High-finesse Fabry–Perot cavities with bidimensional Si$_3$N$_4$ photonic-crystal slabs

Xu Chen$^1$, Clément Chardin$^1$, Kevin Makles$^1$, Charles Caër$^{1,2}$, Sheon Chua$^1$, Rémy Braive$^{3,4}$, Isabelle Robert-Philip$^3$, Tristan Briant$^1$, Pierre-François Cohadon$^1$, Antoine Heidmann$^1$, Thibaut Jacqmin$^1$ and Samuel Delégise$^1$

Light scattering by a two-dimensional photonic-crystal slab (PCS) can result in marked interference effects associated with Fano resonances. Such devices offer appealing alternatives to distributed Bragg reflectors and filters for various applications, such as optical wavelength and polarization filters, reflectors, semiconductor lasers, photodetectors, bio-sensors and non-linear optical components. Suspended PCS also have natural applications in the field of optomechanics, where the mechanical modes of a suspended slab interact via radiation pressure with the optical field of a high-finesse cavity. The reflectivity and transmission properties of a defect-free suspended PCS around normal incidence can be used to couple out-of-plane mechanical modes to an optical field by integrating it in a free-space cavity. Here we demonstrate the successful implementation of a PCS reflector on a high-tensile stress Si$_3$N$_4$ nanomembrane. We illustrate the physical process underlying the high reflectivity by measuring the photonic-crystal band diagram. Moreover, we introduce a clear theoretical description of the membrane scattering properties in the presence of optical losses. By embedding the PCS inside a high-finesse cavity, we fully characterize its optical properties. The spectrally, angular- and polarization-resolved measurements demonstrate the wide tunability of the membrane’s reflectivity, from nearly 0 to 99.5470 ± 0.0025%, and show that material absorption is not the main source of optical loss. Moreover, the cavity storage time demonstrated in this work exceeds the mechanical period of low-order mechanical drum modes. This so-called resolved-sideband condition is a prerequisite to achieve quantum control of the mechanical resonator with light.

Keywords: Fano resonance; high-reflectivity membrane; low-loss optical reflector; nanomembrane resonator; photonic-crystal slab; quantum optomechanics

INTRODUCTION

Fano resonances resulting from the interference between a discrete resonance and a broadband continuum of states are ubiquitous in physical science and constitute a unique resource in the field of nanophotonics$^1$. The scattering properties of subwavelength periodic structures can be tailored by engineering their asymmetric Fano lineshapes. These extraordinary and controllable optical properties hold great promise in the context of nanophotonics, where fully integrated photonic-crystal slabs (PCS) can replace traditional Bragg multi-layers for various optical components. This approach has been successfully implemented in the context of optical filters$^2$, switches$^3$, sensors$^4$, lasers$^5$, detectors$^6$, slow-light and non-linear devices$^7$. It has also been proposed as a possible route to reduce thermal noise in the mirrors of large-scale gravitational-wave interferometers$^8$.

Moreover, nanophotonics is playing an increasing role in the field of optomechanics by allowing sub-micron-scale mechanical resonators to interact via radiation pressure with highly confined optical fields. A very successful approach consists in co-localizing a photonic and a phononic mode in the small volume of a defect cavity in the plane of a PCS$^9,10$. In this setup, the mechanical resonator consists of a GHz internal vibrational mode localized in a very small mode volume around the defect cavity. More recently, defect-free suspended PCSs have been used as lightweight mirrors of sub-micron thickness$^{11-13}$. The out-of-plane vibrational modes of the membrane can be coupled to an optical field by integrating the membrane inside a high-finesse cavity. Because of their very low mass and low mechanical frequency in the MHz range, such resonators are highly susceptible to radiation pressure. Moreover, they are good candidates to achieve hybrid optoelectromechanical transducers$^{14,15}$ because the out-of-plane vibrational modes of a suspended PCS can be simultaneously coupled with a nearby interdigitated capacitor. Such a device could have a decisive role in future (quantum) information networks because it allows up-conversion of microwave signals onto an optical carrier for subsequent detection or transmission into optical fibers.
Suspended membranes made from thin layers of high-stress materials are an advantageous platform for the development of optomechanical PCSs because they present excellent mechanical properties\(^\text{16}\). For instance, recent experiments have demonstrated Q-factors exceeding 10\(^8\) with high-stress Si\(_3\)N\(_4\) films at room\(^\text{17,18}\) and cryogenic\(^\text{19}\) temperatures. Moreover, on the optical side, a stringent requirement is the resolved-sideband (or good cavity) limit\(^\text{20}\), which is achieved for the first time with a PCS used as the end mirror of a Fabry–Perot cavity. The cavity finesse of 6390 ± 150 is, to the best of our knowledge, an unprecedented value with free-space PCS cavities. The inferred membrane reflectivity is given by 1 − \(R = 530 ± 25\) ppm. Moreover, we measured the band diagram of the guided resonances responsible for the Fano resonances in the PCS with an angle-resolved spectrometer. In contrast with previous studies conducted in the context of PCS optical filters\(^\text{22}\) and reflectors\(^\text{23}\), we give a physical interpretation of the observed band diagram and shed new light on the physics of these structures. Finally, we introduce a theoretical description of the scattering properties of the PCS in the presence of optical losses and demonstrate that the current reflectivity is not limited by material absorption. Demonstrating high-reflectivity PCS in a high-tensile stress film, such as Si\(_3\)N\(_4\), as evidenced here could also be beneficial in fields other than optomechanics, such as the generation of tunable optical filters\(^\text{24}\) or optomechanical lasers\(^\text{5}\).

