Optomechanical cavities caracterization

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Abstract: Optomechanical crystals are periodical nanostructures designed to present bandgaps for both photons and phonons. By introducing a slight defect into the optomechanical crystal, phonons and photons can be localized inside the gaps. This permits interaction between the optical and mechanical modes inside the cavity. The optomechanical interaction enables transduction of nanomechanical motion with near quantum-limited sensitivity, which drives to applications such as signal processing and high-speed sensing systems. The experiment performed in this study aims to characterise a recently fabricated set of cavities using the new e-beam installed in the Nanophotonics Technology Center (NTC) in Valencia. After comparing it to the older version fabricated with a different equipment, I have found that the cavities in the new set do not behave as expected. The results of the measurements suggest that an error in the fabrication process might have occurred. This error could come from a miss calibration of the e-beam electron dosage, leading to an alteration of the dimensions of the resulting cavities.

I. Introduction

Light carries momentum which gives rise to radiation pressure forces. These forces were already postulated in the 17th century by Kepler. Since then, the field studying light's interaction with matter has been on the rise. Particularly, in the last decade, cavity optomechanics have been a focus of interest.

The research field of cavity optomechanics studies the relation between light and mechanical motion inside an optical cavity. The cavities that will be analyzed in this experiment are called optomechanical cavities (OMCs). These are nano-patterned metamaterials that control the propagation of sound and light. Their design aims to combine the properties of photonic and phononic crystals. By doing so, they can confine optical and mechanical modes and form a complete optomechanical system [1].

The cavities we aim to study are embedded within photonic crystals. Photonic crystals are periodic dielectric nanostructures that affect electromagnetic wave propagation in the same way a semiconductor crystal affects the propagation of electrons, determining allowed and forbidden electronic energy bands. They simulate a "perfect mirror" for the wavelengths whose energy is inside the gap. These cavities are created within two mirror regions by introducing a defect on the nanostructure. This defect is created by reducing the unit cell parameters with the same percentage ($\Gamma = 0.85$) from the original values (see Fig.(1)): the cell width (a), stub width (d), and hole radius (r). The reduction is made from both side to the center keeping the thickness (e) as a constant along the structure, since it is determined by the silicon layer thickness [2].

The samples we will analyse have a particular design. They are pairs of cavities which include a mechanical connection between them (Fig.(2)). This will allow for mechanical interaction to occur. They are also anchored to the wall to limit their movement outside the region where we want to confine light.

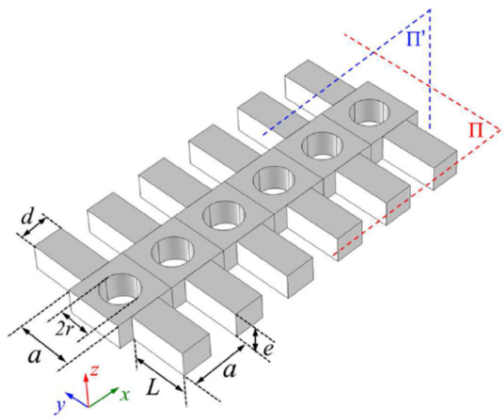

FIG. 1: Optomechanical crystal with its symmetry planes (Π and Π′) and geometry parameters (a, L, d, r and e). The crytal was constructed by periodically repeating a unit cell. The mirror regions of the OMC are constructed with this geometry [1]

The experiment performed aims to characterise a recently fabricated set of cavities. This set was built using the new e-beam installed in Nanophotonics Technology Center (NTC) in Valencia. The characterisation will allow to determine if the newly produced set can be compared to the previously built using the old equipment. To do so, an equivalent set to the old one has been fabricated with the new equipment. We also want to know if these structures that come in pairs are similar enough to each other so that it would be possible to perform synchronization experiments similar to those of [3].

