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Federico Galeotti,1,a) Ivana Seršič Vollenbroek,1 Maurangelo Petruzella,1,2 Francesco Pagliano,1,2 Frank W. M. van Otten,1 Žarko Zobenica,1 Abbas Mohtashami,3 Hamed Sadeghian Marnani,3 Rob W. van der Heijden,1 and Andrea Fiore1

AFFILIATIONS
1Department of Applied Physics and Institute for Photonic Integration, Eindhoven University of Technology, Eindhoven, The Netherlands
2nanoPHAB B.V., Eindhoven, The Netherlands
3Nano-Opto-Mechanical Instruments, Department of Optomechatronics, Netherlands Organisation for Applied Scientific Research TNO, Delft, The Netherlands

a)Author to whom correspondence should be addressed: f.galeotti@tue.nl

ABSTRACT
Miniaturization of displacement sensors for nanoscale metrology is a key requirement in many applications such as accelerometry, mass sensing, and atomic force microscopy. While optics provides high resolution and bandwidth, integration of sensor readout is required to achieve low-cost, compact, and parallelizable devices. Here, we present a novel integrated opto-electro-mechanical device for displacement sensing that has sub-nanometer resolution. The proposed sensor is a micron-sized double-membrane photonic crystal cavity with integrated electro-optical readout, directly addressed via an on-chip waveguide. This sensor displays a noise floor down to 7 fm/√Hz and is suitable for the realization of integrated arrays.

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High-resolution and high-throughput displacement sensing at the nanoscale is becoming an increasingly important capability in the fields of force sensing, mass sensing, and acceleration. Most commercial applications, such as atomic force microscopy (AFM), employ a mechanical cantilever where changes in the resonance frequency provide information on the forces acting on the cantilever and, thus, on the surface profile. In order to read out the cantilever displacement, a position-sensitive detector is typically employed, for example, using light-deflecting cantilevers. However, this approach requires long optical paths resulting in a relatively bulky readout. This makes parallelization of the system, as needed for high-throughput AFM, very challenging.

Recently, advances in optomechanics have brought exciting possibilities for displacement sensing due to high sensitivity, small sizes, and, therefore, high operating frequencies of nano-optomechanical structures and the possibility of integrated and thereby parallel readout. For scalable implementations, however, optical detectors and actuation must also be integrated. First steps in this direction were already demonstrated. In the current work, we present a nano-opto-electro-mechanical system (NOEMS) with on-chip light delivery, in addition to on-chip detection and actuation, essential for scaling to large sensor arrays on a single chip. The operation and performance of the device as a force and displacement sensor is directly characterized by nanomechanical actuation using a separate commercial AFM.

The proposed device, shown in Fig. 1(a), is based on a double-membrane (DM) photonic crystal cavity (PhCC) coupled to an in-plane ridge waveguide (RW) for optical excitation and an integrated detector for photocurrent readout. Due to the vertical evanescent coupling between the PhCCs, the structure presents two sharp resonances [symmetric (S) and antisymmetric (AS)] corresponding to supermodes of the coupled system. Both S and AS modes could,
in principle, be used, but here we focus on the AS mode since it is typically more prominent in our devices.\textsuperscript{14} Their resonant wavelengths depend on the distance between the two membranes. The mode shift due to the variation of the inter-membrane separation, calculated with a commercial finite element method (FEM) simulation software, is reported in Fig. 1(b). Here, the two colored lines show the fits with an exponential dependence \( \lambda_{S,AS}(d) = \lambda_0 \pm \xi e^{-d/d_0} \), where \( \lambda_0 \), \( d \), \( d_0 \), and \( \xi \) are the uncoupled-cavity resonant wavelength, the cavity separation, the extension of the cavity mode, and a term proportional to the in-plane mode overlap, respectively. The wavelength shift gives us the possibility to map the displacement of the top membrane, which is designed to be more compliant, into the optical spectrum of the DM-PhCC.