**MATERIALS AND METHODS**

**Membrane and photon-crystal fabrication**

The commercial membranes\(^\text{25}\) are made of a 200-nm stoichiometric Si\(_3\)N\(_4\) film deposited on a Si substrate and released over a 1 × 1 mm square by chemical etching of the substrate (Figure 1a). The high-stress in the film ensures mechanical modes with quality factors as high as 10\(^8\) at low temperature\(^\text{19}\) and ultra-low mass\(^\text{26}\). The photonic crystal is realized in the center of the membrane. It is obtained by electron-beam lithography on a layer of 200 nm of polymethyl methacrylate (PMMA) resist, followed by reactive ion etching with a plasma of CHF\(_3\) and SF\(_6\). The PMMA is then stripped off with oxygen plasma. The photonic crystal consists of a 270-μm diameter disk patterned with a square lattice of circular holes (Figure 1). The lattice parameter is \(A = 830\) nm, and the design value for the hole radius is 293 nm.

**PCS characterization**

**Band diagram measurement.** We implemented the white-light illumination and imaging setup shown in Figure 2a to measure the PCS band diagram. A white halogen lamp is combined with a set of three lenses (L\(_1\), L\(_2\) and L\(_3\)) and two diaphragms (D\(_1\) and D\(_2\)) to obtain a Köhler illumination configuration. A field diaphragm (D\(_3\)) conjugated to the PCS restricts the illumination to the PCS area, thus reducing the impact of light scattered on the optical elements and mounts. The aperture diaphragm D\(_2\) is used to select the incident beam angles at the PCS position. It is centered on the optical axis, and its aperture width is chosen to reject high angle-of-incidence components that are irrelevant for this experiment. A magnified image of the PCS is obtained with a microscope objective (L\(_4\)) and a lens (L\(_5\)). A field diaphragm (D\(_3\)) sits at the image plane, conjugated to diaphragm D\(_1\), providing additional filtering of unwanted scattered light. A fiber tip is positioned in the focal plane of lens L\(_4\), that is, in the Fourier plane of this imaging system. The light collected by the fiber is guided to a near-infrared spectrometer. By scanning the fiber in the transverse (\(x, y\)) plane, the transmission spectrum can be measured at different angles. Moreover, a polarizer (Pol) is introduced between L\(_1\) and L\(_2\) for polarization selection.

**PCS reflection, transmission and loss measurements.** We implemented a single-ended cavity with the PCS as the end mirror (Figure 2b) to characterize its reflectivity, transmission and losses. The input mirror of the cavity has a 20-mm radius of curvature, and the cavity length is 17.4 mm. This ensures a waist size \(w_0 = 48\) μm on the PCS, smaller than the lateral extent of the photonic crystal, and an angular dispersion \(\Delta \theta = \arctan(\frac{w_0}{\lambda}) = 7 \times 10^{-3}\) rad that has a negligible influence on the optical properties of the PCS. A motorized Littman–Metcalf stabilized diode laser system from Sacher Lasertechnik GmbH (Marburg, Germany) (Lion TEC-520) is used to probe the cavity. The cavity transmission is monitored with an avalanche photodiode (Thorlabs, Newton, NJ, USA, APD110H) and is recorded continuously, while the laser wavelength is scanned over 4.8 nm. Simultaneously, the fringes of an imbalanced fiber interferometer are counted by a digital system (based on an Arduino micro-controller\(^\text{27}\)).

![Figure 1](image-url)

**Figure 1** (a) Optical image of the PCS made of a high-stress Si\(_3\)N\(_4\) membrane suspended on a Si frame. The disk in the center is the photonic crystal. (b) Optical microscope image of the PCS. (c) Scanning electron micrograph of the PCS.
where the symmetry of the membrane with respect to the xOy plane is used to assume that the direct (r,t) and reciprocal (r仲t仲) complex reflection and transmission coefficients are equal. The previous assumption allows S to be diagonalized

\[ S = V \begin{pmatrix} r + t & 0 \\ 0 & r - t \end{pmatrix} V^{-1} \]  

with the change of basis \( V = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \).