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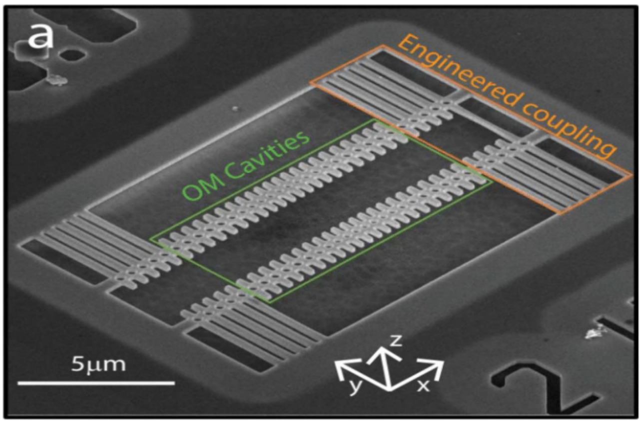

FIG. 2: Pair of OMCs that include an engineered coupling. The green square indicates the cavity where the light will couple.

The comparison will consist of the analysis of some cavities on both sets. For each one of these cavities, optical and mechanical spectrum have been measured. This spectrum will show which modes couple in the cavities and how these cavities behave once coupled.

II. LABORATORY SETUP

The experimental setup is a course with a laser, a polarization controller, the analyzed sample, a light detector and a spectrum analyzer. The laser has adjustable power and wavelength. The power can be set from 0.2 W to 2 W and λ from 1470 nm to 1590 nm. The light generated by the laser is conducted through a fiber and passes through a polarization controller. This controller is used to align the polarization of the light with the polarization of the cavity modes. For our cavities, this is the TE mode (perpendicular to the propagation direction and parallel to the plane of the shape). To be able to introduce light to the cavities, the fiber needs to be thin enough to fit between the pairs of cavities. To do so, the fiber is heated to 1180 ºC and stretched to a diameter on the order of microns. In addition, a loop with a $d \sim 10\mu m$ diameter is made to avoid touching the sample with the rest of the fiber. Due to the small diameter of the fiber, only one mode will propagate through it. Consequently, part of the electromagnetic wave will propagate outside the limits of the fiber material, forming an evanescent wave. This evanescent waves is the light that will enter the OMCs. Once the light enters the cavities, it excites an optical mode that couples with the mechanical modes. After the fiber has gone between the cavities, it reaches the light collector. This collector is set to measure the transmitted signal after the fiber has gone trough the sample. Finally, the collector is connected to a spectrum analyzer that measures the radiofrequency power spectrum of the input signal.

The thin fiber deteriorates easily in a short amount of time. If it loses its structure, the transmission decreases and the power that reaches the cavity may be insufficient to induce mechanical motion. Because of this, the fiber loop had to be remade every week to be able to continue with the measurements.

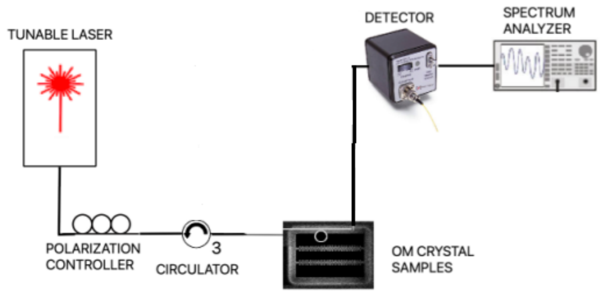

FIG. 3: Experimental setup diagram. Light is emitted from the laser and goes through the fiber. After reaching the polarization controller, the light enters the OMC cavity exciting a particular optical mode that couples with the mechanical modes. The detector collects the light at the end of the fiber and returns the total transmission. Then, via the spectrum analyzer, the mechanical modes confined in the cavity and enhanced by the coupling are identified.

III. OPTICAL Q-FACTOR

The quality factor (Q) is a dimensionless parameter that characterizes the damping rate of resonators. It is also defined as the ratio of the resonance wavelength (λ_0) to its full width at half-maximum ($\Delta\lambda$). For an optical cavity, these last two definitions lead to the following expression [4]:

$$Q_{opt} = \omega_{cav}\tau = \frac{\omega_{cav}}{k} = \frac{2\pi\tau}{T} = \frac{\lambda_0}{\Delta\lambda} \tag{1}$$

, where ω_0 is the resonance frequency, τ the lifetime of the photons inside the cavity, k the cavity decay rate, and T the mode's oscillation period.

