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Imaging Nanophotonic Modes of Microresonators using a Focused Ion Beam

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Abstract

Optical microresonators have proven powerful in a wide range of applications, including cavity quantum electrodynamics^{1–3}, biosensing⁴, microfluidics⁵, and cavity optomechanics^{6–8}. Their performance depends critically on the exact distribution of optical energy, confined and shaped by the nanoscale device geometry. Near-field optical probes⁹ can image this distribution, but the physical probe necessarily perturbs the near field, which is particularly problematic for sensitive high quality factor resonances^{10,11}. We present a new approach to mapping nanophotonic modes that uses a controllably small and local optomechanical perturbation introduced by a focused lithium ion beam¹². An ion beam (radius ≈ 50 nm) induces a picometer-scale dynamic deformation of the resonator surface, which we detect through a shift in the optical resonance wavelength. We map five modes of a silicon microdisk resonator ($Q \approx 20,000$) with both high spatial and spectral resolution. Our technique also enables in-situ observation of ion implantation damage and relaxation dynamics in a silicon lattice^{13,14}.

Optical microresonators have a long and successful history as ultrasensitive detectors, mainly thanks to enhanced light-matter interactions resulting from their appreciable photon lifetime and optical field confinement. The numerous applications typically involve detecting small changes in the optical resonances when a perturber, such as a nanomechanical resonator^{6–8}, biomolecule⁵, or single atom¹⁵, moves within the near-field of the device. Knowledge of the optical mode field distribution is thus of critical importance to predicting the interaction with the perturber, and optimizing device performance. But the ultrahigh sensitivity also makes it challenging to measure the mode shape directly and non-invasively, especially as the device dimensions continue to decrease⁸.

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AUTHOR CONTRIBUTIONS

K.A.T, J.Z., J.J.M. and V.A.A. designed the experiments. J.Z. and V.A.A. fabricated and characterized the microdisk. K.A.T. and J.J.M. operated the lithium ion beam instrument. K.A.T. and J.Z. analyzed the data and wrote the draft manuscript. M.D. and K.S. performed the optical modeling and mode perturbation calculations. All authors contributed to interpreting the data and editing the manuscript.

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Near-field scanning optical microscopy (NSOM) has been the most widely used tool for mapping nanoscale fields. While NSOM has been successfully applied to measure the evanescent field near the surfaces of microresonators^{10,11}, it is hampered by the often-strong interaction between the tip and the optical mode being measured, which can lead to a degraded quality factor (Q) and shifts in the resonance wavelength. Reducing the disturbance by minimizing the probe size and moving it farther away from the surface reduces the collection efficiency and degrades the spatial resolution, as higher spatial frequency components of the evanescent field decay faster with distance.

An alternative approach is to replace the near-field probe with a focused beam of accelerated particles (electrons or ions). Recently, focused electron beams have been used to excite optical modes in passive photonic and plasmonic structures, collecting emitted photons (cathodoluminescence^{16,17}) or measuring the energy loss of the electron (electron energy loss spectroscopy^{18–20}) to map the mode distribution. A hybrid approach^{21,22} uses femtosecond optical excitation in coincidence with energy-resolved ultrafast electron microscopy to probe the optically excited mode. These techniques take advantage of the high spatial resolution of electron microscopy and avoid the limitations of the physical probe, but they have not demonstrated the necessary optical wavelength resolution to resolve the narrow high-Q modes that can be closely spaced in microresonators.

In this Letter, we demonstrate mapping of the electric field intensity distribution of whispering gallery modes in a silicon microdisk cavity (diameter = 10 μm , thickness = 245 nm) by detecting small perturbations to the excited optical mode induced by a focused lithium ion beam (FIB) probe. While a lithium FIB scans across the microdisk resonator, an in-situ optical detection setup is employed to monitor the resonant wavelength of the optical mode. We measure a controllably small resonance shift which is closely related to the magnitude of the electric energy density at the location of the FIB probe. Among multiple possible interactions that can couple the FIB to the optical mode, we attribute the leading contribution to defect creation in the silicon lattice. Localized defects can mechanically deform the microdisk surface, shifting the resonance through an optomechanical perturbation. Comparisons with numerical simulations show that the measurements provide a faithful representation of the mode's spatial distribution with nanometer scale resolution.

