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Brick-Based Silicon Optomechanical Cavity Sensor for Nanoparticles Mass Detection

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Abstract. A novel design for an optomechanical cavity consisting of a series of rectangular silicon nanobricks, with each brick acting as an independent mechanical resonator but all coupled to a same optical field, is proposed, and numerically demonstrated. Each brick is placed on top of a thin silica pillar that provides mechanical support whilst isolates the individual mechanical resonances. The mass sensing capabilities of this cavity are studied through numerical simulations, proving that a point mass approximation can be used for silica nanoparticles with radius smaller than 100 nm, and that different nanoparticles can be measured independently but simultaneously.

1 Introduction

Due to their small size and mass, nanomechanical resonators display a great performance for detecting very small masses [1]. To measure such tiny masses in the dynamic operational mode, the mechanical resonances must be excited by other forces, which can be, for example, thermal, electrostatic, or optical, as is the case of optomechanical cavities (OMCs) [2, 3].

OMCs exhibit several interesting features for mass sensing, mainly because they can support high frequency mechanical modes (in the GHz regime) that can exhibit large Q factor even when operated at room temperature. However, usually such OMCs exhibit many mechanical modes [4] that are all disturbed when depositing an analyte, which limits its practical use. Another limitation occurs in relatively large optomechanical structures, as in disk resonators, where the shift of the mechanical frequency depends upon the exact position of the analyte, which makes difficult to estimate its mass.

Here we propose a novel OMC that can be built on a silicon chip that can solve some of these limitations. It consists of a series of silicon nanobricks that are mechanically (almost) isolated and have slightly different dimensions resulting in different oscillation frequencies whilst being all together coupling to an optical field that can provide the force to actuate and detect the motion. Numerical results show that such cavity should detect simultaneously nanoparticles deposited on different nanobricks with a reasonable estimation of their mass.

2 Results

2.1. Design

The cavity designed consists of a series of rectangular silicon bricks, with each brick acting as an independent mechanical resonator. By slightly changing the dimensions of the bricks, we can have an optical cavity with large Q factors whilst ensuring that each brick acts as an isolated mechanical oscillator. The bricks are supported on silica glass (SiO_2) conical pedestals (to ensure that they are connected to the substrate whilst minimizing acoustic leakage) and placed forming an array of the mirror bricks, that have a width w = 450 nm, a length l = 380 nm and a thickness t = 220 nm. The period of the array a is a = 520 nm. In the middle, we have a defect (l_d = 420 nm, a_d = 560 nm), and we make a parametric transition from the mirror to the defect. By using FEM simulations to calculate the electric mode of this cavity, we find that the frequency obtained is f_O = 198.69 THz.

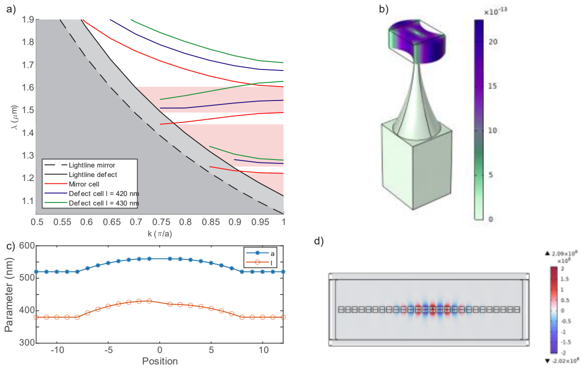

Fig. 1. The band diagram for the defect with length l_a = 420 nm (a) and with l_b = 430 nm. The mechanical (c) and optical (e) modes of the cavity. On (d) we can see the design parameters of this cavity.

