A nanomechanical photonic crystal displacement sensor on a fiber tip

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The design, fabrication and experimental demonstration of a displacement sensor fitted on the 9 μm diameter core at the tip of a single mode optical fiber are presented. It is based on a narrow-band mechanically tunable photonic crystal mirror, optimized for reflection normal to the surface. Displacements at the pm-level were inferred from the reflected light spectrum. The displacement sensor can be generally deployed for the measurement of forces and (ultra)sonic waves.

Introduction

Fiber optic sensors represent an important class of sensors, with a large number of favorable properties, which together with their low-cost, gives them widespread use in many applications. The fiber-optic sensor presented here is among the smallest devices in an emerging class of optical fiber sensors fabricated on the tip of an optical fiber [1]. A double-membrane (DM) nanomechanical photonic crystal cavity with optical modes whose resonant wavelengths strongly depend on the membrane separation [2] was mounted onto the core of a fiber facet, and its operation as transducer of acoustic waves was demonstrated.

Design and manufacturing

In order to couple efficiently with a radiation field perpendicular to the plane a square lattice photonic crystal (PhC) in a double membrane with a band-edge near the wavelength of interest (1300 nm) at the center of the Brillouin zone (zero in-plane wave vector) was chosen [3]. A lateral gradient in the hole-sizes was made to confine the mode field to the size of the core of a single mode fiber (9 μm) and to optimize the Quality Factor (Q). *Figure 1a* shows the field pattern of the optimized mode with a Q around 500. In a double membrane system, due to evanescent coupling between the membranes, every lateral mode is split into a Symmetric and Anti-symmetric mode [2]. *Figure 1b* shows the strong airgap dependence of the fundamental

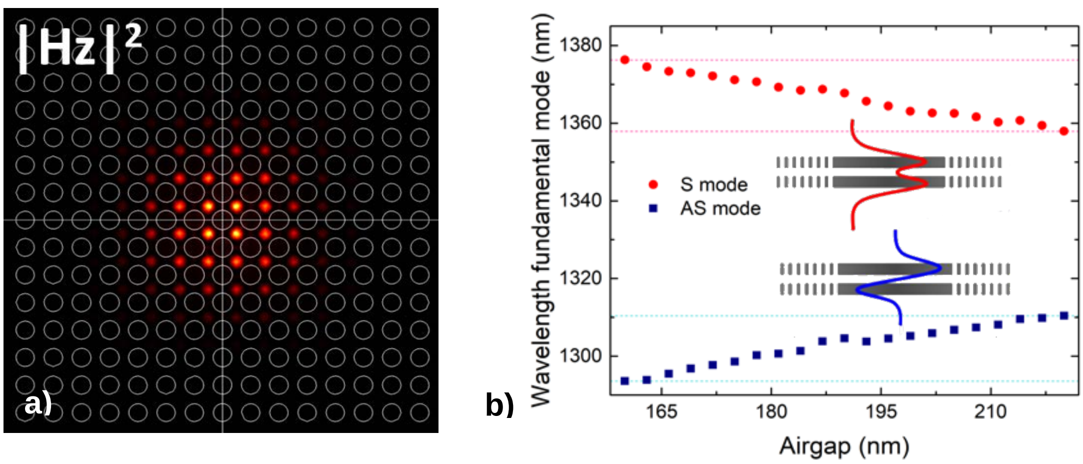

Figure 1: a) Simulated circular shaped $|H_z|^2$ field pattern of the fundamental mode. *b)* Calculated tuning curve of the fundamental symmetric (S) and anti-symmetric (AS) mode of the double membrane structure.