For a lossless membrane, S is unitary (\( r + t = 1 \)), such that within a global phase factor, it is entirely determined by a real parameter, for instance the transmission intensity \( T = |r|^2 \). However, in the presence of losses, the scattered fields have a total intensity smaller than the input fields, and both eigenvalues obey

\[ |r + t| \leq 1 \]  
\[ |r - t| \leq 1 \]

Three real parameters (plus a global phase term) are required to fully describe S: in addition to the transmission intensity \( T \), we introduce the optical losses

\[ L_{\pm} = 1 - |r \pm t|^2 \]  

associated with the symmetric and antisymmetric combinations of the left and right incoming fields \( \begin{pmatrix} a_{in,1} \\ a_{in,2} \end{pmatrix} \). To obtain a measurement of \( L_{\pm} \), the membrane can be positioned in the center of a high-finesse cavity. This setup, initially proposed by the group of J. Harris \( ^{28} \), consists of two single-ended cavities coupled via the transmission of the membrane. If the input and output mirrors have the same reflectivity amplitude \( r \) and if both sub-cavities have the same length \( l \), one obtains, in the absence of fields incident from outside the cavity (Figure 2b):

\[ a_{in,1} = t r e^{-2ikl} a_{in,1} + t r' e^{-2ikl} a_{in,2} \]  
\[ a_{in,2} = t r e^{-2ikl} a_{in,1} + t r' e^{-2ikl} a_{in,2} \]

where \( k = \omega / c \) is the wavenumber of the propagating field. The eigenmodes of the total optical cavity correspond to non-trivial solutions of this system for complex angular frequencies \( \omega \). By taking the sum and difference of the previous equations, we obtain

\[ a_{in,1} + a_{in,2} = (r + t) e^{-2ikl} [a_{in,1} + a_{in,2}] \]  
\[ a_{in,1} - a_{in,2} = (r - t) e^{-2ikl} [a_{in,1} - a_{in,2}] \]

Non-trivial solutions of this system correspond to symmetric (+) (antisymmetric (−)) modes with angular frequency \( \omega_{p,\pm} \) and damping (full width at half maximum) \( \gamma \) given by

\[ \omega_{p,\pm} = \text{Re}(\omega_{p,\pm}) = -\frac{\gamma}{2l} \arg([r \pm t] r') + 2\pi \]  
\[ \gamma = 2\text{Im}(\omega_{p,\pm}) = \frac{\gamma}{t} \log(|r \pm t||r'|) \]
where \( p \) is an integer corresponding to the longitudinal mode number. From Equation (10), the frequency splitting between the symmetric and antisymmetric modes of identical longitudinal numbers is given by:

\[
\Delta \nu = \frac{\alpha_{p+} - \alpha_{p-}}{2\pi} = \frac{c}{4\pi} \arg\left(\frac{r-t}{r+t}\right)
\]

Finally, if the membrane losses \( L_s \) and mirror losses \( L' = 1 - |r|^2 \) are small, Equation (11) simplifies to

\[
y \approx \frac{c}{2\pi} (L_s + L')
\]

Hence, the damping of the symmetric and antisymmetric modes gives direct access to the two parameters \( L_s \) and \( L' \).

To perform this measurement, a 32-mm long cavity is formed by two mirrors with transmission-limited losses \( L' = 455 \) ppm and radii of curvature 20 mm. The PCS is set in the center of the cavity on a three-axis translation stage. To align the cavity axis with respect to the PCS, the end mirror is also mounted on a two-axis translation stage. Finally, the PCS frame is glued on a piezoelectric stack to allow automatic scans of its \( z \) position over several free spectral ranges.

**RESULTS AND DISCUSSION**

**Band diagram of the PCS**

The physics of high-contrast gratings has previously been described in detail. Here we extend it to the case of a PCS, following earlier work. The high-reflection properties of the PCS result from Fano resonances arising from an interference between the direct reflection from the PCS and light leaking out from internal high-Q guided modes in the PCS. To unveil the band structure of the guided modes, we calculate the transmission of the PCS by rigorous coupled wave analysis (RCWA), which is suitable for periodic structures, such as our square lattice of holes (lattice parameter \( \Lambda = 830 \) nm, membrane thickness \( h = 213 \) nm and hole radius \( \eta = 276 \) nm). We begin the analysis with the unpatterned membrane limit, for which the dielectric constant of both the membrane material and the holes is set to an average value \( \varepsilon_{\text{eff}} = \eta_{\text{air}} + (1 - \eta) \varepsilon_{\text{Si3N4}} = 2.95 \). The field solutions are guided modes, referred to as 'unperturbed modes' in the following discussion. They are plane waves reflected by total internal reflection upon the two faces of the membrane. In this regime, the unperturbed modes are evanescent outside of the membrane: the \( z \) component of their wavevector fulfills \( k_z = \frac{\pi}{n} \) inside the membrane and \( k_z = \frac{\pi}{n} + \frac{\pi}{\Lambda} \) in the surrounding medium. TE (TM) modes have their electric (magnetic) field within the plane of the membrane and are represented in Figure 3 in red (blue). The eight modes are sorted according to their symmetry class with respect to the \( xOz \) plane.
Symmetric modes (TM(±1, 0)) are not excited under s-illumination, whereas antisymmetric modes (TE(±1, 0)) are not excited under p-illumination. The complex coefficients describing the reflection inside the membrane for the electric field are given by Fresnel’s law