The DM-PhCC sensor has been fabricated on a GaAs wafer with a well-established fabrication process that has been previously described.\textsuperscript{14,19,20} The layer stack of the sensor consists of two 170 nm-thick GaAs membranes separated by a 240 nm-thick layer of Al\textsubscript{0.73}Ga\textsubscript{0.27}As, grown on top of a bottom 1.5 \textmu m-thick Al\textsubscript{0.73}Ga\textsubscript{0.27}As layer. The AlGaAs layers are selectively etched away in the sensing region, whereas they form an integral part of the on-chip waveguide. The two membranes are patterned with a hexagonal PhC, with lattice constant \( a = 370 \) nm, including a PhCC coupled to a PhC waveguide (PhCW). SEM images of the fabricated device are reported in Figs. 1(c) and 1(d). The patterned PhCC is an L3, i.e., line defect of three missing holes in the photonic lattice, which was modified by shrinking down and displacing six holes (three per side) in order to increase the quality factor of the confined mode.\textsuperscript{18} A W1 PhCW, consisting of a row of missing holes, is coupled to a supported ridge waveguide (RW) via an adiabatic coupler,\textsuperscript{23} visible in the bottom part of Fig. 1(c). The incoming light is coupled via a lensed fiber aligned with the cleaved facet of the RW [Fig. 1(d)] and reaches the PhCC by propagating through the RW, the adiabatic coupler, and the PhCW. The photodetection in the sensor is achieved with a layer of InAs self-assembled quantum dots (QDs), embedded in the top membrane, which absorbs the injected light and converts it into current. In order to collect the generated carriers, the top membrane contains two doped layers that define a p-i-n diode. The bottom part of the top slab is n-doped \((n = 2 \times 10^{18} \text{ cm}^{-3})\) and the upper layer is p-doped \((p_{QD} = 1.5 \times 10^{18} \text{ cm}^{-3})\). Moreover, a third doped layer in the bottom membrane defines, together with the n-layer of the photodiode, a second p-i-n junction that can be used for electromechanical actuation\textsuperscript{19} of the DM-PhCC mode wavelength \((p_{CAV} = 2 \times 10^{18} \text{ cm}^{-3})\). A sketch of the full system is shown in Fig. 1(a).

To detect the shift \( \delta \lambda \) of the cavity mode related to a change in distance \( \delta d \) between the membranes, we measure the photocurrent generated in the top membrane that is resonantly enhanced when incoming light is resonant with the PhC cavity modes. Due to homogeneous and inhomogeneous broadening, the QD absorption spectrum has a full width half maximum (FWHM) of around 50 nm, much larger than the width of the PhCC modes (<1 nm) and also larger than the typical tuning range of the DM-PhCC (~10 nm). In order to characterize the device resonances, the photocurrent is measured at a fixed membrane separation as a function of the excitation wavelength generated by a tunable laser source, which we will refer to as "photocurrent sweep." Examples of photocurrent sweeps are shown in Fig. 2(a). The most prominent features are the broad background due to the QD absorption, with sharp mode resonances on top. Due to the fact that the QDs are dispersed over the chip, light absorption occurs all along the optical path generating a background that affects the visibility of the resonant mode. To prevent that, in a second generation of devices, the QDs are removed from the RW by etching the upper part (130 nm) of the top membrane, including the QD layer. The edge of the etched section is indicated by the arrow visible in the bottom of Fig. 1(c). As shown in the inset of Fig. 1(d), the guided mode in the etched RW is mainly confined in

![FIG. 1. (a) Sketch of the NOEMS with the scheme for photocurrent readout and electrical tuning. (b) FEM simulation of detuning with respect to the intermembrane separation for the two supermodes, S and AS. The corresponding calculated electric field profiles are depicted in the bottom-right of the graph. (c) SEM image of the DM sensor and zoomed-in view on the center of the bridge where the L3 PhC cavity and part of the W1 PhC waveguide are visible. The arrow indicates the start of the etching of the RW. (d) Cross section of the RW at the edge of the chip. The cavity and part of the W1 PhC waveguide are visible. The arrow indicates the start of the etching of the RW. (e) Cross section of the RW at the edge of the chip. The cavity and part of the W1 PhC waveguide are visible. The arrow indicates the start of the etching of the RW. (f) Normalised intensity distribution of the electric field, \( \langle \mathbf{E}^2 \rangle \), of the guided mode.](image-url)