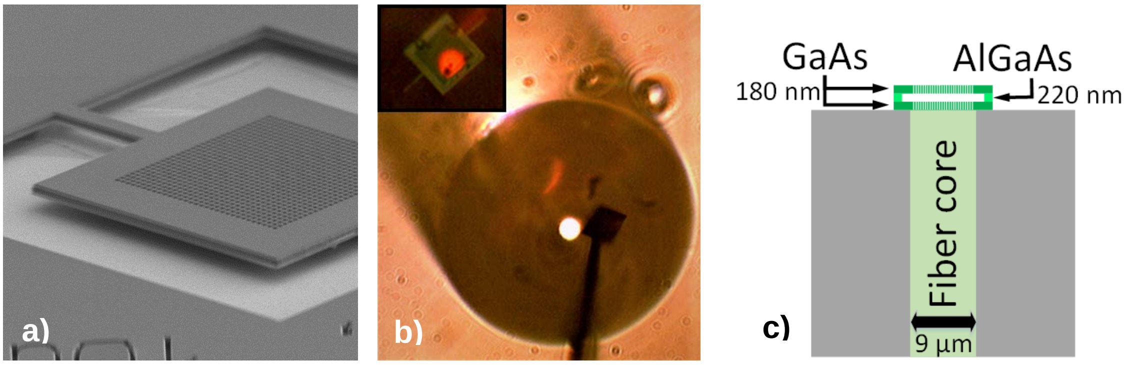

Figure 2: a) SEM image of the fully released DM structure on chip. *b)* Fiber tip & nanomanipulator during pick&place procedure. *Inset:* Top view of device placed on fiber core with red laser applied via the fiber (note some misalignment). *d)* Schematic side view of DM on fiber core (not to scale).

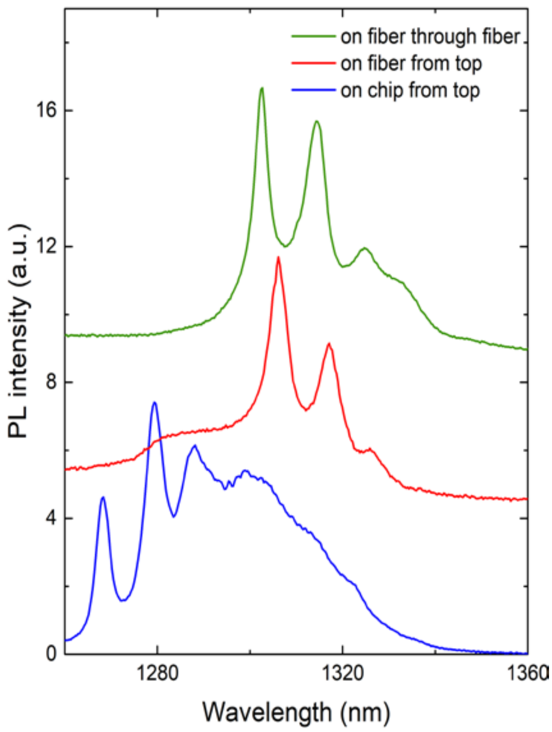

Figure 3: PL-spectra of DM structure. Blue (bottom): as on chip before picking. Red (middle) and green (top): after mounting on the fiber tip, from the free space side with an objective (red) and from the fiber side (green)

symmetric and anti-symmetric resonant modes as required for displacement sensor applications. The optimized design was patterned into a semiconductor layer stack (GaAs) with sacrificial layers (AlGaAs) and a total size of $17 \times 17\ \mu\text{m}^2$. The upper layer contains InAs Quantum Dots to generate (micro-)photoluminescence (μ-PL). A trench was etched around the PhC, leaving only two thin supporting bridges, to make releasing the device possible. Before the sacrificial etching, a protective silicon-nitride layer was deposited to retain the most outer part of the AlGaAs and keep the membranes from collapsing. *Figure 2a* shows a SEM image of a fully under-etched structure. As is shown in *Figure 2b*, by breaking the supporting bridges on both sides, the devices can be mounted on a fiber tip under an optical microscope by using a `pick&place` method, similar to the one previously used for mounting single PhC membranes on the fiber facet [4]. Alignment to the core is facilitated by illuminating it from the other side (see inset of *Figure 2b*). *Figure 2c* is a schematic representation of the device. The double membrane acts as a mirror with a reflection spectrum corresponding to the cavity resonant modes.

