A Novel Integrated Optomechanical Transducer and Its Application in Atomic Force Microscopy

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ABSTRACT

We represent a novel cavity optomechanical transducer which may find use as an atomic force microscopy probe. The transducer consists of a nanoscale cantilever, a microdisk, waveguides, and pigtailed fibers. A sharpened tip of the cantilever is of 20 nm radius, comparable to commercial atomic force microscopy probes. We demonstrate nanoscale resolution in a contact-mode operation. The detection needs to be improved in order to enhance the resolution. The resonant frequency of the fundamental in-plane mode is ~3.5 MHz, higher than common atomic force microscopy probes. With further miniaturization, the resonant frequency of the nanoscale cantilever can be even higher and it may enable higher scanning speed. Moreover, this integrated design can be easily combined with other metrology tools, such as scanning electron microscopes.

Keywords: optomechanics, atomic force microscopy, MEMS, nanotechnology, photonics

1 MOTIVATIONS

Cavity optomechanics [1, 2] studies the coupling of optical and mechanical degrees of freedom in an optomechanical system. Great progress has been made in recent years. It has enabled quantum-limited measurement of mechanical motion and cooled the resonant mode of a nano- or micro-mechanical resonator into quantum ground state [3, 4].

Besides the interest in fundamental science, one important application is in the field of atomic force microscopy (AFM) where one uses a mechanical cantilever to image the surface of a sample [5-8]. Under the current trend of miniaturization, the fabrication of a nanoscale cantilever is not technically difficult [9]. A proper-designed nanoscale cantilever not only leaves smaller footprint and saves cost, but may also provide higher scanning rate and resolution. However, when the dimensions of the cantilever become comparable or smaller than the optical wavelengths (hundreds of nanometers), traditional optical transduction schemes (e.g. beam deflection and laser interferometry) become ineffective because of the diffraction [10]. This prevents the utilization of the nanoscale cantilever. Other transduction schemes like piezo-resistive or piezo-electric transduction are bandwidth-limited and provide much poorer sensitivity.

Cavity optomechanics [7,8, 11-14] overcomes the diffraction limitation as it utilizes the near-field coupling, which is not limited by the wavelength. Combining a high-Q optical cavity and a nanoscale cantilever, the fully integrated optomechanical transducer is a potential candidate for a next-generation AFM probe. Besides the benefits aforementioned, the integrated transducer does not require the time-consuming procedure of optical alignment, which is necessary in traditional optical transduction schemes.

2 EXPERIMENTAL RESULTS

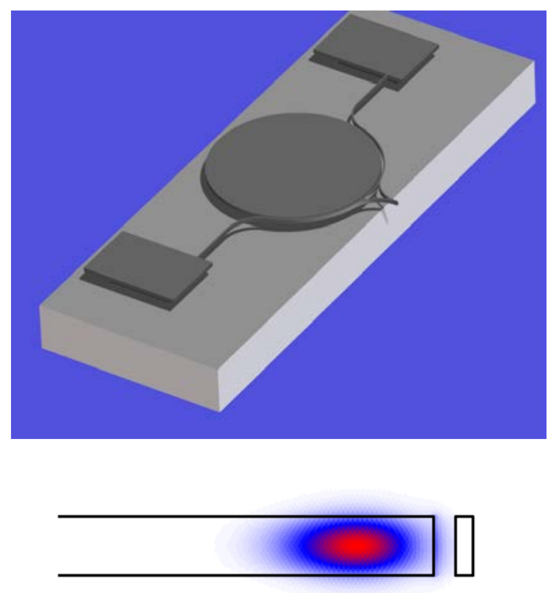

Figure 1: The upper panel shows schematic of the disk-cantilever system. A nanoscale silicon cantilever (w*t=100 nm * 260 nm) curves around a silicon microdisk with 10 μm diameter. The gap between the cantilever and the microdisk is about 100 nm. The lower panel displays cross sectional schematic of the disk-cantilever system. Black boxes represent the boundary of the disk and the cantilever. The color represents the amplitude of the optical field. Red corresponds to a higher value.

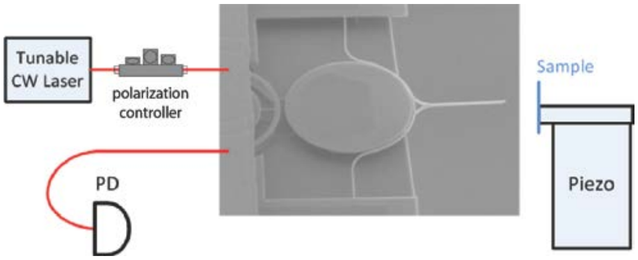

Figure 2: Schematics of the experimental setup. PD: photon detector.