![FIG. 2. (a) Photocurrent spectra of a DM-PhCC employing a normal and an etched RW. (b) Spectra of the etched RW without and with reverse bias of the photodiode. Both spectra in (a) and (b) are obtained setting the power at the laser source to 5 mW. (c) Photocurrent spectra for different actuation voltages (laser power 0.1 mW).](image-url)
the bottom membrane that does not prevent efficient guiding to the PhCC (see the supplementary material). Regarding the photocurrent spectra, the effect of the etching can be seen in Fig. 2(a). The spectra of two devices, with normal and etched RWs, are reported in blue and black lines, respectively. We can notice the increased visibility of the PhCC modes on top of the broad QD absorption. The signal-to-background ratio of the etched device can be further improved by applying a reverse bias, as visible in Fig. 2(b). Here, the interplay between the increased extraction efficiency of the charges from the QDs and the improved QD-mode alignment related to the Stark-shift of the QDs produces a significant amplification of the PhCC modes. A device dependent dark current ranging typically from 20 nA to 200 nA is observed for an applied voltage of −1 V. The experimental photodetector responsivity, given by \( R = I_0/P_0 \), where \( I_0 \) is the generated photocurrent at the cavity peak and \( P_0 \) is the power injected by the lensed fiber, is measured to be about 1.3 mA/W. The expected responsivity is given by \( R = \frac{e}{h} \eta \), where \( e \) is the elementary charge, \( h \) is the photon energy, and \( \eta \) is the external quantum efficiency (QE) of our device. This is equal to \( \eta = \eta_i \eta_d \), where \( \eta_i \) is the coupling efficiency from the lensed fiber to the PhCW and \( \eta_d \) is the detector QE, referred to as the number of photons in the PhCW. \( \eta_d \) can be derived by using coupled mode theory (CMT) \( ^3 \) (see the supplementary material), obtaining

\[
\eta_d = \frac{y_{abs}}{y_0} \frac{4 y_0 y_{nw}}{(y_0 + y_{nw})^2},
\]

with \( y_{abs}, y_0, \) and \( y_{nw} \) being the energy absorption rate by the QDs, the energy loss rate of an isolated PhCC (including absorption and scattering), and the energy loss rate into the PhCW, respectively. By including the values derived from experiments and simulations, we calculate an expected responsivity \( R = 2 \text{mA/W} \), which is in the same order as the experimental value. Furthermore, we tested the possibility of actuating the top membrane by applying a reverse bias on the \( p_{CAV-n} \) junction indicated in Fig. 1(a) with \( V_{CAV} \). In Fig. 2(c), an example of electrical actuation capability is reported, showing a tuning range of 10 nm for a low reverse bias of −3 V. This actuation can be used to modulate the top membrane while measuring its oscillation amplitude, as needed in most AFM modes. Additionally, in a multiple sensor arrangement, it can be used to tune each sensor on the chip to the same laser wavelength. Such functionality, together with the light delivery, is key to the realization of sensor arrays for parallel sensing.

We characterized the displacement and force sensing capability of our NOEMS device by measuring the DM-PhCC optical response to an imposed deflection. In order to apply a precise force on our sensor, we employed a commercial AFM cantilever with an appropriate spring constant. This allows us to press it onto the DM while at the same time obtaining information about the resonance shift from the integrated photodetector. With this configuration, we performed two experiments: characterization of the quasi-static mechanical tuning and characterization of the continuous mechanical tuning.

We calibrated the AFM sensitivity \( S \) (measured in V/m) by indenting the cantilever on the bulk GaAs of our chip, and we obtained \( S = 38.66 \pm 0.07 \text{V}/\mu\text{m} \). The spring constant of the used cantilever (Team Nanotec SS-ISC75), which is needed to calculate the applied force, was obtained via the well-known method of thermal tuning, \(^2\) providing \( k_C = 3.53 \pm 0.03 \text{N/m} \). We then placed the AFM tip right above the center of the PhCC in order to measure the force–distance curve and thereby measure the DM spring constant, noting that the AFM cantilever and the DM form a system of two springs in series. The vicinity of the Si AFM tip causes a small tuning as well, \(^-1\) estimated to be less than 0.4 nm, but once in contact, the effect is fixed and, therefore, not affecting our experiment. We define \( \Delta x_{DM}, \Delta x_{C}, \) and \( \Delta x_{P} \) as the displacement of the DM, the deflection of the cantilever, and the displacement of the AFM piezo, respectively. When we press the cantilever onto the DM, the DM moves by \( \Delta x_{DM} = \Delta x_{P} - \Delta x_{C} \), and by applying Newton’s third law, we obtain in a linear approximation the DM spring constant \( k_{DM} = k_C \frac{\Delta x_{DM}}{\Delta x_{P}} = 13.3 \pm 0.1 \text{N/m} \). At this point, knowing \( S, k_C, \) and \( k_{DM} \), we can calculate the applied force on the DM with the AFM cantilever for a specific voltage setpoint \( V \) and consequently its displacement as

\[
\Delta x_{DM} = \frac{k_C}{k_{DM}} \Delta x_C(V).
\]