Generally speaking, the cavity decay rate k can have two contributions, one from losses that are associated with the input coupling (extrinsic), and another from the internal losses (intrinsic). For the case of a high-Q cavity, the total cavity loss rate can be written as the sum of the individual contributions:

$$k = k_e + k_i. \tag{2}$$

The total value of k can be found from Eq.(1).

$$k = \frac{\omega_{cav}}{Q_{opt}} = \frac{2\pi c}{\lambda_0 Q_{opt}}. \tag{3}$$

In the experiment performed in this study, the extrinsic losses come from the losses trough the fiber. Light escapes from the fiber and enters the cavity but it can also escape from the cavity back to the fiber. The intrinsic loss rate refers to the losses of the system due to surface/volume scattering and/or material absorption.

Finally, joining Eq.(1) and Eq.(2) we find:

$$\frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_e}. \tag{4}$$

The transmitted field collected by the channels allows us to compute the values of Q and Q_e. The transmission has the following expression:

$$T = |\frac{a_{out}}{a_{in}}| = |1 - \frac{\eta k}{i\Delta + k/2}|^2. \tag{5}$$

Where $\Delta = \omega_0 - \omega_{laser}$ and the coupling efficiency $\eta = 2\frac{k_e}{k}$. In perfect resonance $\Delta = 0$. Then, the transmission can be expressed as:

$$T = T_0 = (1 - 2\eta)^2 = (1 - \frac{k_e}{k})^2. \tag{6}$$

The transmission depth (T_0) is defined as the lowest transmission reached in the optical spectrum of a mode divided by the power when light is not coupled. Then, it is easy to find the value of k_e as:

$$k_e = k(1 - \sqrt{T_0}). \tag{7}$$

From Eq.(2), the value of k_i is found and used in Eq.(1) to determine the value of Q_i.

A. Measurements

To make an accurate approximation of the quality factors value, a closer look into a single mode is needed. The full-scale optical spectrum is measured with a power around $0.2mW$. The high power leads to the cavity warming, changing the resonance mode. This can be seen on Fig.(4), where some modes get a "saw tooth" asymmetric shape, depending on the thermal effect.

After the complete optical spectrum, I measured the first resonance mode of each cavity again. This measurement was made with a lower power, around $P \sim 0.02mW$, to avoid thermal heating effect. In addition, the λ step was lowered to achieve a higher definition. This individual spectrum will be the data needed to compute the Q factor.

B. Calculations

Once the meaning of the quality factor has been explained, we proceed to compute it. The data is arranged in a non-linear fitting to approximate it to a Lorentzian function. This way, it gives the value of the mode's width ($\Delta\lambda$) and the center of the peak.

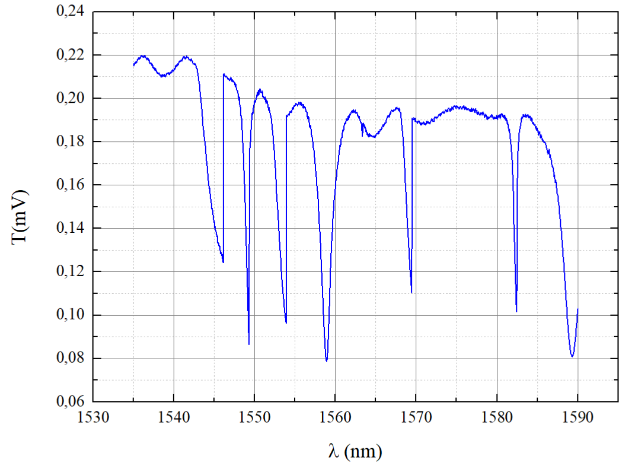

FIG. 4: Optical spectrum of a cavity on the new set. It shows the dependency between the transmission measured by the collector, and the wavelength of the light the laser is emitting. The measurements were made at $P = 0.2W$. A "saw tooth" peak can be seen in the first mode.

