Imaging nanophotonic modes of microresonators using a focused ion beam

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Optical microresonators have proven powerful in a wide range of applications\textsuperscript{1}, including cavity quantum electrodynamics\textsuperscript{2-4}, biosensing\textsuperscript{5}, microfluidics\textsuperscript{6}, cavity optomechanics\textsuperscript{7-9} and optical frequency combs\textsuperscript{10}. Their performance depends critically on the exact distribution of optical energy, confined and shaped by the nanoscale device geometry. Near-field optical probes\textsuperscript{11} can image this distribution, but the physical probe necessarily perturbs the near field, which is particularly problematic for sensitive high-quality-factor resonances\textsuperscript{12,13}. We present a new approach to mapping nanophotonic modes that uses a controllably small and local optomechanical perturbation introduced by a focused lithium ion beam\textsuperscript{14}. An ion beam (radius of \textasciitilde 50 nm) induces a picometre-scale deformation of the resonator surface, which we detect through shifts in the optical resonance wavelengths. We map five modes of a silicon microdisk resonator (Q \textgtrsim 20,000) with high spatial and spectral resolution. Our technique also enables \textit{in situ} observation of ion implantation damage and relaxation dynamics in a silicon lattice\textsuperscript{15,16}.

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\textsuperscript{7-9}, biomolecule\textsuperscript{15} or single atom\textsuperscript{17}, 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 the device performance. However, the ultrahigh sensitivity also makes it challenging to measure the mode shape directly and non-invasively, especially as the device dimensions continue to decrease\textsuperscript{8}.

Near-field scanning optical microscopy (NSOM) has been the most widely used tool for mapping nanoscale fields. It has been successfully applied to measure the evanescent field vector and phase near the surfaces of microresonators\textsuperscript{12,13,18}. However, because the probe tip is introduced from the outside, it tends to interact first with the slow-decaying fields far from the resonator surface. Mapping with high spatial resolution requires a closer approach in order to sample the higher-spatial-frequency components of the evanescent fields, which decay faster with distance. For high-quality-factor (Q) optical resonator modes, a technique is desired that can sample locally at the surface of the resonator with minimal perturbation of the slow-decaying evanescent fields outside it.

An alternative approach is to replace the physical 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\textsuperscript{19,20}) or measuring the energy loss of the electron (electron energy loss spectroscopy\textsuperscript{21-23}) to map the mode distribution. A hybrid approach\textsuperscript{24-26} uses femtosecond optical excitation in combination 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, which 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 \textmu m; 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 \textit{in situ} optical detection set-up is used 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 nanometre-scale resolution.

A schematic of the experiment is shown in Fig. 1. A tunable diode laser is connected through a polarization controller to a fibre pigtailed on-chip waveguide\textsuperscript{9} (see 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 (see Methods), as shown in Fig. 2b. The optical set-up allows tuning onto a selected absorption line and \textit{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 sample\textsuperscript{14} (see Methods). The beam energy is kept at 3.9 keV, the instantaneous current is \textasciitilde 1 pA and the beam is modulated by controlling the ionization laser with an acousto-optical modulator. We chose a lithium ion...
The resonant wavelength redshift is assumed to be linearly proportional to the measured transmission change, because 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 Fig. 3). For qualitative comparison, the two-dimensional profiles above the graphs in Fig. 3 show the calculated electric energy density ($|E|^2$) of the respective optical modes (see Methods). A strong correspondence is evident between the data and the calculated energy density near the surface of the micro-disk (the surface sensitivity is expected due to the shallow implantation depth of the low-energy ions, \( \approx 30 \text{ nm} \)), 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 due to a unique combination of light mass and low penetration depth compared with other ion species available in FIBs (Supplementary Section 1). Compared with electrons, ions more readily produce lattice defects, which we expect to be the dominant interaction in our measurement.
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 use optical eigenmode perturbation theory\(^\text{27}\) to calculate the expected wavelength shifts. We find that a defect-induced surface swelling, expected to be on the order of 100 pm, can explain, by itself, the observed wavelength shifts. The normalized results of the surface swelling perturbation theory (Supplementary equation (2)) 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 when compared with any volumetric perturbation, such as a refractive index change, because 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 Fig. 1). A defect-induced refractive index change and other interaction mechanisms may also play a role, and 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 \textit{in situ} optical detection opens up many interesting possibilities. The primary advantage of a scanning beam probe over a scanning tip probe is the precise control over the strength of the probe and the size of the perturbation to the system, so our technique is ideally suited for measuring modes in high-quality-factor devices. In fact, the method requires at least a modestly high \(Q\) mode in order to accurately detect small shifts in the resonance wavelength. As the probe strength can be controlled to match the \(Q\) (and the sensitivity) of the device, the technique will in principle work equally well for arbitrarily high-\(Q\) devices. It is expected to be particularly useful for measuring the high-\(Q\) modes of photonic-crystal cavities. Such microresonators have more complicated modes with smaller mode volumes and are more susceptible to fabrication imperfections than the well-understood microdisk system we chose for this study.

