Design for hybrid SOI/Silicon Nitride high cooperativity optomechanical cavity

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We propose an optomechanical cavity design with greater than one cooperativity, based on an external high tensile stress SiN mechanical oscillator on top of a planarized SOI TM ring resonator. The high tensile stress SiN beams allow for a very high mechanical quality factor. Moreover, we investigate the use of electrostatic tuning in order to tune both optomechanical coupling, dissipative vs dispersive coupling ratio and FSR.

Introduction

Strong optomechanical interactions have previously been demonstrated between free standing waveguides [1], single TE waveguide on a pillar [2] and single under etched TE waveguide [3]. Our design is taking advantage of the CMOS compatible silicon integrated platform and high mechanical quality factor provided by LPCVD Silicon Nitride [4]. It is composed of a planarized SOI TM ring resonator on top of which is deposited via LPCVD high tensile stress SiN mechanical resonator (see Fig. 1). This design has been implemented in order to maximise optomechanical coupling g_0 while not decreasing the optical quality factor Q_o of the cavity. It allows a cooperativity per photon $C_0 = \frac{g_0}{Q_m Q_o} > 1$ needed to achieve any quantum regime [5].
In the following we will first discuss the optical mode used in the structure, then the chosen mechanical mode, the strength of the optomechanical coupling, especially which geometric configuration allows a cooperativity greater than one, and eventually we will investigate the dispersive coupling in the resonator and the possibility of using electrostatic actuation to tune the resonance parameter.

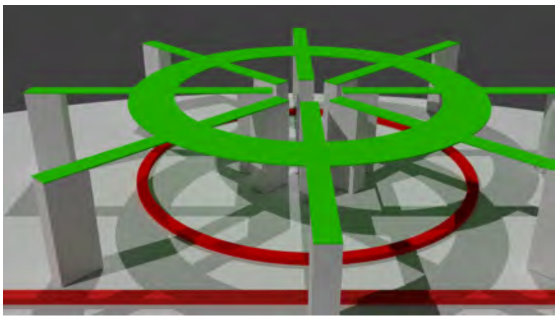

Figure 1: 3D view of the proposed design: in red the Si resonator and its bus waveguide, in green the SiN mechanical resonator.

Optical Mode

The fundamental TM mode (see fig. 2) has been chosen in order to take advantage of classical deposition techniques allowing a nanometer scale control of the gap between the ring and the mechanical resonator. The SiN resonator being on top of all the ring, there is no mode mismatch at any point of the ring like in [6], allowing very small gap without decreasing the optical Q factor. The symmetry of the structure allows us to limit our study to the cross section.

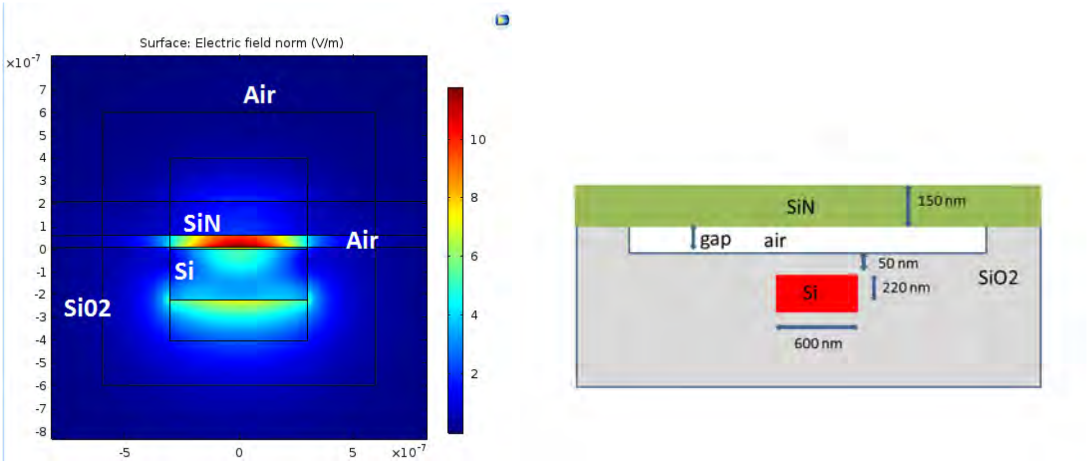

Figure 2: Optical mode (left) and cross-section of the resonator (right).