Using this procedure, we characterized the quasi-static mechanical tuning and, in particular, the DM-PhCC tuning rate, i.e., optomechanical coupling \( G_t = d^2 x/dx_{DM} \). We performed photocurrent sweeps for increasing values of the cantilever setpoint, corresponding to an increasing force and thus displacement, as indicated in Fig. 3(a). For each setpoint, we measured the wavelength shift \( \Delta \lambda \) of the DM-PhCC mode. As already shown in Fig. 1(b), the DM-PhCC mode wavelength response is exponential, and in this particular case, we were looking at the AS mode, so we expect a decrease in wavelength due to the decreased inter-membrane separation. In Figs. 3(b) and 3(c), we report the combined data of three consecutive measurements. Figure 3(b) shows an exponential fit of the AS-mode shift that seems to represent well the dataset for displacements lower than 30 nm. Steps are more evidently observable around −15 nm and −35 nm of displacement, which relate to the particular way the mechanical motion is imposed to the membrane by changing the setpoint of the external AFM tip, which might slightly slide over the surface or interact with a PhC hole. For small displacements (<10 nm), the tuning can be approximated as linear, as shown in Fig. 3(c), with the tuning rate \( G_t = 0.16 \pm 0.01 \text{nm}/\text{nm} \) or \( G_t/2\pi = 29 \pm 2 \text{GHz}/\text{nm} \) from the AFM imaging, the designed DM separation of \( \approx 220 \text{nm} \) was confirmed, which yielded the simulated tuning rate of 0.17 nm/nm, which has a very good agreement with the measured value.

As a proof of principle of nanoscale metrology, we explored the possibility of sensing the force applied on the top membrane in real-time during an approach of the AFM tip. We recorded the photocurrent signal with the tunable laser fixed close to the top of the DM-PhCC resonance, as shown in Fig. 3(d), while a force–distance measurement on the DM was performed using the AFM cantilever. Such continuous mechanical tuning is reported in Fig. 3(e). When the cantilever approaches the DM, the tip gets into contact, \(^-2\) deflecting the membrane upwards, redshifting the AS resonance, \(^-3\) and so generating the small dip visible in Fig. 3(e) at \( t = 0 \). For \( t > 0 \), the tip in contact deflects the membrane downwards, resulting in a blueshift of the resonance, which first increases the current up to the peak maximum, after which it continuously drops. This continuous shift gives us the opportunity to directly measure the variation in photocurrent, while the mode peak is continuously tuned across the
where \( \delta \), expected value from the simulation.

values obtained in the quasi-static experiment \([\text{Fig. } 3(\text{c})]\) and to the obtained from DC measurements, also applies at the frequencies side of the PhCC mode. In order to confirm that such derivative, laser wavelength, typically chosen to be at the steepest point on the side of the PhCC mode. In order to confirm that such derivative, obtained from DC measurements, also applies at the frequencies of interest for AFM sensing, we compare the calculated and the measured displacement amplitude while the top membrane was undergoing a nm-scale sinusoidal actuation under combined DC bias \( (V_{\text{bias}} = -2.5 \text{ V}) \) and AC driving [with frequency \( \Omega_L = 95 \text{ kHz} \) and root-mean-square (rms) amplitude \( \Delta V = 71 \text{ mV} \)]. The displacement amplitude \( \Delta x \) in these conditions is calculated from the electromechanical tuning in \( \text{Fig. } 4(\text{a}) \) as \( \Delta x = \Delta \omega / G_1 = 260 \text{ pm} \pm 40 \text{ pm} \). Then, the spectrum \( P_{\text{ESA}}(f) \) of the photocurrent signal is measured, after amplification by using a transimpedance amplifier (TIA) \((\text{gain } A_{\text{TIA}} = 500 \text{ kV/A})\), by using an electrical spectrum analyzer (ESA) with the laser tuned to the side of the PhCC mode. In \( \text{Fig. } 4(\text{b}), P_{\text{ESA}}(f) \) is reported for four different configurations where the applied modulation \( (M) \) and the incoming laser \( (L) \) are present or not (indicated by on or off). As expected, a peak is present at \( \Omega_L \) when both modulation and laser are present \((M^\text{on}L^\text{on})\) with an intensity \( P_{\text{ESA}}(\Omega_L) \approx -9 \text{ dBm} \), which closely matches the estimated power \( P_{\text{ESA}}^{\text{est}} = -8 \pm 3 \text{ dBm} \), calculated from