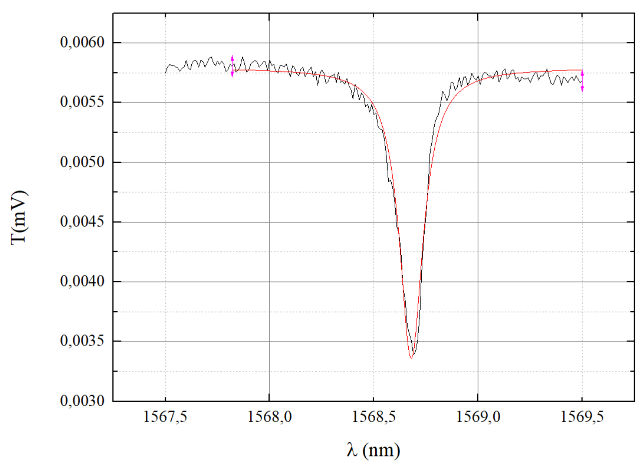

FIG. 5: Optical spectrum with a lower power ($P \sim 0.02W$) and lower λ range. It is the same mode as the 5th on Fig.(4). The red line is the result of the Lorentzian fitting of the experimental data.

From Eq.(1), the value of Q_{opt} is computed. Eq.(5) can be rearranged to find the value of k_e/k:

$$\frac{k_e}{k} = 1 - \sqrt{T_0} \tag{8}$$

From Eq.(2), k_i is found and finally, Q_i can be determined from Eq.(3).

It is important to note the significance of Q_i. The total value Q_{opt} can change every time the experiment is performed since it depends on external factors. A slight difference on fiber placement will make this value change. The value that is expected to be consistent every time the experiment is performed is the intrinsic, since it is defined by the cavity structure.

The computed Q_i values of the new cavity came around $Q_i \sim 2{\cdot}10^4$. These values are similar to the ones found for the old set of cavities ([5]). This shows that the quality of both new and old sets are similar.

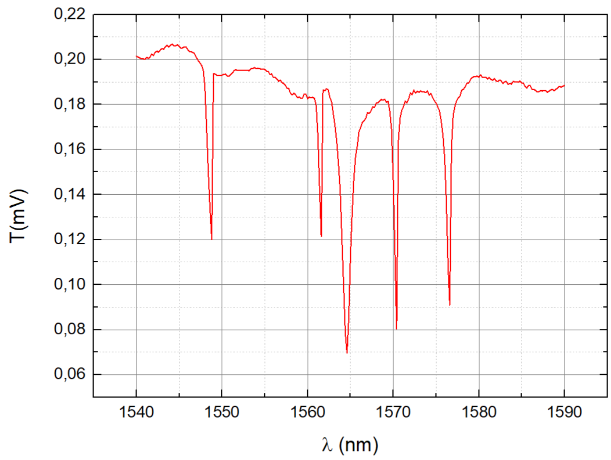

FIG. 6: Optical spectrum of a cavity in the old set. The measurements were made at P = 0.2W.

IV. MECHANICAL Q-FACTOR

The transduction mechanism is the connection between the optical quality factor and the observation of mechanical modes. The mechanical motion moves the photonic cavity at the mechanical eigenfrequencies, resulting in modulation of the transmitted signal. If Q_{opt} is high enough, the modulation amplitude will increase, allowing mechanical modes to surpass the noise.

The cavities' mechanical modes have low frequencies (MHz - GHz) and are populated at room temperature. The optical modes with higher frequencies ($\sim 10THz$) need to bee populated with the light coming from the laser. If the spacial distribution of the mechanical modes and the optical modes overlap, an optical mode can be excited to measure the mechanical oscillations thermally activated (see Fig.(7). If conditions are met, the coupled light might pump coherently a mechanical mode. Only if a high quantity of optical energy is coupled into the cavity, the later enters a high-amplitude coherent regime that surpasses the dissipation in the system. This regime is identified as phonon lasing [6]. In this regime, a much higher signal of the mechanical activity can be recorded as it is visible from Fig.(7) and Fig.(8).

A. Measurements

Not every mode in the optical spectrum will couple with a mechanical mode. The ones that do will show on the spectrum analyzer some interaction that exceeds the base noise.

The measurements taken are the average of multiple readings of the spectrum analyzer for one optical mode. To have a significant mechanical coupling, the power of the laser has to be high. The spectrum is measured again with higher resolution for a specific mode. This will allow to compute the mechanical Q factor from the mechanical spectrum.