Results

Before and after mounting the devices on the fiber tip the cavity spectra were obtained from micro μ-PL measurements. *Figure 3* shows the μ-PL spectra for the DM structure as fabricated (blue), as well after releasing and mounting on the fiber (red), obtained by excitation and collection from top by using a microscope objective. The fundamental resonance mode has the lowest wavelength, due to the hole-like character of the PhC band dispersion. The results show an expected red-shift of the peaks after mounting the device, due to the replacement of air with the higher refractive index glass. Finally, the PL spectrum as obtained by excitation and collection through the same fiber is shown in *Figure 3* (green). The spectrum is very bright and similar to the one measured from the top, indicating good coupling of the DM device to the fiber facet. However, the wavelength-shift seen between the two upper curves in *Figure 3* (red and green) could point to slight issues at the glass-semiconductor interface, e.g. a partial release or capillary wetting with water. Apart from the occurrence of a small wavelength (blue-)shift, the structure was very stable over the observation time of several weeks.

Figure 4a shows the reflection spectrum obtained by performing a wavelength-sweep of a tunable laser around the resonant wavelength region of the DM device. The resonances are clearly present in the reflection spectrum, far above the background. The rapid oscillations are arising from the coupling circuit. The reflection signal can thus be used as a probe for the cavity, which supports the effectiveness of the cavity design. This is a great advantage compared to PL read out [4], as the low intensity of PL requires expensive spectrometers equipped with liquid-nitrogen cooled InGaAs detector arrays.

A microphone can be viewed as a prototype displacement sensor. Strong activities are currently underway with the aim of developing ultra-small integrated optical resonators operating as (ultrasound) micro- or hydrophones [5]. Previously, single-membrane PhC devices on a fiber tip have been used as hydrophones [6]. A large DM PhC micromechanical device on a fiber tip has been shown as a displacement sensor for an Atomic Force Microscope application as well [7]. As a preliminary demonstration of the application of our fiber-tip sensor, the setup of *Figure 5* was used to test its performance as a microphone. An audio speaker driven at a nominal sound level of 100dB, corresponding to a pressure amplitude of 2 Pa, at an (arbitrary) frequency of 4.3 kHz, was placed directly in front of the fiber facet (*see inset*). The reflected light signal at the audio-drive frequency was sensitively detected using a lock-in amplifier, referenced to the audio drive. The result of *Figure 4b* shows a clear sign-changing signal near the cavity resonances. The oscillating membrane leads to a resonance frequency modulation of the cavity, which translates to intensity variations at a given laser frequency. Ideally, the intensity variations are proportional to the slopes in the reflection spectra so that a derivative, and so sign changing, audio-frequency intensity spectrum is expected. Comparing *Figures 4a* and *4b*, this is seen to be not exactly the case; the deviations are attributed to a non-uniform motion of the membrane, different for different optical modes, which might be due to the misalignment, under-etch issues, or (observed) accumulated dust.

With a pressure amplitude of 2 Pa, an area of approximately $3x10^{-10}$ m^2, a value of the spring constant of ~ 40 N/m obtained from mechanical simulations (COMSOL), and *neglecting the holes in the membrane*, a maximum