\[
P_{\text{ESA}}^{\text{est}} = \frac{A_{\text{TIA}}^2}{R} \left( \frac{dI}{d\lambda} \right) \left( \frac{\Delta \lambda}{2} \right)^2,
\]

where \( R = 50 \Omega \) is the ESA’s input impedance. This confirms the ability of our device to sense sub-nm displacements and the derived transduction efficiency \( dI/d\lambda \) of \( (3) \). From \( \text{Fig. } 4(\text{b}) \), we note that the peak does not disappear when the laser is switched off \((M^\text{on}L^\text{off})\), indicating the presence of an electrical crosstalk probably related to a capacitive coupling between the actuation diode and the photodiode. We also note that the power noise floor increases in the presence of the laser light \((M^\text{off}L^\text{on}) \) with respect to \( M^\text{on}L^\text{on} \) due to an unwanted power noise of the employed laser source at the used frequency. Since the AFM mode of operation not necessarily involves modulation, thus taking the value of the noise floor \( P_{\text{NF}} \), in the \( M^\text{on}L^\text{on} \) signal of \( \text{Fig. } 4(\text{b}) \), by using \( (3) \) with \( \delta I = \sqrt{2P_{\text{NF}}/R} \), and by considering the used bandwidth \( \Delta f = 100 \text{ Hz} \), we obtain a displacement noise floor of \( \delta x/\sqrt{\Delta f} \approx 7 \text{ fm/}\sqrt{\text{Hz}} \) in the investigated measurement.
range of 15–150 kHz. This value compares well with state-of-the-art non-integrated AFM cantilevers\(^2\), although lower values have been reported for nanomechanical resonators.\(^6\) While this value is in the same order as the calculated thermomechanical noise,\(^7\) we observed that the noise floor does not depend on the slope of the resonance, but rather on the absolute photocurrent value. This shows that both thermomechanical noise and thermal fluctuations\(^8\) are not the dominant contributions to the noise floor. As the observed noise floor increases with the photocurrent, we attribute it to power noise in the laser. Moreover, the observed noise is larger than the fundamental shot noise limit,

\[
\sqrt{SN_{xx}} = \sqrt{2 e I_0(\lambda L)} \left( G_1 \frac{dL}{d\lambda} \right)^{-1}, \tag{5}
\]

where \(I_0(\lambda L) \approx 7 \mu A\), giving \(\sqrt{SN_{xx}} \approx 1 \text{fm} / \sqrt{\text{Hz}}\), which will be the ultimate limit for the current design. The improved resolution estimate as compared to previous work\(^3\) is mainly a result of the use of more compact electrical probes with correspondingly lower pick-up noise.

In conclusion, we have designed, fabricated, and characterized a nano-opto-electro-mechanical transducer and we have demonstrated its use as a sensor for nanoscale displacements. Such a device is integrated with a waveguide-coupled light delivery, photodetection, and actuation on the same chip. We have demonstrated the sensing capability in quasi-static and continuous experiments, showing that it has a sensitivity of about 0.17 nm/nm (wavelength/displacement) and a displacement (force) noise floor of about 7 fm/√Hz (≈ 90 fN/√Hz). Due to its sub-nanometer resolution, small footprint of the sensing element (≈150 μm\(^2\)), and fabrication based on semiconductor processing technology, it holds potential for the integration of large sensor arrays on a single chip for high-resolution and high-throughput atomic scale imaging.

See the supplementary material for a detailed discussion on the characterization of the photodetector responsivity.

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