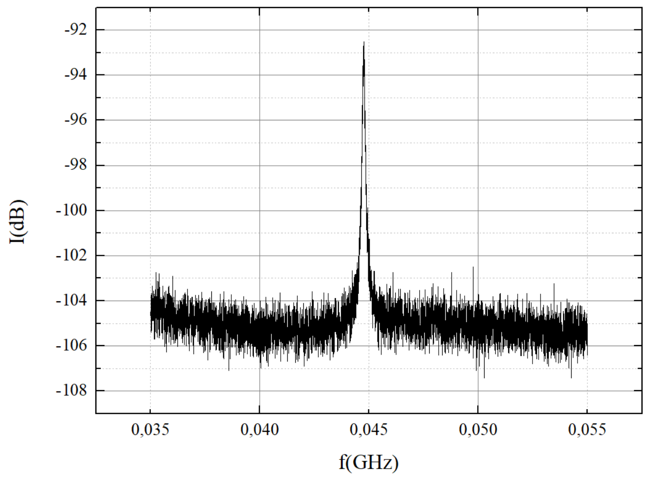

FIG. 7: Measurement of the mechanical spectrum of a cavity on the new set to compute the Q factor of the cavity. The mechanical mode at 40 MHz has been thermally activated.

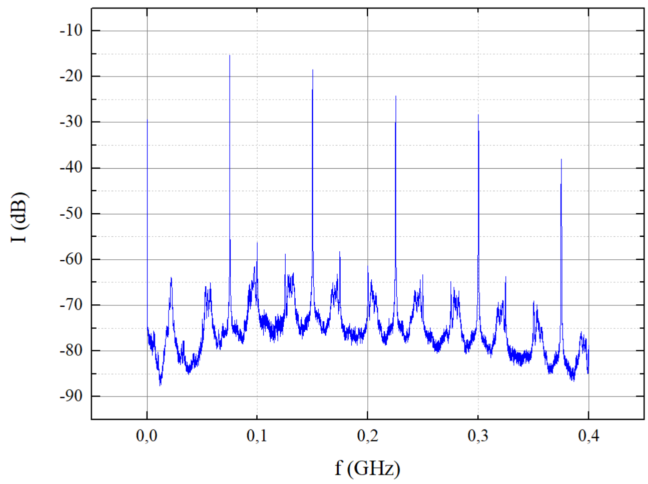

FIG. 8: Mechanical spectrum of a cavity mode on the new set where lasing is occurring.

On the old set, it was not rare to see optical modes that induced lasing on the cavities. This was not as common for the new set, where only one out of the 8 pairs analyzed achieved lasing regime.

B. Calculations

The mechanical Q factor does not need to be separated into extrinsic and intrinsic factors. The reason why the extrinsic value does not need to be factored in is that the fiber is not touching the cavities. Because of this, all the loses the cavity experiments are associated to its structure (intrinsic value).

This time, the measurements were taken with the spectrum analyzer that gave the $I(f)$ behavior of the cavity mechanical modes. After the non-linear adjustment and getting the necessary parameters, the value of the mechanical quality factor this cavity showed was $Q = 384,3$. This is a reasonable value for the mechanical quality factor, and it is higher than the one found on the old set of cavities $Q_{old} \sim 300$ ([5]).

V. CONCLUSIONS

This experiment aimed to characterize the new set of cavities and see which pairs functioned as expected. The behavior of the cavities through the experiment was mostly consistent. This allows to take some conclusions from the set's fabrication:

- The new set of cavities has an odd behavior on the optical modes. There were more than expected, sometimes overlapping. Moreover, it was hard to determine which mode from each cavity was on display.
- Generally, it was hard to see any activity on the mechanical spectrum for most of the cavities. The old set of cavities showed more optomechanical resonance between the optical and mechanical modes. Nevertheless, I could find a pair of cavities on the new set with great optomechanical coupling. The cavities presented self-pulsing and lasing regimes for an optical mode but not much interaction for the other modes.
- The unexpected results might come from a defect in the fabrication of the set. If the e-beam used was not well calibrated (off ratio of electrons per unit of area per second), the resulting geometries of the structure could be bigger or smaller than the design. These possible fabrication imperfections could explain the presence of more and different optical modes on the new set. The imperfections could also be the reason why the mechanical modes were displaced from the optical modes, meaning optomechanical resonance could not occur.

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