Here, we fabricate an integrated optomechanical transducer with a sharp tip overhanging on the chip edge and demonstrate it as an AFM prototype working in the contact mode. As displayed in Fig.1, the transducer consists of a nanoscale cantilever, a microdisk, waveguides, and pigtailed fibers. The devices are fabricated with silicon-on-insulator (SOI) wafers. The silicon cantilever and microdisk are lithographic defined and etched in the same steps. The curved design of the cantilever greatly enhances the optomechanical coupling g_{OM}. The silicon microdisk acts as a whispering-gallery-mode optical cavity. The color in the lower panel of Fig. 1 represents the amplitude of the electromagnetic wave. The evanescent wave extends outside the disk and overlaps with the cantilever. Thus, the motion of the cantilever effectively alters the optical length of the cavity owing to the evanescent wave coupling. Thereby, the motion of the cantilever is measured from the resonant frequency shift of the whispering gallery mode of the microdisk. The highest optical Q factor of the studied microdisk resonator is observed to be about 57,000, probably limited by imperfect plasma etching in this particular sample (Figure 3). Q factors up to 1 million have been achieved for microdisks with similar designs [7]. Setting the laser wavelength on the sharp slope of the whispering gallery mode, the motion of the cantilever modulates the amplitude of the transmission. The Brownian motion of the cantilever is measured and the resonant frequency of the lowest in-plane mode is found to be 3.5 MHz.

The tip of the cantilever is exposed and sharpened before removing the exposed oxide by hydrofluoric acid (HF). As displayed in Fig. 4, the radius of the tip is found to be about 20 nm using scanning electron micrographs. This is comparable to state-of-the-art AFM tips.

Next the tip of the transducer is brought close to and in contact with a sample under investigation. The sample (high-purity gold on mica) is mounted on a piezo scanner (attoCube nanopositioners). While the sample approaches and retracts from the cantilever tip, we record the cantilever displacement that is linear with the force between the sample and cantilever. In Figure 5, we observed ‘snap-in’ (marked by A) and ‘pull-off’ (marked by B) that correspond to the tip jumping onto and off from the sample. This force-distance curve is repeatable. In order to measure the

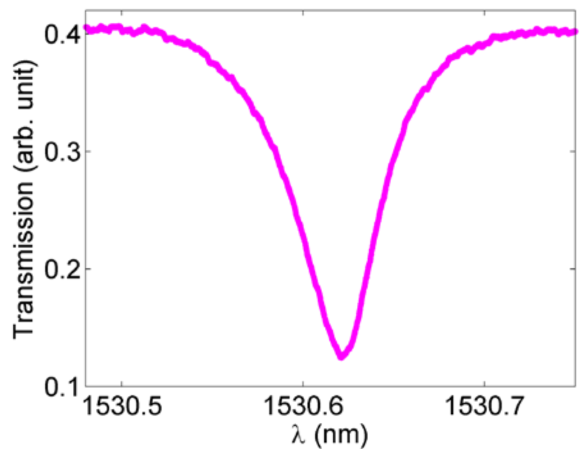

Figure 3: The transmission spectrum of a high-Q optical whispering-gallery mode.

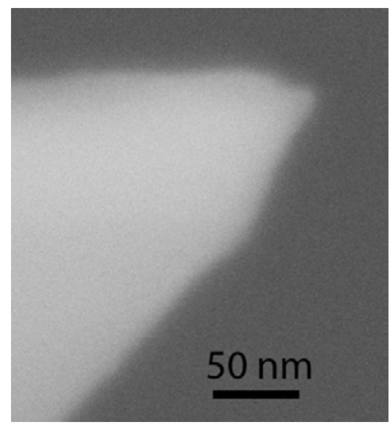

Figure 4: Scanning electron micrograph of the sharpened tip.

topography of the sample surface, the position of the cantilever is then set in the repulsive-force regime. The transducer works as an AFM probe in the contact mode and x/y piezo positioners are turned on to scan the surface. The measured displacement of the cantilever reflects nanoscale height changes on the surface. The scanned image in Fig. 6 captures the slightly curved nature of the gold-on-mica sample. However, the surface of the sample should be much smoother and flatter. The fluctuation in the scanned image is originated mostly from the detection noise rather than the surface roughness.