A scanning beam probe is better suited for the imaging of microresonators with complex three-dimensional geometries and mechanical sensitivity. Complicated nanopositioner feedback systems, required in NSOM to keep the probe at a constant height, are avoided. Our technique also provides different information about the nanophotonic modes being measured, complementary to NSOM. The ion beam probe does not directly interact with or perturb the evanescent fields outside the dielectric device, but instead interacts with the field at the dielectric boundary. On the other hand, our technique measures a specific scalar combination of the electric field vector components and is not phase-sensitive.
Mapping surface plasmons on a single metallic nanoparticle. Shows data for Nature Photon. 16, 313–17 (2012).

Coupling a single trapped atom to a nanoscale optical field (1,563 nm) and the plot in Nature 340, 74–76 (2007).

Comparisons of radial scan measurements and simulations. Figure 3 shows data for the zeroth radial order modes with two main peaks at 1,547 nm and 1,563 nm. The plot in a shows data for the zeroth radial order modes with two main peaks at 1,547 nm and 1,563 nm. The plot in b shows data for the first radial order modes TM_{129} (1,547 nm) and TM_{128} (1,563 nm). The plot in c shows data for the second radial order mode TM_{225} (1,554 nm). The simulation results for adjacent azimuthal mode numbers are within 5% of each other (Supplementary Fig. 1), so only one result is shown for each radial order. 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 are shown compared to the optical mode in a. So it provides less detailed information than is available in some implementations of NSOM.

Although our mode measurements can be performed 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 a device. For example, after 12 radial scan measurements, the TM_{233} mode was permanently redshifted by approximately one linewidth, and its Q was reduced by ≈15% (Supplementary Section 5). This could be used as an advantage, for example, to control device uniformity post-fabrication, to alter the coupling strength in multi-microresonator systems, or to spectrally align, permanently and with great precision, the optical resonance with optical transitions in chip-scale cavity quantum electrodynamic systems.

Finally, 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,e) can be used as a real-time measure of defect creation and relaxation in the silicon lattice. Relaxation of ion-beam-induced defects has been a problem of long-standing theoretical and experimental 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
Methods and any associated references are available in the online version of the paper.