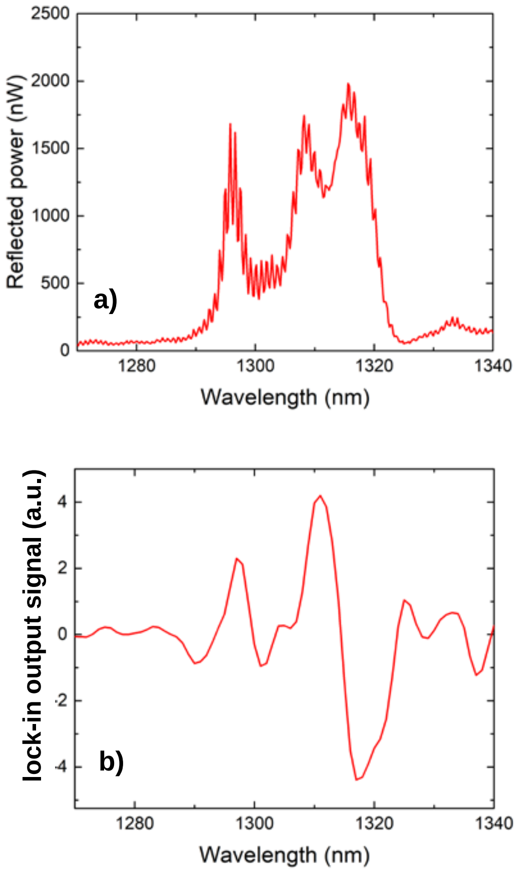

Figure 4: a) Optical reflectivity spectrum measured through the fiber. *b)* Lock-in output signal referenced by the 4.3 kHz frequency of the transducer drive voltage.

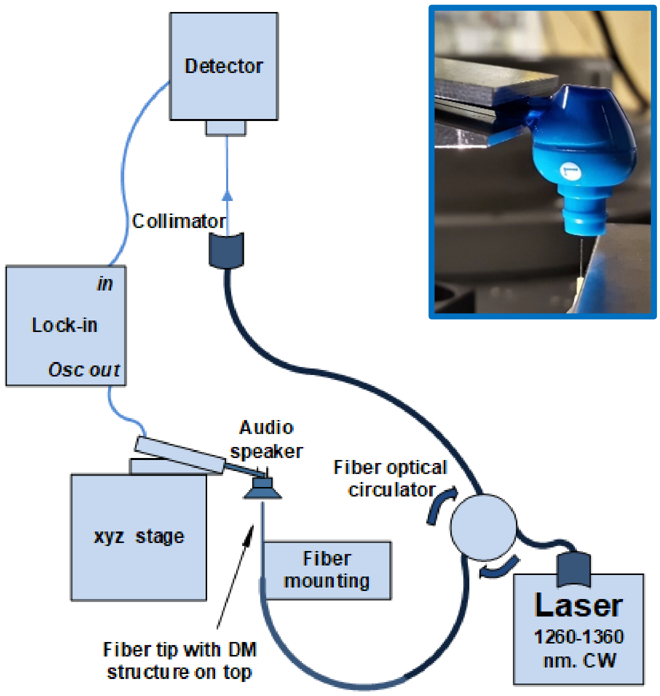

Figure 5: Experimental setup used to measure the mechanical displacement introduced by applying a sound wave using an audio speaker. *Inset:* Picture of the headphone speaker placed above the fiber tip.

displacement of the order of 10 pm is expected. The signal to noise ratio in *Figure 4b* is entirely due to non-optimized background reflection intensity variations. From the tuning curve of *Figure 1b*, the steepest slope of *Figure 4a*, and the Noise Equivalent Power (*NEP*) of 10^{-11} W/Hz$^{1/2}$ of the detector used, a displacement sensitivity of $\delta x=(dx/d\lambda)(d\lambda/dP)\times NEP$ of 10^{-13} m/Hz$^{1/2}$ is possible in principle. This displacement sensitivity can be improved by increasing $dP/d\lambda$. Together with the high mechanical resonance frequencies of > 1 MHz, this implies that the application as a fiber coupled acoustic sensor is interesting by itself.

Conclusion

A fiber-optic tip sensor is presented consisting of a DM PhC nanomechanical device, with potential application as a general displacement sensor. In particular it may be operated as an acoustic sensor, which excels by its ultrasmall size. This could make it interesting for applications where size is important e.g. in medical intravascular applications or for high-frequency (>1 MHz) ultrasound measurements.

References

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