Mechanical mode

The mechanical mode is on the fundamental flexural mode of the radial beams leading to a vertical oscillation of the disc (see fig. 3a).

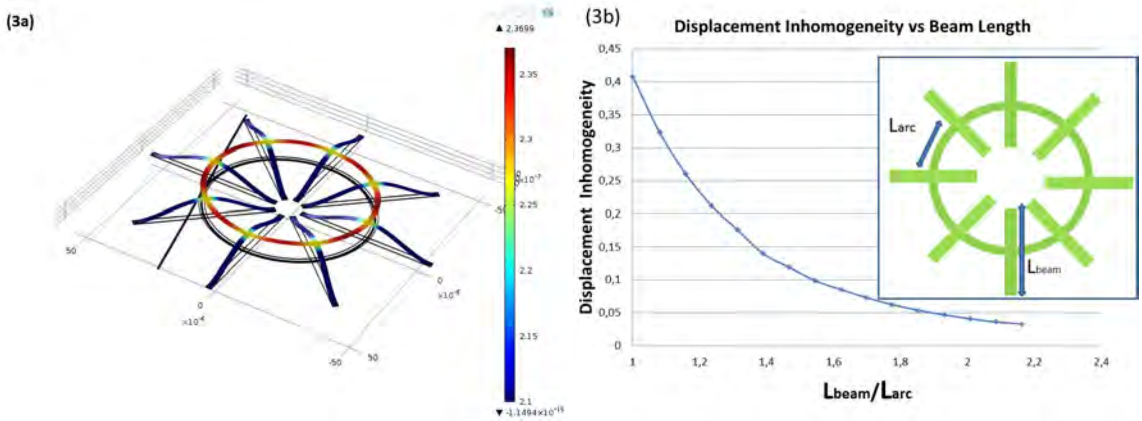

Figure 3: a) Mechanical mode of the SiN mechanical resonator. b) Top view of the SiN mechanical resonator.

The center of the arc has a higher displacement amplitude than the portion of the ring intersecting the beam. We define the inhomogeneity Δ of the ring movement as $\frac{d_{max}-d_{min}}{d_{mean}}$, d_{min} and d_{max} being the minimum and maximum vertical displacement at any point of the ring, respectively. Δ decreases if the ratio between the arm length L_{beam} over the arc length L_{arc} (length of the arc between two intersections between the arm and the ring) increases (see fig. 3b). For $L_{beam} = 2 \cdot L_{arc}$, Δ is less than 5%. In the folowing paragraph we will make the assumption of vertical movement of the ring, no flexural mode being exited, i.e. average vertical displacement $d_{mean} = d_{min} = d_{max}$.

Opto mechanical coupling and cooperativity

The simulated value of the change in effective index per displacement, $\frac{\partial n_{eff}}{\partial gap}$, is shown in Figure 5 a). The change in effective index gives rise to a shift in the optical frequency and the frequency shift per displacement $G = \frac{\partial f_{res}}{\partial gap} = f_{res}\frac{\partial n_{eff}}{\partial gap}$ is shown in Figure 5 b).

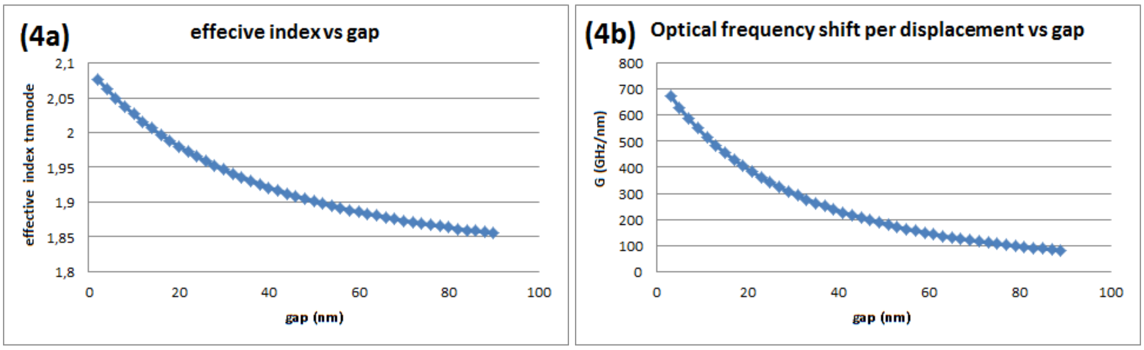

Figure 4: a) Finite element simulation of the effective index of the TM mode for different gap. b) Frequency shift per displacement G for different gaps.

