Fiber-Top Cantilevers: a New Generation of Micromachined Sensors for Multipurpose Applications

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Abstract. Fiber-top cantilevers are new monolithic devices obtained by carving a cantilever out of the edge of a single-mode optical fiber. Here we report evidences of their potential impact as sensing devices for multipurpose applications.

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1. Fiber-top cantilevers: description of the design

Micromachined cantilevers are commonly used for a wide variety of applications, such as atomic force microscopy [1], selective detection of chemicals or biological species [2-4], monitor of chemical and physical parameters [5,6], et cetera. These devices rely on the possibility to measure the mechanical deformation of the cantilever in response to certain external events. Measurements of the deflection of the cantilever can be performed by means of either electronic or optical readouts (see references in [7]). Electronic readouts are not always compatible with the surroundings (e.g., conductive liquids, explosive gases, high and low temperatures, et cetera). Optical readouts are more versatile, in that they can be used, in principle, in any (optically transparent) medium. However, they typically require an accurate procedure for the alignment of the optical equipment, a major disadvantage for non-skilled users and for applications in small environments, where there is no room for manipulators or translational stages.

Our group has recently introduced a new concept for the implementation of monolithic cantilevers with *plug-and-play* optical readout: the *fiber-top cantilever* [7,8]. In Fig. 1.a we report a scanning electron microscope image of one of these devices. Fiber-top cantilevers are obtained by carving a thin rectangular beam directly at the center of the cleaved edge of a single-mode optical fiber. The cantilever is integral part of the optical fiber, robustly anchored to it, and already aligned with its core. Deflections of the cantilever can be inferred by coupling light into the fiber and measuring the amplitude of the interference signal obtained from the superimposition of the light reflected by the fiber-to-air interface with that reflected by the cantilever itself [7].

In this paper, we will briefly review the fabrication procedure, the readout technique, and the results obtained so far by our group in the development of fiber-top devices for multipurpose applications.

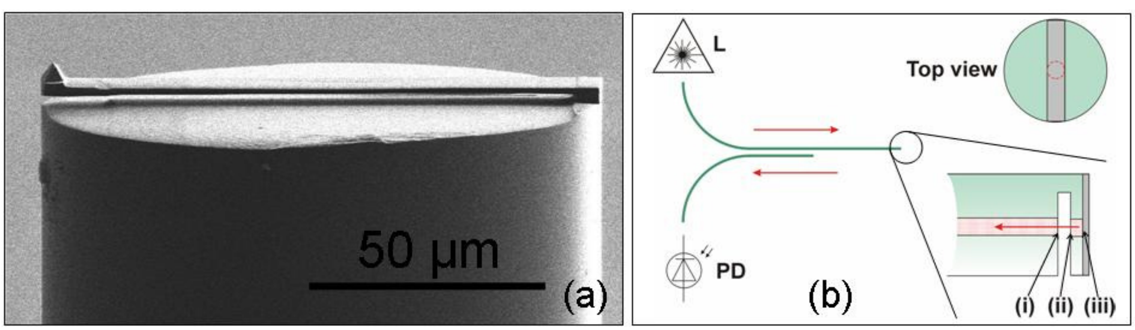

Fig. 1. (a) Scanning electron microscope image of a fiber-top cantilever equipped with a pyramidal tip. (b) Schematic view of the readout apparatus: L=laser, PD=photodiode, (i)=fiber-to-air interface, (ii)=air-to-cantilever interface, (iii)=cantilever-to-air interface.

2. Fabrication and readout apparatus

Fabrication of fiber-top cantilevers [7,8] is currently based on focus ion beam (FIB) milling. The machining steps are illustrated in Fig. 2. The cleaved edge of a single-mode optical fiber (cladding=125 µm, core=9 µm), stripped of its jacket and coated with a thin metallic film (5 nm of Cr and 20 nm of Pd), is first machined in the form of a rectangular ridge (Fig 2a and 2b). The ridge is then carved in the form of a thin rectangular beam, suspended over the center of the fiber by means of an anchor post positioned at one of its ends (Fig. 2e and 2f). For utilization in scanning probe measurements (or other applications that might require it), it is also possible to fabricate a sharp pyramidal tip at the hanging end of the cantilever (Fig. 2c and 2f). The dimensions of the cantilever can be greatly varied according to the application for which they serve. We refer the reader to [8] for more details on the fabrication procedure.