\[ r_{TM} = \frac{k_{z,m} - n_{air}k_{z,air}}{k_{z,m} + n_{air}k_{z,air}}, \quad r_{TE} = \frac{n_{air}k_{z,air} - k_{z,m}}{n_{air}k_{z,air} + k_{z,m}} \]

We have numerically solved the round-trip resonance condition within the membrane

\[ r_j^2 e^{-2ik_{z,abh}} = 1 \]  

for \( j = TE \) or \( TM \) and for the lowest possible value of \( \omega = \epsilon (k_x + 2p_x \pi /A)^2 + (2p_y \pi /A)^2 + k_{z,m}^2 \), (where \( p_x, p_y = (\pm 1, 0) \) or \( p_x, p_y = (0, \pm 1) \) are the diffraction orders in the \( x \) and \( y \) directions, respectively). Note that the periodicity \( A \) is not a property of the unpatterned membrane and is arbitrarily chosen to match that of the patterned membrane. Given the phases of \( r_{TE} \) and \( r_{TM} \), we find that TE modes have a lower fundamental resonance frequency than TM modes. Finally, the symmetry of the mode with respect to the \( xOy \) plane is given by the sign of the half round-trip propagation coefficient

\[ r_j^2 e^{-2ik_{z,abh}} = \pm 1 \]  

From the expressions of \( r_{TE} \) and \( r_{TM} \), it follows that the fundamental TE (TM) mode is antisymmetric (symmetric) with respect to \( xOy \). The calculated mode frequencies as a function of transverse wavevector \( k_x \) are represented by the lines in Figure 3c and 3d. To first order, the frequency of the modes diffracted along the \( y \) direction is not affected by the transverse \( k_x \) component, contrary to the modes diffracted along the \( x \) direction.

The results of the RCWA for the patterned membrane are superimposed as a color plot in Figure 3c and 3d (the refractive index of Si3N4 is given by \( \epsilon_{Si3N4} = 1 + 2.89392 \lambda^2 / (\lambda^2 - 0.13867 \mu m^2) \)). In this case, the modes described in the unpatterned case are now coupled by diffraction, giving rise to avoided crossings. In addition, the reflections at the membrane/air interfaces couple the guided modes to the zeroth-order modes propagating in free-space, leading to an effective loss channel. The guided resonances acquire a finite lifetime inversely proportional to the width of the Fano resonance (cut along a fixed value of \( k_z \) in Figure 3). The lifetime of the TM modes is ~20 times that of the TE modes. At normal incidence, the \( yOz \) plane constitutes an additional plane of symmetry (antisymmetry) in the \( s- \) (p-) polarization, and, hence, only the combinations TE(1, 0)+TE(−1, 0) and TM(0,1)+TM(0,−1) (respective TE(0, 1)+TE (0,−1) and TM(1,0)+TM(−1,0)) are effectively coupled to free-space modes: the linewidth of the other Fano resonances vanishes close to \( k_z = 0 \). The white-light angle-resolved spectrometer described previously allowed us to measure the band structure of the guided modes for small transverse wavevectors \( k_x \). The experimental transmission with \( s- \) (p-) illumination is presented in Figure 3e and 3f, together with three different cuts with incidence angles 3.45°, 1.32° and 0.33°. The simulation is fitted to the data with the hole radius and membrane thickness as free parameters. The former is only specified to within 10% accuracy, and the latter may differ from the design value due to imperfect pattern transfer on electron-beam lithography and etching. The fitted values \( h_1 = 276 \text{ nm} \) and \( h_2 = 213 \text{ nm} \) are in good agreement with the design values. The theoretical fits are represented in blue in Figure 3g and 3h. The reduced visibility of the peaks, particularly pronounced with the TM modes, is accounted for by convolving the theoretical map with the 4-nm wide response of the spectrometer.

In the next section, we analyze in greater detail the TE Fano resonance responsible for the largest dip in transmission close to \( v = c \times 0.929 \mu m^{-1} = \epsilon / (1.076 \mu m) \) in Figure 3g and 3h.