3 FUTURE DIRECTIONS

In future, we plan to implement a Hansch-Couillaud polarization spectroscopy (shown schematically in Fig. 7) in order to improve the sensitivity and stability. Hansch-Couillaud polarization spectroscopy sets the polarization to

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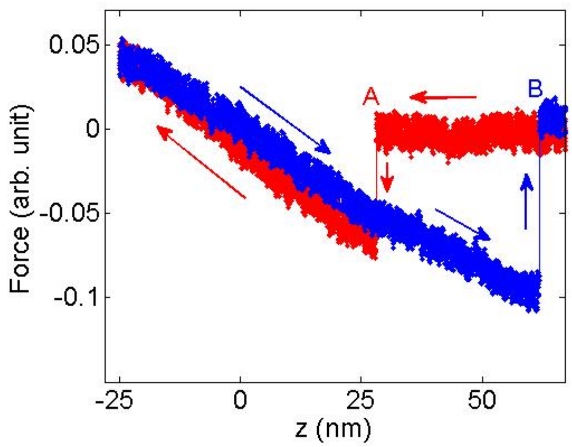

Figure 5: The force-distance curve. ‘Snap-in’ and ‘pull-off’ are marked by A and B, respectively.

be almost perpendicular to the one that is designed with largest coupling. As a result, a small part of the input field couples to the cavity and serves as the signal, while a large part with an orthogonal polarization serves as the local oscillator (LO). The interference signal is further analyzed using polarizing beam splitter and a balanced photodetector. Instead of the amplitude, the phase is measured and provides better sensitivity when the LO is sufficiently large. In principle, the LO should be increased to the level where the shot noise dominates other noise sources. We expect this improvement, combining with a feedback loop to lock the laser wavelength at the largest slope of the optical resonance, will greatly enhance the resolution and increase the scanning speed of the atomic force microscopy using our cavity optomechanical transducers.

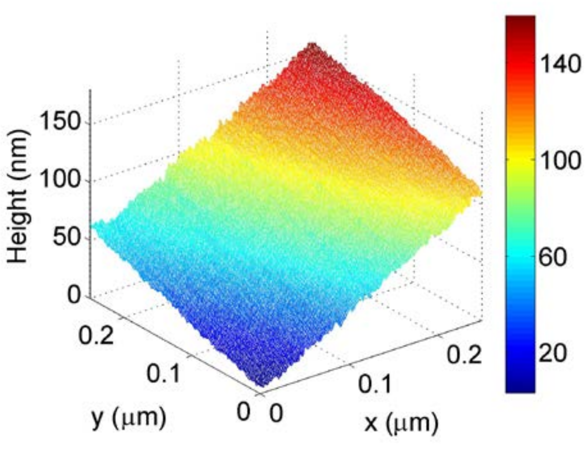

Figure 7: The scanned image of a slightly tilted surface of gold-on-mica.