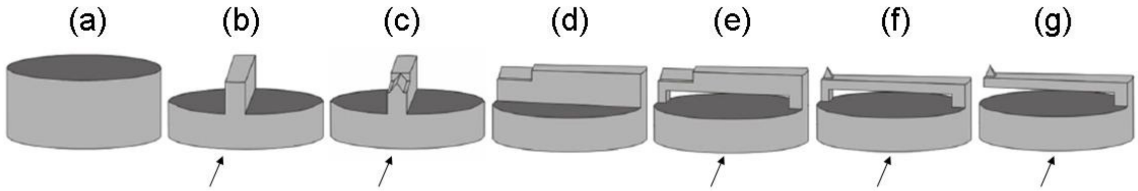

Fig. 2. Schematic view of the focused ion beam milling steps followed for the fabrication of fiber top cantilevers. The arrows indicate the direction of the ion beam with respect to the orientation of the fiber.

In order to measure the vertical displacement of the cantilever, the optical fiber is connected to the readout apparatus sketched in Fig. 1.b [7]. The light of an infrared laser (wavelength λ=1.31 µm), coupled to the fiber, is partially reflected at the fiber-to-air, air-to-cantilever, and cantilever-to-air interfaces. While propagating backwards, the three signals pass through an optical fiber coupler that transmits 50% of the light to another fiber aligned with an infrared photodiode. As a result of the interference of the three signals, the output of the photodiode is given by [7]:

$$W = W_0\left(1 - V\cos\left(\frac{4\pi d}{\lambda} + \phi\right)\right) \qquad (1)$$

where W_0 is the midpoint output, V is the fringe visibility, ϕ is a constant that depends on the thickness of the cantilever, and d is the distance between the fiber-to-air and the cantilever-to-air interfaces [7]. It is thus clear that the deflection of the cantilever can be measured by monitoring the output signal of the photodiode.

3. Proof-of-concept experiments

For a first series of tests, a tip-less fiber-top cantilever (length≈112 µm, width≈14 µm, thickness≈3.7 µm) was coated with a 100 nm thick metallic layer by means of thermal evaporation. Fig. 3.a shows the output signal of the readout apparatus upon mechanical deformation the cantilever [7]. Roughly 800 ms after starting data acquisition, a tip was brought to contact with the edge of the fiber. The first spike in the trace corresponds to the approaching movement. The cantilever was then left in contact position for 500 ms, as indicated by the flat part of the signal between the two spikes. Finally, the tip was retracted (second spike of the trace), allowing the cantilever to go back to its initial position (flat signal after 1.5 s). This experiment demonstrates that the device can be used as an optomechanical transducer.

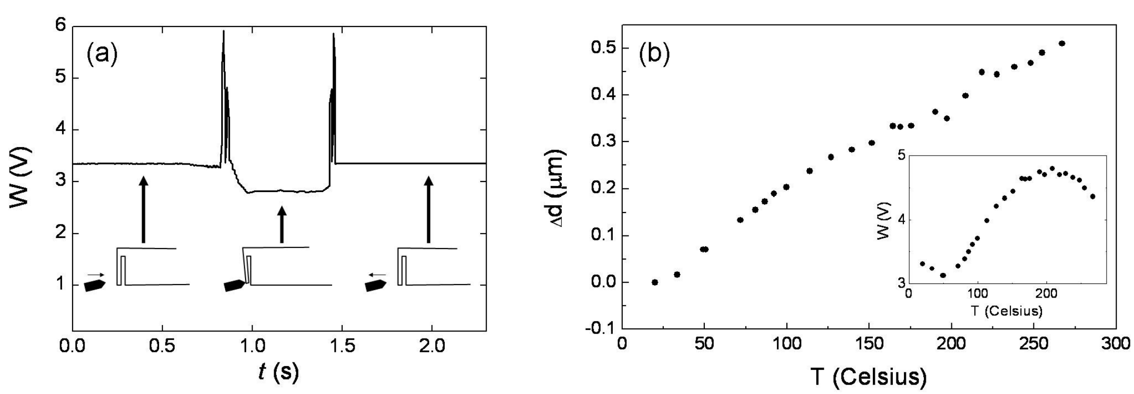

Fig 3. (a) Output signal of the readout apparatus obtained in correspondence of mechanical contact of a metallized fiber-top cantilever with an external object. The drawings illustrate the position of the object and of the cantilever before contact, at contact, and after contact. (b) Vertical displacement of the same fiber-top cantilever induced by thermal expansion of the metallic coating layer upon heating. Inset: output signal of the readout apparatus obtained in the same experiment.