**Detailed characterization of a Fano resonance**

For optical frequencies \( v = c/\lambda \) close to a guided mode resonance, the PCS complex reflection and transmission coefficients \( r \) and \( t \) are given in good approximation by the simple two-mode model

\[ r(\lambda) = r_d \pm \frac{\gamma}{i(\lambda - \lambda_0) + \gamma} (\pm r_d - t_d) \]

\[ t(\lambda) = t_d + \frac{\gamma}{i(\lambda - \lambda_0) + \gamma} (\pm r_d - t_d) \]

where \( r_d \) and \( t_d \) are the off-resonant coefficients \((|r_d + t_d| = |r_d - t_d| = 1)\), \( \lambda_0 \) is the wavelength of the guided mode resonance, \( \gamma \) is the resonance width and the plus/minus sign in Equation (15) reflects the symmetry of the guided mode: as discussed in the previous section, the lowest-order TE mode is antisymmetric with respect to the \( xOy \) plane; thus, the minus sign applies. In the absence of optical losses, a striking feature of this Fano lineshape is the existence of a frequency \( \lambda_1 = \lambda_0 + i \gamma \Gamma / \gamma (\lambda_1) \) for which the PCS transmission vanishes: \( T(\lambda_1) = |t(\lambda_1)| = 0 \), and, accordingly, the reflectivity tends to unity: \( R(\lambda_1) = |r(\lambda_1)|^2 = 1 \).

By fitting the RCWA results with Equations (15) and (16) around the largest TE Fano resonance, we determine \( \lambda_1 = 1076 \text{ nm} \) and \( \gamma = 12 \text{ nm} \). To study the optical behavior of the PCS around \( \lambda_1 \), a single-ended optical cavity of length \( L_0 \) is achieved, using the PCS as the end mirror (Figure 2). The transmission of the cavity is monitored, whereas a tunable diode laser is swept across the Fano resonance. The recorded signal, shown in Figure 4a, displays a comb of peaks spaced by the free-spectral range of the cavity given by

\[ \Delta \lambda_{FSR} = \frac{\lambda_0^2}{2\Gamma} \]  

The linewidth \( \Delta \lambda(\lambda) \) of each longitudinal cavity mode \( n \) is then obtained by fitting a Lorentzian profile to each of the individual peaks. To minimize the impact of scan-speed fluctuations, we generate 50 MHz sidebands in the laser spectrum with an electro-optic modulator for frequency calibration of the instantaneous scanning speed. Denoting the finesse of the cavity by \( F(\lambda) \), the total round-trip loss of the cavity is given by \( \Gamma_{RTL}(\lambda) = 2(1 - F(\lambda)) = 2\Delta \lambda(\lambda)/\Delta \lambda_{FSR}(\lambda) \). The results are plotted in blue in Figure 4b as a function of the laser wavelength. The lowest level of \( \Gamma_{RTL} = 985 \pm 25 \text{ ppm} \) corresponds to a finesse of 6385 ± 25 was found at \( \lambda_1 = 1070.9 \text{ nm} \). The 5.1 nm discrepancy with respect to the results of Figure 3 is quite small considering that two different membranes from the same microfabrication run were used in these experiments. In the simulations, it is accounted for by changing the hole radius from \( r_h = 276 \text{ nm} \) to \( r_h = 285 \text{ nm} \). Taking into account the 455 ppm transmission of the input mirror, we infer a membrane reflectivity as good as \( 1 - R(\lambda_1) = 530 \text{ ppm} \).

To discriminate between the contributions of the membrane transmission \( T(\lambda) = |t(\lambda)|^2 \) and the optical losses \( L(\lambda) = 1 - R(\lambda) - T(\lambda) / \Gamma_{RTL}(\lambda) \), we use the extra information embedded in the height of the transmitted peaks. The transmission \( T_n(\lambda) \) of the cavity at resonance with the \( n \)th mode is given by

\[ T_n(\lambda) = \frac{4\Gamma_c T(\lambda)}{\Gamma_{RTL}(\lambda)} \]
signal proportional to \( T_c(\lambda) \) is measured, so that we can deduce \( T(\lambda) \) from Equation (18) within a multiplicative constant \( \alpha \). By assuming that the losses \( L(\lambda) \) are within the interval \([0, L_{RTCL}(\lambda_1)]\) at the highest accessible wavelength, we obtain a confidence interval for \( \alpha \) and hence for \( T(\lambda) = T_{RTCL}(\lambda) - L(\lambda) \) (in green in Figure 4c and 4d) and \( T(\lambda) \) (in red) over the whole wavelength range. For comparison, the transmission calculated by RCWA is displayed by a green solid line in Figure 4c and 4d. The agreement between RCWA and the experimental results is excellent. At the Fano resonance \( \lambda_1 = 1070.9 \) nm, the round-trip damping is vastly dominated by membrane losses. The lowest cavity bandwidth \( \kappa/2 = c/4dF(\lambda_i) = 675 \) kHz measured in this single-ended cavity setup approaches the resolved-sideband condition for the first-order flexure modes of the suspended membrane.