A schematic of the experiment is shown in Fig. 1. A tunable diode laser is connected through a polarization controller to a fiber pigtailed on-chip waveguide⁷ (Methods), which is evanescently coupled to the microdisk resonator. Optical transmission through the waveguide is measured by a high-speed photoreceiver. The absorption lines in the transmission spectrum in Fig. 2a indicate excitation of transverse magnetic (TM) polarized optical modes (electrical field oriented out of the plane of the microdisk). These modes can be grouped into families of the same radial order, each family having a distinct free spectral range and radial field distribution, which can be determined by numerical simulation (Methods) as shown in Fig. 2b. The optical setup allows tuning onto a selected absorption line and in-situ monitoring of the transmission while the device is placed in the vacuum chamber of a custom-built lithium FIB.

The lithium ion beam is generated by photoionizing ultracold lithium atoms held in a magneto-optical trap, accelerating the ions, and focusing them onto the sample¹² (Methods). The beam energy is kept at 3.9 keV, the instantaneous current is about 1 pA, and the beam is modulated by controlling the ionization laser with an acousto-optical modulator. We have chosen a lithium ion probe in part due to a unique combination of light mass and low penetration depth compared to other ion species available in FIBs (Supplementary Section 1). Compared to electrons, ions more readily produce lattice defects, which we expect to be the dominant interaction in our measurement.

To observe the effect of the FIB on the optical transmission, we first quickly scan the beam over a large area to locate and image the microdisk resonator by detecting the secondary electrons. This image serves as a map to selectively aim pulses of lithium ions at specific locations. Next, we set the monitoring laser wavelength (tunable between 1520 nm and 1570 nm) on the shoulder of an optical mode's absorption line (Figure 2c) and monitor the transmission change in response to short, rectangular ion pulses of controlled duration, typically 1 ms (Figure 2d). During the ion pulse, the observed transmission changes nearly linearly in time, while thereafter the accumulated change decays and settles to a finite residual value (Figure 2e). This transmission change only occurs when the ion beam is focused near the periphery of the microdisk, where the whispering gallery mode energy is localized. As Fig. 2c and 2d show, the change has opposite sign when the laser is fixed on either side of the resonance, indicating it is mainly due to a red shift of the resonance wavelength as opposed to a changing loss. With the ion beam focused near the peak of the $TM_{0,33}$ mode, we measure a resonant wavelength shift of approximately 1 pm ($\delta\lambda/\lambda \approx 7 \times 10^{-7}$) for a pulse containing 6000 lithium ions (Fig. 2d). Therefore, lithium ions are capable of generating a controllably small perturbation to the microdisk, with a perturbation strength related to the local optical mode intensity.

To measure the optical mode's spatial shape, we fix the laser wavelength on the blue shoulder of a given absorption line and monitor the optical transmission while the beam scans in a radial direction across the edge of the disk. Only radial line scans are performed because all the measured optical modes are traveling wave whispering gallery modes which are axially symmetric. The ion beam is modulated at 10 kHz and the change in transmission is measured via a lock-in amplifier. The resonant wavelength red shift is assumed to be linearly proportional to the measured transmission change, since the total shift for a single scan is typically less than 10 % of the resonance width. The results are shown in Fig. 3 for the zeroth, first, and second radial order TM modes. The mode shapes produced by lock-in measurement are similar to those produced by plotting the maximum transmission change during single pulse measurements (Supplementary Figure 2). For qualitative comparison, 2D profiles above the graphs in Fig. 3 depict the calculated electric energy density ($\epsilon|\mathbf{E}|^2$) of the respective optical modes (Methods). A strong correspondence is evident between the data and the calculated energy density near the surface of the microdisk (the surface sensitivity is expected due to the shallow implantation depth of the low energy ions, about 30 nm), indicating the measurement provides a faithful representation of the mode distribution.

The mechanism by which a lithium ion beam causes a wavelength shift in the microdisk resonant modes can be elucidated by considering the various interactions that occur when an

ion impacts the surface. These include multiple defect creations in the silicon lattice, sputtering, lithium implantation, heating, and charge deposition. As outlined in detail in Supplementary Section 2, we find that defect creation is likely to be the most important of these interactions, in part because each incident ion can generate a large number of vacancies (about 70 for our parameters, Fig. 1c). This results in a large amplification effect compared with other interactions.