In the inset of Fig. 3.b we report the output signal of the readout apparatus as a function of the temperature of the same fiber-top cantilever [7]. In this case, the deflection of the cantilever was caused by the different thermal expansion of the metallic coating on the silica cantilever (bimorph effect). The rms noise of the output signal at room temperature, measured with a digital oscilloscope (bandwidth DC-400 MHz) over a 0.2 s time interval, was ≈3.5 mV. This value corresponds to a displacement sensitivity in quadrature of ≈4 Å [7], which is comparable with that achievable with commonly used cantilever-based devices. For a better visualization of the data, using Eq. 1 we have converted the amplitude of the photodiode signal to the correspondent vertical displacement of the cantilever. The results are reported in Fig. 3.b. This experiment proves that fiber-top cantilevers are still well-functioning at very high temperatures, and suggests the use of bimorph fiber-top cantilevers as temperature sensors and infrared detector systems.

A similar fiber-top cantilever [9] was coated with a ≈150 nm thick palladium film and mounted inside a ≈10 cm^3 chamber. The chamber was flushed with a hydrogen-argon mixture (5% hydrogen, 250ml/min flow, ≈10.5 minutes exposure) and then with an oxygen-argon mixture (20% oxygen, 250ml/min flow, ≈10.5 minutes exposure). In Fig. 4.a and 4.b we report the output signal of the readout apparatus as recorded during gas circulation and the corresponding cantilever vertical deflection as extracted by means of Eq. 1. It is evident that, during hydrogen exposure, hydrogenation of the palladium layer causes large deflections of the cantilever; during oxygen exposure, the release of hydrogen from the palladium film brings the cantilever back to its original position. This experiment demonstrates that fiber-top cantilevers can be successfully used for selective hydrogen detection. More generally, changing the coating layer, one can obtain different chemical or biological sensors.

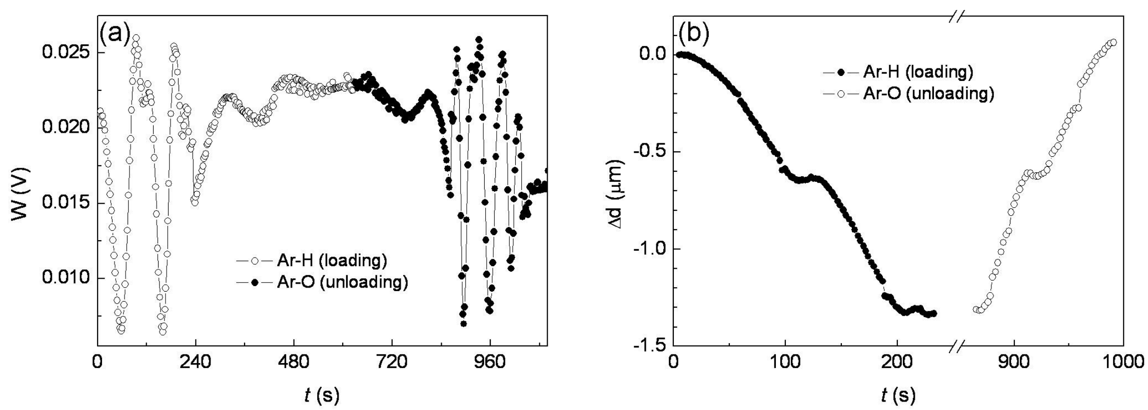

Fig. 4. (a) Signal of the readout apparatus obtained with a palladium-coated fiber-top cantilever when exposed first to hydrogen (open circles) and then to oxygen (closed circles). (b) Vertical displacement of the same fiber-top cantilever as a function of time as obtained by elaborating the data of Fig. 4. a by means of Eq. 1.

4. Conclusions

Fiber-top cantilevers represent an interesting alternative to commonly used cantilever-based instrumentation. The monolithic structure of the device (which completely eliminates any problem associated to the alignment of the optical components of the readout apparatus) and the absence of electronic contacts on the sensing head make this design the ideal solutions to all those situations in which sensors must operate in small volumes and/or in the presence of harsh conditions. Furthermore, the performances of a fiber-top cantilever are not inferior to those achieved by similar commercially available devices: its simplicity facilitates *plug-and-play* utilization, a detail that might be preferred by users who are not used to operate with complicated optical or electronic readouts. It is thus reasonable to envision applications of fiber-top cantilevers in standard environments as well.

A large variety of instruments can be implemented on the basis of fiber-top design. Our group is now exploring the possibility to develop fiber-top cantilevers or other fiber-top micromachined devices for measurements of liquid flows, vibrations, pH, material stiffness, surface forces, biological and chemical species, magnetic and electric fields, temperature, surface topography, et cetera. We are investigating procedures to fabricate biocompatible fiber-top sensors for utilization in the human body as well. Other fabrication methods to reduce the production costs and time are also under investigation.

5. Acknowledgements

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