To understand the exact form of the scattering matrix and to gain insight into the origin of the losses observed in the previous experiment, a PCS is positioned in the middle of a high-finesse cavity. The PCS position \( \Delta l \) is scanned along the cavity axis with a piezoelectric actuator. In this configuration, the PCS couples two cavities of length \( l_1 + \Delta l/2 \) and \( l_1 - \Delta l/2 \), where \( l_1 \approx l_2 \approx l \) are the initial lengths of the first and second sub-cavities, which are assumed to be simultaneously resonant with the central laser wavelength \( \lambda_c \) for \( \Delta l \approx 0 \). The cavity transmission, recorded as a function of \( \Delta l \) and laser detuning \( \Delta \nu = \nu_c - \lambda_c \), is represented in the color plots of Figure 5a–5c. The avoided crossing of the symmetric and antisymmetric modes is visible in the center of the figure. From a Lorentzian fit of the peaks at the avoided crossing and along the vertical axis, we extract the frequency spacing \( \Delta \nu \) and the linewidth \( \gamma \), of the symmetric and antisymmetric modes. The experiment is then reproduced for several laser wavelengths \( \lambda \) close to the Fano resonance, and the corresponding frequency spacings and linewidths are shown in Figure 5d and 5e, respectively.

In Figure 5a and 5c, the upper and lower branches of the avoided crossing are strongly asymmetric. This is a direct consequence of the difference between \( L_+ \) and \( L_- \). For \( \lambda \approx \lambda_1 \) (Figure 5a), the phase of \( (r-t)/(r+t) \) is positive, such that from Equation (12), the symmetric mode (angular frequency \( \omega_+ \)) constitutes the upper branch of the crossing, whereas the antisymmetric mode (angular frequency \( \omega_- \)) is the lower branch. On the other hand, for \( \lambda > \lambda_1 \) (Figure 5c), \( \Delta \nu = (\omega_+ - \omega_-)/2\pi \) changes its sign and the upper and lower branches are exchanged. Finally, at the Fano resonance \( \lambda = \lambda_1 \), \( r \) and \( t \) are in phase, so the symmetric and antisymmetric modes are perfectly degenerate. Combined with the inequalities of Equation (3), an upper bound for the transmission of the membrane can be derived: \( |t| \leq 1 - |r| \) at the Fano resonance. For \( 1 - R = 985 \) ppm, this corresponds to a transmission as low as \( T \leq 0.2 \) ppm. Hence, the residual transmission of 100 ppm observed in Figure 4 is in contradiction with the two-port description developed in this work. A first explanation is the possible scattering into non-overlapping spatial modes due to surface roughness. Moreover, given our experimental parameters, we expect from RCWA that the wavevector components of the input Gaussian beam not aligned with a symmetry plane of the membrane should give rise to \( \approx 20 \) ppm transmission into the polarization orthogonal to the input beam (with a spatial distribution that is antisymmetric with respect to the \( xOz \) and \( yOz \) planes). Nevertheless, as shown in Figure 4, the residual transmission only accounts for a small fraction of the total cavity losses close to the Fano resonance, and the nature of these losses remains to be elucidated.

The difference between the losses \( L_\pm \) experienced by the symmetric and antisymmetric modes is captured by a simple phenomenological model; because the Fano resonance results from the interference between direct PCS transmission and a high-Q guided resonance, it can be safely assumed that the losses mostly affect the former. Hence, Equations (15) and (16) are modified to include a phenomenological loss rate \( \gamma' \) in the high-Q response as

\[
\begin{align*}
r(\lambda) &= r_d + \frac{7}{2(\lambda - \lambda_0)^2 + \gamma'^2} (r_d + t_d) \\
t(\lambda) &= t_d - \frac{7}{2(\lambda - \lambda_0)^2 + \gamma'^2} (r_d + t_d)
\end{align*}
\]
Using this model, it follows that

\[ L_+ = 0 \]  

\[ L_- = \frac{4\gamma'\gamma}{(\gamma + \gamma')^2 + (\lambda - \lambda_0)^2} \]

