity separation. This in contrast to quantized options in cavity separation offered by the discreet number of rows in a photonic crystal. It enables us to get a mode splitting closer to the limits of an avoided crossing imposed by the optical quality factor while maintaining the cavities other properties and by that enhance the nonlinear component further.

The Optomechanical Resonator

The optomechanical resonator consists of a pair of slotted optomechanical crystals, see figure 1b. The optical mode is confined along the optical axis by a band gap, the band diagram is visible in figure 2, and in the other two dimensions by internal reflection. By gradually increasing the period of the band structure we introduce a defect with a
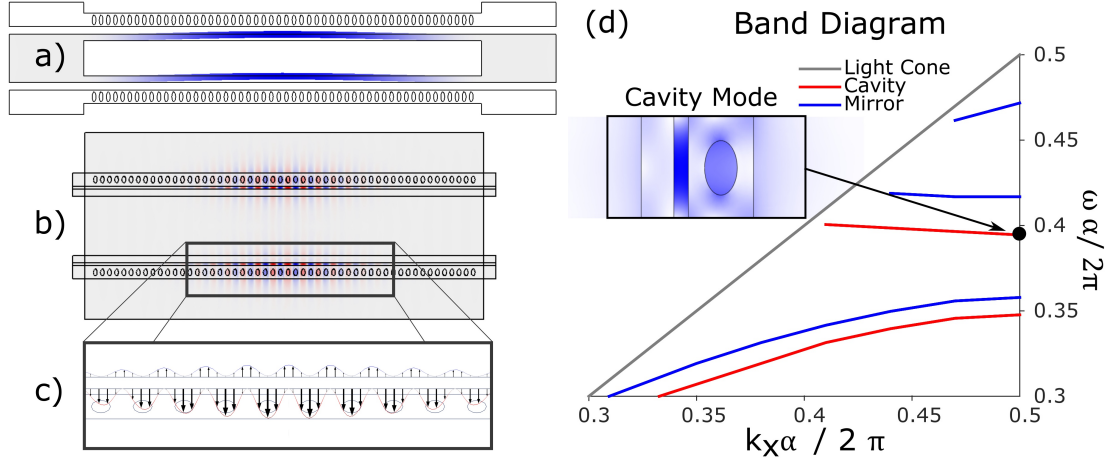
Figure 1: a) Simulation of the first order symmetric mechanical mode and b) the first order optical mode. c) The coupling between the optical and the mechanical mode. The arrows are scaled according to the work performed on the surface of the vibrating beam. d) Band diagram for the optical part of the OMC.

gaussian mode shape. Simulations show that we can hope for an optical Q well above a million for a mode around 1550 nm. The slot focuses most of the light into the void in-between the silicon avoiding two photon absorption. The strong influence of slot width on mode volume means a strong optomechanical coupling to vibrational modes that effect the slot. Another effect from the absence of light in the silicon is that the optomechanical coupling component stemming from the overlap of light and vibration induced stress is insignificant. This is to our benefit as it has the opposite sign in this case. The calculations for the coupling are well described in[7] and eigenmode simulations in COMSOL show a coupling, G=136 THz/μm. The dominating device dimensions for the optomechanical coupling is the slot width, 80 nm, and the width of the vibrating beam, 180 nm. The slot width is limited by smallest resolution offered by the fab but would benefit from shrinking further. In order to maintain a band gap enough of the light interact with the beam that has the periodic defect. Because of that the vibrating beam can not be so thick as to attract too much of the light. If it did attract more light however it would enhance the optomechanical coupling. The force distribution along the moving beam can be seen in figure1c.

The mechanical mode can be described as the symmetric supermode of two coupled beams with a resonance at Ω=1.4 $MHz/2\pi$. The 25 um and 180 nm wide beam pair has an effective mass of m_{eff} = 1.1 pg and a zero point motion of $x_{zpm}=\sqrt{\hbar/2\Omega m_{eff}}$ = 47 pm, where $\hbar$ is the reduced Planck constant. The mechanical mode fails to exploit the low clamping losses of the asymmetric tuning fork mode but for future designs it should be possible to rectify that using a phononic crystal at the anchoring points.