As for the mechanical modes, the idea is that each brick acts as an independent resonator, so we made two slightly different defects, with the same period (a) but with

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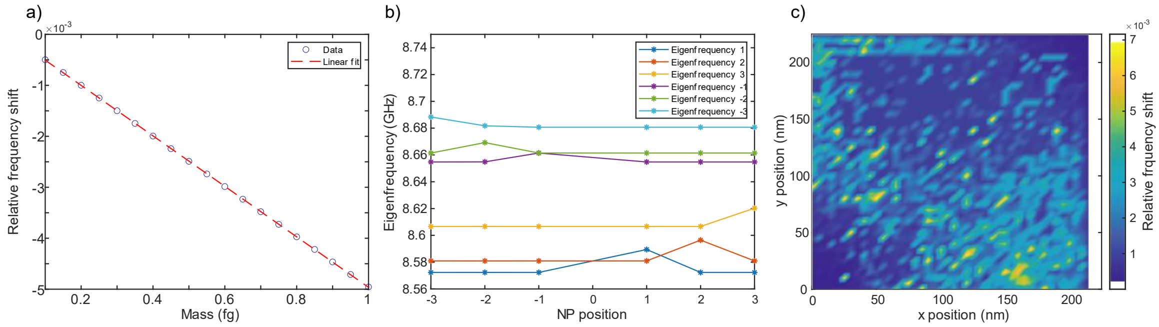

Fig. 2. Relative shift of the mechanical frequency of the brick ($\Delta f_m/f_{m,0}$) as a function of the mass uniformly distributed over the resonator (a). Mechanical frequency of each of the 6 central bricks depending on which brick the nanoparticle is on (b), proving that each resonator is independent. The dependence on the position of the nanoparticle is shown too, with a representation of the relative shift of the mechanical frequency of the brick on a quadrant of the brick (c).

different length, lb = 430 nm. The design parameters can be seen on Fig. 1 (c). Calculating the band diagrams of both defects (Fig. 1 (a)) we can see that the optical modes are similar, and by simulating the cavity, we can find a single mode confined, with optical frequency $f_O = 197.49$ THz. That mode can be seen on Fig. 1 (d). As for the mechanical modes, the profile seen on the same image is the one with the higher optomechanical coupling for both defects, with frequency $f_{m,a} = 8.572$ GHz and $g_{OM} = 104.278$ kHz for one defect and $f_{m,b} = 8.655$ GHz and $g_{OM} = 79.858$ kHz for the second one.

2.2 Nanoparticle detection

For a first approximation at mass detection, we simulate an ideal uniformly distributed mass on top of a resonator, the first defect on the right, with a length la = 420 nm. The response of the mechanical resonance we expect is a linear correlation, corresponding to following equation:

$$\frac{\Delta f_m}{f_m} = -\frac{m}{2\, m_{eff}} \tag{1}$$

Where f_m is the mechanical frequency of the brick, m is the added mass and m_{eff} the effective mass of the cavity. On Fig. 2 (a) we can see that this relation is true on this case.

To further test the possibilities of this cavity as a mass sensor, we study the response of both the optical and mechanical modes of this cavity as well as its optomechanical coupling when adding a silica glass nanoparticle on top of a brick, to have a more realistic approach. At first, we will put the nanoparticle on the resonator where we added the mass. if we consider the origin of coordinates on the centre of the brick, the nanoparticle is on the position (0, w/2). When we add the nanoparticle we see a shift on the optical frequency $\Delta f_O = -4.247$ GHz, and for the mechanical frequency that shift is $\Delta f_m = 17.3$ MHz. Also, we could measure several nanoparticles simultaneously because each resonator is independent. On Fig. 2 (b) we can see that the only frequencies that change when we put a nanoparticle is the eigenfrequency of the brick with the nanoparticle on it.

Now that we have proven that the nanoparticle causes a measurable change on the response, we can further study it to see if it approximates to the point mass approximation:

$$\frac{\Delta f_m}{f_m} = -\frac{m}{2\, m_{eff}} u(x,y)^2 \tag{2}$$

Where *u (x, y)* the displacement of the mechanical mode. The frequency shift is supposed to be proportional to the displacement of the mechanical mode, so on Fig. 2 (c) we can see the relative frequency shift of the cavity when we move a 30 nm silica nanoparticle on the top left quadrant of the 420 nm long brick, and we can see that the places with a bigger shift coincide with the bigger displacement of the mechanical mode seen on Fig. 1 (b). This means that if we know where the particle fell, we could determine the mass of it by measuring the mechanical resonance.

3 Conclusions

We have designed and numerically studied a novel OMC aimed at mass sensing with promising results, in the sense that it should enable to achieve high resolution and simultaneous detection of nanometric mass detection using a point mass approximation. The next step on this study would be trying to fabricate these cavities and measure experimentally their sensing applications.

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