In order to determine which gap distance leads to a cooperativity which is greater than one, we need to determine the optomechanical single-photon coupling strength $g_0 = x_{zpf} \cdot G$, where $x_{zpf} = \sqrt{\hbar/(2m_{eff}\Omega_m}$ is the mechanical zero-point fluctuation amplitude. Given the effective mass m_{eff} of the mechanical resonator $m_{eff} = n_{beam} m_{eff_{beam}} + m_{eff_{disk}} = 0.735 \cdot n_{beam} wtl\rho + 2\pi Rw\rho = 5.196 * 10^{-13} g$, we obtain $x_{zpf} = 4.90461 \cdot 10^{-15} m$. Making the conservative hypothesis of an optical and mechanical quality factor $Q_{op} = 2.10^4$ and $Q_m = \frac{1}{n_{beam}} \cdot \cdot 10^5 = 1.25 \cdot 10^4$ respectively we obtain the following decay rates:
The optical line width $\kappa_{op} = f/Q_{op} = 2 \cdot 10^{14}/2 \cdot 10^4 = 10GHz$.
The mechanical line width $\Gamma_m = \Omega/Q_m = 5\ 10^6/1.255 \cdot 10^4 = 400Hz$.

In order to get $C_0 = \frac{g_0}{\kappa_{op}\Gamma_m}$ greater than 1 we need $G > \sqrt{\kappa_o \Gamma_m x_{zpf}^{-2}}$ or $G > 400GHz \cdot nm^{-1}$, corresponding to a gap smaller than 20 nm.

Dissipative coupling

The displacement of the mechanical resonator is not only shifting the ring resonance frequency, a phenomenon called dispersive coupling, it also affects the coupling between the bus waveguide and the ring, a phenomenon called dissipative coupling. By simulating the effective index difference between the symmetric and anti-symmetric TM mode for different gaps, the ring/bus coupling K shift per displacement can be simulated. Although much weaker than the dissipative coupling, this effect could nevertheless be used to tune Q_{op}, and a 30nm displacement leads to an increase of K by a factor 10.

Electrostatic tuning

The possibility of taking advantage of the electrostatic force, as is widely used in MEMS, to tune the ring resonator frequency, optical Q factor, and optomechanical coupling, has also been explored. This can be implemented by adding electrodes on the SOI level and on each single arm (see Figure 7). Using finite element electromechanical simulation, we find that with a voltage lower than 3V we can change the gap between the mechanical resonator and the optical resonator from an initial value 100nm to 50nmm. Moreover by applying a different voltage on each arm, it is possible to tilt the mechanical resonator, enabling independent tuning of resonance frequency and resonance line width.

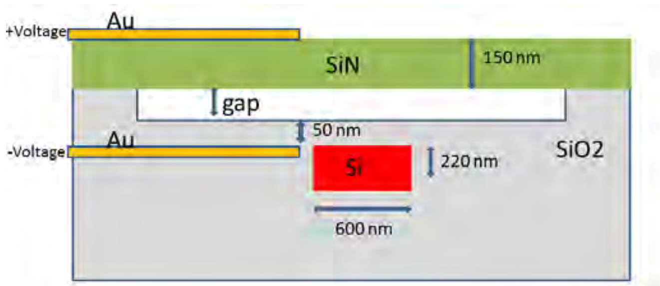

Figure 5: Cross section of the electrostatic tuning scheme.

Conclusion

We show a design based on a SiN mechanical resonator on top of SOI TM ring resonator that has a cooperativity greater than one. Furthermore we have shown that we can tune it using standard electrostatic tuning technique.

References

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