thus, only the antisymmetric mode of the two-cavity setup is affected by the optical losses, with a value proportional to the Lorentzian response of the guided resonance. This is an intuitive result because the antisymmetric guided resonance under study is not driven by a symmetric incoming field (and vice versa for the symmetric TM mode resonance). The previous model shows that the asymmetry is a direct consequence of the physics of Fano resonances and is not specific to a particular loss mechanism, such as absorption or scattering, because both would preferentially affect the high-Q guided mode. This finding is in stark contrast with a model recently proposed in Ref. 21, where such an asymmetry was attributed to absorption in the material. Moreover, we show in the following that absorption should have a negligible influence on the optical loss of our PCS. If the losses observed in our experiment were entirely due to optical absorption, the value \( \text{Im}(\eta) = (3.5 \pm 1.5) \times 10^{-5} \) could be derived for the absorption of the Si3N4 layer. The values of \( L_+ + L' \) obtained by RCWA simulation, including an absorption of \( 2 \times 10^{-5} \leq \text{Im}(\eta) \leq 5 \times 10^{-5} \) are located within the shaded areas in Figure 5e. Because previous experiments have found values for the absorption of a similar layer that are an order of magnitude smaller (\( \text{Im}(\eta) = 2.0 \times 10^{-6} \)), we conclude that scattering is the main source of losses. In the single-ended cavity case, where the field is essentially incident on one side of the membrane, the relevant optical losses are given by \( L = (L_+ + L'_-) / 2 \). Thus, the decrease of optical losses with optical wavelength visible in Figure 4b is consistent with Equations (19) and (20). With the previous smaller value of Si3N4 absorption, RCWA simulation shows that a reflectivity as high as \( R \approx 80 \) ppm, corresponding to a finesse close to 80 000, could be achieved by improving the PCS fabrication process.

**CONCLUSIONS**

High-stress Si3N4 films have been successfully patterned to achieve a 2D PCS and have provided a detailed study of the rich mode structure underlying the high reflectivity of the crystal. We have fully characterized the scattering and loss properties of the device. We have also experimentally demonstrated the wide tunability of the membrane reflectivity via adjustment of the laser wavelength close to a Fano resonance. Such tunability is highly desirable in the context of...
membrane-in-the-middle optomechanics experiments. In particular, the ability to reach a very narrow energy gap between the eigenmodes of the coupled cavities can be used to enter the regime where the photon exchange time becomes comparable to the mechanical period. This would enable the observation of mechanically induced coherent photon dynamics, such as Autler-Townes splitting or Landau-Zener-Stueckelberg dynamics. Finally, the bandwidth of the single-ended cavity described in this work, as low as 675 kHz, is in the resolved sideband regime for the first-order harmonics of the drum mode, ranging from 596 kHz for the (0, 1) mode to 1.2 MHz for the (2, 2) mode used in previous quantum optomechanics experiments. Hence, this technique results in devices suitable for the development of optomechanical transducers.

ACKNOWLEDGEMENTS

We acknowledge M. Corcos, I. Krasnokutski, X. Pennevaou and L. Pinol for preliminary experimental developments. We thank J. Palomo and M. Rosticher for developing the first steps of the microfabrication process. Finally, we thank J. Lawall and R. Guérout for insightful scientific discussions. This research has been partially funded by the Agence Nationale de la Recherche programs ‘ANR-2011-B504-029 MINOTORe’ and ‘ANR-14-CE26-0002 QuNaT’, the Marie Curie Initial Training Network ‘cQOM’, and the DMINo-K Illé-de-France program ‘NanomecAtom’. SC is supported by the Marie Skłodowska-Curie Individual Fellowship program, XC is supported by a fellowship ‘Research in Paris’ from the city of Paris.