Defects will perturb the optical resonance both by swelling the surface, thus changing the boundary geometry, and by changing the refractive index within the damaged volume. In Supplementary Section 2, we estimate the magnitude of these two perturbations as a function of ion dose and we use optical eigenmode perturbation theory²³ to calculate the expected wavelength shifts. We find that a defect-induced surface swelling, expected to be of order 100 pm, can by itself explain the observed wavelength shifts. The normalized results of the surface swelling perturbation theory are plotted as a function of position in Fig. 3 (orange solid lines), showing good agreement with the measurements. The optomechanical (surface swelling) perturbation is unique compared to any volumetric perturbation, such as a refractive index change, since the resonance shift depends differently on the in-plane and surface-normal components of the mode field (compare Supplementary Equations 2 and 4). This results in a distinct functional form of the expected curves, leading to smaller contrast between the signal peaks and nodes, as observed in the experimental data (Supplementary Figure 1). While a defect-induced refractive index change and other interaction mechanisms may also play a role, further experiments will be necessary to separately quantify each effect and develop a complete understanding of the underlying physics.

The combination of a FIB probe and in-situ optical detection opens up many interesting possibilities. A scanning beam probe is superior to a scanning tip probe not just for controlling the level of perturbation, but also because it enables imaging of microresonators with more complex three-dimensional geometries and mechanical sensitivity. Complicated nanopositioner feedback systems, required in NSOM to keep the probe at a constant height, are avoided. While our mode measurements can be done with controllably small damage, it is important to note that repeated probing with a FIB can eventually permanently spectrally shift and degrade the Q of the device. For example, after 12 radial scan measurements, the $TM_{0,33}$ mode was permanently red-shifted by roughly one linewidth, and its Q was reduced by about 15 % (Supplementary Section 4). This could be used as an advantage, for example, to control device uniformity post-fabrication, to alter the coupling strength in multi-microresonator systems²⁴, or to spectrally align, permanently and with great precision, the optical resonance with optical transitions in chip-scale cavity quantum electrodynamic systems²⁵.

Lastly, we note that it is possible to take advantage of our technique in a reverse sense, using the microresonator as a sensor to study the interaction of the ion beam with a solid. The response to single ion beam pulses (Fig. 2d and 2e) can be used as a real-time measure of defect creation and relaxation in the silicon lattice. Relaxation and diffusion of ion beam induced defects has been a problem of long-standing theoretical^{13,26} and experimental^{14,27} interest, primarily for the study of ion implantation in silicon microelectronics. Our methods may provide a way to study this relaxation with high spatial and temporal resolution and

unprecedented sensitivity. The broadly successful application of microresonators as high-bandwidth and high-sensitivity detectors can now be extended to study the rich physics of ion-solid interactions.

METHODS

Device fabrication

The silicon microdisk was fabricated on the device layer of a silicon-on-insulator (SOI) wafer. The oxide layer of the SOI wafer is 1 μm thick. Electron beam (E-beam) lithography followed by reactive-ion etching is performed to define the microdisk, waveguides, and light couplers. After removing the E-beam resist, layers of $\approx 2 \mu\text{m}$ silicon dioxide and $\approx 0.4 \mu\text{m}$ silicon nitride are then sequentially deposited. The nitride layer is photo-lithographically patterned and dry-etched to open windows for a later oxide removal step in the vicinity of the microdisk. Additional photolithography and etching are performed to produce the V-grooves that are aligned with the light couplers and waveguides. After removing etching masks and cleaving into individual chips, the device is dipped in a solution of 49 % hydrofluoric acid (HF) in water by weight. The HF removes the SiO_2 above and around the microdisk, suspending its edge and the portion of the on-chip waveguide evanescently coupled to the microdisk. Finally, cleaved optical fibers are glued onto the V-grooves to couple light in and out of the on-chip waveguides.

Lithium FIB

The lithium FIB is a custom FIB system that uses a new type of high-brightness ion source based on the photoionization of laser-cooled neutral lithium atoms. Lithium atoms are laser-cooled and trapped at a temperature of about 600 μK , and then photoionized in an electric field. The extracted ions are accelerated, coupled into a conventional ion column, and focused onto the sample²⁸. Images are obtained by scanning the ion beam over the surface and collecting either secondary electrons (SE) or backscattered ions¹² similar to a scanning electron microscope. The system has demonstrated spot sizes of a few tens of nanometers at beam energies from 500 eV to 5 keV and beam currents of a few picoamperes. In this work, the operating ion energy is kept at 3.9 keV and the beam current is about 1 pA. The ion beam radius and the average implantation depth are about 50 nm and 30 nm, respectively. The spot size was measured by scanning the ion beam across the edge of the silicon wafer supporting the microdisk and measuring the change in SE signal. The implantation depth profile is calculated from Monte Carlo simulations using the SRIM software²⁹. SRIM is also used to calculate the ion trajectories shown in Fig. 1c.