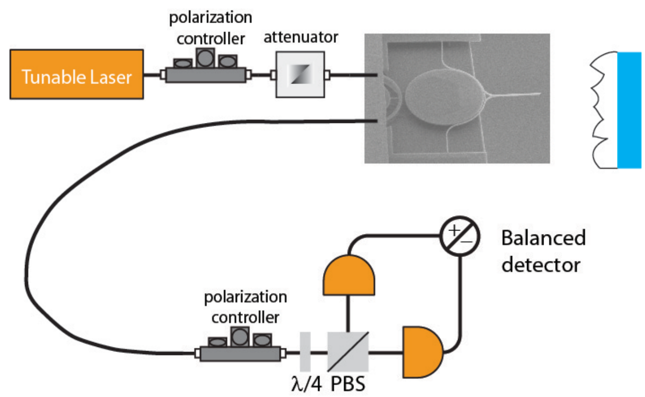

Figure 7: Schematics of Hansch-Couillaud polarization spectroscopy

4 CONCLUSION

To conclude, we demonstrate a fully-integrated optical transducer as an AFM probe in the contact mode. The resonant frequency is at 3.5 MHz, higher than typical AFM cantilevers. With Q factors in the order of tens in ambient conditions, it offers very high bandwidth which is especially useful in detecting force dynamics between the surface and the probe. It also potentially allows a fast scanning rate, while the current scanning rate is limited by the piezo scanner. Flexibility in the cantilever design allows a large range of the resonant frequency (from 200 kHz to 110 MHz) and the spring constant (from 0.01 N/m to 290 N/m) [15]. Future development of on-chip electrostatic or other actuations will enable dynamic AFM modes. Nanoscale resolution has been achieved in the scanned image. The compact size of the transducer makes it easy to be integrated with other metrology tools, such as transmission electron microscopes and scanning electron microscopes. However, the fabrication and detection schemes need to be improved in order to achieve the atomic resolution [16].Except from the application in AFM, the overhanging mechanical resonator may couple with other physical systems, including spins [17] and superconducting qubit [18], and enable novel hybrid quantum mechanical systems.

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REFERENCES

[1] T. J. Kippenberg, and K. J. Vahala, “Cavity Optomechanics: Back-Action at the Mesoscale,”

Science, 321, 1172-1176, 2008.
[2] D. Van Thourhout and J. Roels, “Optomechanical device actuation through the optical gradient force,” Nat. Photonics, 4, 211–217, 2010.
[3] J. D. Teufel, et al. “Sideband cooling of micromechanical motion to the quantum ground state,” Nature, 475, 359-363, 2011.
[4] J. Chan, et al. “Laser cooling of a nanomechanical oscillator into its quantum ground state,” Nature, 478, 89-92, 2011.
[5] Binnig, G., C. F. Quate, and C. Gerber, “Atomic force microscope,” Phys. Rev. Lett. 56, 930, 1986.
[6] F. J. Giessibl, “Advances in atomic force microscopy,” Rev. Mod. Phys., 75, 949, 2003.
[7] K. Srinivasan, H. Miao, M. T. Rakher, M. Davanco, and V. Aksyuk, “Optomechanical transduction of an integrated silicon cantilever probe using a microdisk resonator,” Nano Letters, 11, 791-797, 2011.
[8] H. Miao, K. Srinivasan, and V. Aksyuk, “A microelectromechanically controlled cavity optomechanical sensing system,” New Journal of Physics, 14, 075015, 2012.
[9] J. L. Yang, M. Despont, U. Drechsler, B. W. Hoogenboom, P. L. T. M. Frederix, S. Martin, A. Engel, P. Vettiger, and H. J. Hug, “Miniaturized single-crystal silicon cantilevers for scanning force microscopy,” Appl. Phys. Lett., 86, 134101, 2005.
[10] T. Kouh, D. Karabacak, D. Kim, and K. Ekinci, “Diffraction effects in optical interferometric displacement detection in nanoelectromechanical systems,” Appl. Phys. Lett., 86(1), 013106, 2005.
[11] A. Schliesser, G. Anetsberger, R. Rivière, O. Arcizet and T. J. Kippenberg, “High-Sensitivity Monitoring of Micromechanical Vibration using Optical Whispering Gallery Mode Resonators,” New Journal of Physics, 10, 095015, 2008.
[12] G. Anetsberger, O. Arcizet, Q. P. Unterreithmeier, R. Rivière, A. Schliesser, E. M. Weig, J. P. Kotthaus, T. J. Kippenberg, “Near-field cavity optomechanics with nanomechanical oscillators,” Nature Physics 5, 909, 2009.
[13] E. Gavartin, P. Verlot, T. J. Kippenberg, “A hybrid on-chip opto-mechanical transducer for ultra-sensitive force measurements,” Nature Nanotechnology, 7, 509-514, 2012.
[14] O. Basarir, S. Bramhavar, and K. L. Ekinci, “Monolithic integration of a nanomechanical resonator to an optical microdisk cavity,” Opt. Express, 20, 4272–4279, 2012.
[15] Y. Liu, et al. “Wide cantilever stiffness range cavity optomechanical sensors for atomic force microscopy,” Optics Express, 20, 18268-18280, 2012.
[16] F. J. Giessibl, “Atomic resolution of the silicon (111)-(7×7) surface by atomic force microscopy,” Science, 267, 68, 1995.
[17] D. Rugar, R. Budakian, H. J. Mamin, and B. W. Chui, “Single spin detection by magnetic resonance force microscopy,” Nature, 430, 329–332, 2004.
[18] M.D. LaHaye, J. Suh, P.M. Echternach, K.C. Schwab, M.L. Roukes, “Nanomechanical measurements of a superconducting qubit,” Nature, 459, 960, 2009.