1 Zhou WD, Zhao DY, Shuai YC, Yang HJ, Chuwongin S et al. Progress in 2D photonic crystal Fano resonance photonics. Prog Quantum Electron 2014; 38: 1–74.
2 Lin CC, Lu ZL, Shi SY, Jin G, Prather DW. Experimen tally demonstrated filters based on guided resonance of photonic-crystal films. Appl Phys Lett 2005; 87: 091102.
3 Yacomotti AM, Raineri F, Vecchi G, Monnier P, Raj R et al. All-optical bistable band-edge Bloch modes in a two-dimensional photonic crystal. Appl Phys Lett 2006; 88: 231107.
4 Magnusson R, Wawro D, Zimmerman S, Ding YW. Resonant photonic biosensors with polarization-based multiparametric discrimination in each channel. Sensors 2011; 11: 1476–1485.
5 Yang WJ, Adair Gerke S, Wei Ng K, Rao Y, Chase C et al. Laser optomechanics. Sci Rep 2015; 5: 13700.
6 Yaqin MF, Fan SH. Stopping and storing light coherently. Phys Rev A 2005; 71: 013803.
7 Yacomotti AM, Monnier P, Raineri F, Ben Bakir B, Seassal C et al. Fast thermo-optical excitability in a two-dimensional photonic crystal. Phys Rev Lett 2006; 97: 143904.
8 Friedrich D, Barj BW, Brückner F, Hild S, Nelson J et al. Waveguide grating mirror in a fully suspended 10 meter Fabry-Perot cavity. Opt Express 2011; 19: 14959–14963.
9 Gavartin E, Braive R, Sagnes I, Arcizet O, Beveratos A et al. Optomechanical coupling in a two-dimensional photonic crystal defect cavity. Phys Rev Lett 2011; 106: 203902.
10 Alegre TPM, Safavi-Naeini A, Winger M, Painter O. Quasi-two-dimensional optomechanical crystals with a complete phononic bandgap. Opt Express 2011; 19: 5658–5669.
11 Kemiktarak U, Metcalfe M, Durand M, Lawall J. Mechanically compliant grating reflectors for optomechanics. Appl Phys Lett 2012; 100: 061124.
12 Bui CH, Zheng JJ, Hoch SW, Lee LYT, Harris JGE et al. High-reflectivity, high-Q micromechanical membranes via guided resonances for enhanced optomechanical coupling. Appl Phys Lett 2012; 100: 021110.
13 Makles K, Antoni T, Kuhn AG, Deléglise S, Briant T et al. 2D photonic-crystal optomechanical nanoresonator. Opt Lett 2015; 40: 174–177.
14 Andrews RW, Peterson RW, Purdy TP, Cicak K, Simmonds RW et al. Bidirectional and efficient conversion between microwave and optical light. Nat Phys 2014; 10: 321–326.
15 Bagci T, Simonson A, Schmid M, Villanueva LG, Zuehlin E et al. Optical detection of radio waves through a nanomechanical transducer. Nature 2014; 507: 81–85.
16 Purdy TP, Peterson RW, Regal CA. Observation of radiation pressure shot noise on a macroscopic object. Science 2013; 339: 801–804.
17 Reinhardt C, Müller T, Bourassa A, Sankey JC. Ultralow-noise SiN trampoline MEMS for sensing and optomechanics. Phys Rev X 2016; 6: 021001.
18 Norte RA, Mora JP, Gröblacher S. Mechanical resonators for quantum optomechanics experiments at room temperature. Phys Rev Lett 2016; 116: 147202.
19 Yuan MY, Cohen MA, Steele GA. Silicon nitride membrane resonators at millikelvin temperatures with quality factors exceeding 10⁹. Appl Phys Lett 2015; 107: 263501.
20 Schlesier A, Rivière R, Anetsberger G, Arcizet O, Kippenberg TJ. Resolved-sideband cooling of a micromechanical oscillator. Nat Phys 2008; 4: 415–419.
21 Stambaugh C, Xu HT, Kemiktarak U, Taylor J, Lawall J. From membrane-in-the-middle to mirror-in-the-middle with a high-reflection sub-wavelength grating. Annal Phys 2015; 527: 81–88.
22 Qiang ZX, Chen L, Yang HJ, Pang HQ, Ma ZQ et al. Fano filter modal analysis based on transferred silicon nanomembranes on plastic substrates. Appl Phys Lett 2008; 93: 061106.
23 Singh Chadha A, Zhao DY, Chuwongin S, Ma ZQ, Zhou WD. Polarization- and angle-dependent characteristics in two dimensional photonic crystal membrane reflectors. Appl Phys Lett 2013; 103: 211107.
24 Stornes T, Grande M, Rainé G, Passaeo A, D’Orazio A et al. Optical filter based on two coupled PHC GaAs-membranes. Opt Lett 2010; 35: 411–413.
25 Norcada Inc., Edmonton, AB, Canada. Available at http://www.norcada.com.
26 Purdy TP, Peterson RW, Yu PL, Regal CA. Cavity optomechanics with Si₃N₄ membranes at cryogenic temperatures. New J Phys 2012; 14: 115021.
27 Arduino. Available at http://www.arduino.cc.
28 Thompson JD, Zwickl BM, Jayich AM, Marquardt F, Girvin SM et al. Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane. Nature 2008; 452: 72–75.
29 Karagodsny V, Sedgwick FG, Chang-Hassnain CJ. Theoretical analysis of subwavelength high contrast grating reflectors. Opt Express 2010; 18: 16973–16988.
30 Karagodsny V, Chang-Hassnain CJ. Physics of near-wavelength high contrast gratings. Opt Express 2012; 20: 10888–10895.
31 Fan SH, Joannopoulos JD. Analysis of guided resonances in photonic crystal slabs. Phys Rev B 2002; 65: 235112.
32 Liu V, Fan SH. S4: A free electromagnetic solver for layered periodic structures. Comp Phys Commun 2012; 183: 2233–2244.
33 Phillips HR. Optical properties of silicon nitride. J Electrochem Soc 1973; 120: 295–300.
34 Serra E, Bawaj M, Borrelli A, Di Giuseppe G, Forte S et al. Microfabrication of large area high stress silicon nitride membranes for optomechanical applications. AIP Adv 2016; 6: 065004.
35 Heinrich G, Harris JGE, Marquardt F. Photon shuttle: Landau-Zener-Stückelberg dynamics in an optomechanical system. Phys Rev A 2010; 81: 011801.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-sa/4.0/

© The Author(s) 2017