The slot separates the two sides of the photonic crystal so it is possible to electrostaticallay push or pull the slot wider or narrower. The cavity frequency scales with the slot width at a rate of 0.6 THz/nm. By doing this it is possible to align the frequencies of the cavity pair making the design robust to fabrication imperfections.
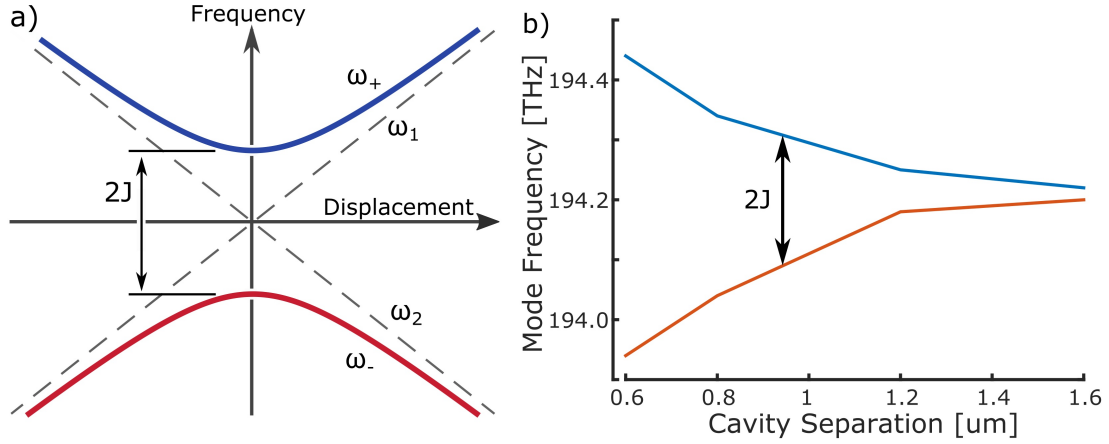
Position Squared Coupling

Figure 2: a) Resonance frequency of the optical modes as a function of the mechanical displacement. In absents of a coupling between the two optical modes (ω_1, ω_2), the resonances cross at the origin. In the presence of an optical coupling rate J between the optical modes they hybridize (ω_+, ω_-) resulting in an avoided mode crossing. This introduces higher order mechanical coupling to the optical resonance frequency. b) The coupling rate between the two optical modes is dependent on the inter cavity distance. The figure shows the resonance frequency of the two super modes as a function of distance and from the splitting between the modes it is possible to deduce the coupling rate, J.

The coupling between the optical modes induces a non-linear component in the optomechanical coupling, see figure 2a. In the case where the mechanical frequency, Ω, is much smaller than the optical splitting, J, the eigenfrequency of the optical supermodes, $\omega_\pm$ can be written as [6],

$$\omega_\pm(\delta_x) \approx \omega_0 + \frac{G_1 + G_2}{2}\delta_x \pm J(1 + \frac{(G_1 - G_2)^2}{8J^2}\delta_x{}^2) \tag{1}$$

where ω_0 is the eigenfrequency of the two modes should they have been uncoupled, G_1 and G_2 their corresponding optomechanical coupling rates and δ_x the instantaneous displacement amplitude of the mechanical mode. The requirement on the cavity pair for an avoided crossing is that the optical loss rate is smaller than the coupling.

The symmetric mechanical mode makes the mechanical coupling rates identical in magnitude but of opposite signs. It is therefor possible to write the position squared coupling as G'=$G^2/2J$ = 15 THz/nm^2 for a splitting J = 400 MHz, twice that of the limit imposed by an optical loss rate of a million. The resulting single-photon to two-phonon optomechanical coupling rate is $g'_0 = G' x^2_{zpm}$ = 5.3 kHz/2π.

This is in it self close to being able to resolve individual phonon jumps. Using the calculations shown in the supplementary information of [5] we find that increasing the g_0 by 4 times to 5.6 MHz/2π we should reach a signal to noise ratio of unity. This could be achieved by using a thinner slot and the design of the cavity so far is limited to the resolution constraints of deep UV. With E-beam we could fabricate a thinner slot which would enhance the coupling significantly.

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