Optical modeling

Microdisk optical whispering gallery modes were computed with a full-vector finite element method. Time-harmonic solutions with spatial electric field distributions of the type $E_{n,m}(r,z) \exp(i*m\phi)$ were obtained (r , ϕ and z are the radial, azimuthal and axial coordinates), where m and n are the azimuthal and radial modal order numbers. For a fixed azimuthal order m ($m = 0, 1, 2, \dots$), a variety of modes with radial order n and eigenfrequency $\omega_{n,m}$ were obtained. The refractive index of silicon was considered to be $n_{\text{Si}} = 3.48$, and the disk radius and thickness were varied within reason until the computed eigenfrequencies

approximately matched the measured optical transmission spectrum. This allowed us to assign each transmission dip to one mode of radial order n , as shown in Fig. 2a, all assigned to transverse magnetic modes, $TM_{n,m}$, with major magnetic field component parallel to the disk plane. The roughness of the sidewalls of the microdisk, which can reduce the Q of the resonances, was not considered in the numerical simulation. According to scanning electron micrographs, the sidewall roughness is tens of nanometers at most and considerably smaller than the wavelength. We expect that this omission causes negligible perturbations (i.e., much smaller than our measurement error) to the calculated mode shapes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Schematic of the measurement

a, Light from a tunable diode laser (Monitoring Laser) is coupled into the microdisk through optical fibers and on-chip waveguides. A photodiode monitors the transmission of light at the output. The ion beam is produced by photoionizing cold lithium atoms held in a magneto-optical trap between two electrodes. The ions are accelerated and focused onto the microdisk. The ion beam is turned on and off by modulating the light from the ionization laser with an acousto-optic modulator (AOM). For dose-response measurements (DC data), a single pulse of ions is applied to the microdisk and the change in transmission is recorded directly from the photodiode as a function of time. For mode profile measurements (AC data), the ion beam is modulated at about 10 kHz and the photodiode output is sent through a lock-in amplifier to record the magnitude of the oscillation in optical transmission. **b**, Scanning electron micrograph of the microdisk cavity and coupling waveguide. The simulated mode profile of the $TM_{1,29}$ mode is superimposed. **c**, Schematic of lithium ion implantation at the microdisk surface. Example trajectories of Li^+ implantation are calculated (Methods) and displayed. Black circles mark collision sites where the Li^+ creates a vacancy or cluster of vacancies in the Si lattice, and purple circles mark the Li^+ stopping location. The localized defect creation can induce a surface swelling, indicated by the gray dashed line (the scale of the line is exaggerated for clarity).

Figure 2. Optical transmission through the microdisk cavity

a. Measured optical transmission spectra. Sharp dips in the transmission indicate the wavelengths of high-Q cavity modes which have been labeled by their radial order number. **b.** Simulated 2D electric field distributions for the optical modes with different radial orders. **c.** Transmission spectrum for the single mode highlighted in **a**. For the ion beam measurements, the wavelength of the monitoring laser is fixed on either the blue or red side of the resonance (as indicated by the blue and red vertical lines) and the change in transmission is measured. **d.** Change in transmission in response to three ion beam pulses each of 1 ms duration applied at 0 s, 8 s, and 16 s. Blue and red lines show the response when the laser is tuned to the blue and red side of resonance. The absolute wavelength shift is calculated from a linear fit to the side of the resonance peak. **e.** Wavelength shift for the first pulse of the blue curve in **d** on a shorter time scale.

Figure 3. Radial scan measurements compared to simulations for the zeroth (a), first (b), and second (c) order radial modes

The 2D intensity maps show the simulated local electric field intensity for each mode. The black circles (and the blue triangles in **a** and **b**) are the normalized resonance wavelength shifts measured using the lock-in technique. The orange solid lines are the wavelength shifts calculated from the surface perturbation theory. Part **a** shows data for the zeroth radial order modes with two adjacent azimuthal mode numbers, $TM_{0,33}$ (1556 nm) and $TM_{0,34}$ (1541 nm). Part **b** shows data for the first radial order modes $TM_{1,29}$ (1547 nm) and $TM_{1,28}$ (1563 nm), and part **c** shows data for the second radial order mode $TM_{2,25}$ (1554 nm). The difference in the simulation results for adjacent azimuthal modes is within the thickness of the line (Supplementary Figure 1). Error bars represent one standard deviation statistical uncertainty of 4 to 15 measurements made at each ion beam position. The uncertainty in

position is ± 50 nm, the approximate size of the ion beam. The ion beam size and depth profile is shown compared to the optical mode in **a**.