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References
1. Ilchenko, V. S. & Matsko, A. B. Optical resonators with whispering-gallery modes—Part II: applications. IEEE J. Sel. Top. Quantum Electron. 12, 15–32 (2006).
2. Raimond, J., Brune, M. & Haroche, S. Manipulating quantum entanglement with atoms and photons in a cavity. Rev. Mod. Phys. 73, 565–582 (2001).
3. Mabuchi, H. & Doherty, A. C. Cavity quantum electrodynamics: coherence in context. Science 298, 1372–1377 (2002).
4. Pogorelov, O. V., Pogorelov, O. V. & Pogorelov, O. V. Quantum optical applications of cavity QED. Rev. Mod. Phys. 86, 363–393 (2003).
5. Vollmer, F. & Arnold, S. Whispering-gallery-mode biosensing: label-free detection down to single molecules. Nature Methods 5, 591–596 (2008).
6. Monat, C., Domachuk, P. & Eggleton, B. J. Integrated optofluidics: a new river of light. Nature Photon. 1, 106–114 (2007).
7. Kimpenberg, T. J. & Vahala, K. J. Cavity optomechanics: back-action at the mesoscale. Science 321, 1172–1176 (2008).
8. Srinivasan, K., Miao, H., Rakher, M. T., Davanço, M. & Aksyuk, V. Optomechanical transduction of an integrated silicon cantilever probe using a microdisk resonator. Nano Lett. 11, 791–797 (2011).
9. Eichenfield, M., Camacho, R., Chan, J., Vahala, K. J. & Painter, O. A picogram- and nanometre-scale photonic crystal optical microcavity. Nature 459, 550–555 (2009).
10. Kimpenberg, T. J., Holzwarth, R. & Diddams, S. A. Microresonator-based optical frequency combs. Science 332, 555–559 (2011).
11. Rotenberg, N. & Kuipers, L. Mapping nanoscale light fields. Nature Photon. 8, 919–926 (2014).
12. Götzinger, S., Demmerler, S., Benson, O. & Sandoghdar, V. Mapping and manipulating whispering-gallery modes of a microsphere resonator with a near-field probe. J. Microsc. 202, 117–121 (2001).
13. Mujumdar, S. et al. Near-field imaging and frequency tuning of a high-Q photonic crystal microcavity. Opt. Express 15, 17214–17220 (2007).
14. Twedt, K. A., Chen, L. & McClelland, J. J. Scanning ion microscopy with low energy lithium ions. Ultramicroscopy 142, 24–31 (2014).
15. Morehead, F. F. & Crowder, B. L. A model for the formation of amorphous Si by ion bombardment. Radiat. Eff. 67, 27–32 (1970).
16. Myers, M., Chrambach, K., Slawin, L. & Kucheyev, S. Pulsed ion beam measurement of the time constant of dynamic annealing in Si. Phys. Rev. Lett. 109, 095502 (2012).
17. Thompson, J. D. et al. Coupling a single trapped atom to a nanoscale optical cavity. Science 340, 1202–1205 (2013).
18. Knight, J. C. et al. Mapping whispering-gallery modes in microspheres with a near-field probe. Opt. Lett. 20, 1515 (1995).
19. Sapienza, R. et al. Deep-subwavelength imaging of the modal dispersion of light. Nature Mater. 11, 781–787 (2012).
20. Coenen, T., van de Groep, J. & Polman, A. Resonant modes of single silicon nanocavities excited by electron irradiation. ACS Nano 7, 1689–1698 (2013).
21. Nelayah, J. et al. Mapping surface plasmons on a single metallic nanoparticle. Nature Phys. 3, 348–353 (2007).
22. García de Abajo, F. J. Optical excitations in electron microscopy. Rev. Mod. Phys. 82, 209–275 (2010).
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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. analysed the data and wrote the draft manuscript. M.D. and K.S. performed the optical modelling and mode perturbation calculations. All authors contributed to interpreting the data and editing the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to V.A.A.

Competing financial interests

The authors declare no competing financial interests.
The silicon microdisk was fabricated on the device layer of a silicon-on-insulator (SOI) wafer. The oxide layer of the SOI wafer was 1 μm thick. Electron-beam lithography followed by reactive-ion etching was performed to define the microdisk, waveguides and light couplers. After removing the electron-beam resist, layers of SiN and SiO2 were deposited sequentially. The nitride layer was 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 were performed to produce the V-grooves, which were aligned with the light couplers and waveguides. After removing the SiO2 above and around the microdisk, suspending its edge and the portion of the on-chip waveguide evanescently coupled to the microdisk. Finally, cleaved optical fibres were glued onto the V-grooves to couple light in and out of the microdisk.

**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 was 1 μm thick. Electron-beam lithography followed by reactive-ion etching was performed to define the microdisk, waveguides and light couplers. After removing the electron-beam resist, layers of SiN and SiO2 were deposited sequentially. The nitride layer was 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 were performed to produce the V-grooves, which were aligned with the light couplers and waveguides. After removing the SiO2 above and around the microdisk, suspending its edge and the portion of the on-chip waveguide evanescently coupled to the microdisk. Finally, cleaved optical fibres were glued onto the V-grooves to couple light in and out of the on-chip waveguides.

**Lithium FIB.** The lithium FIB was a custom-built FIB system that uses a new type of neutral lithium atoms. The detailed properties of the ion source and the design and operation of the custom FIB system have been presented in previous publications. Lithium atoms were laser-cooled and trapped at a temperature of ≈600 μK, and then photo-ionized in an electric field. The extracted ions were accelerated, coupled into a conventional ion column, and focused onto the sample. Images were obtained by scanning the ion beam over the surface and collecting either secondary electrons (SEs) or backscattered ions, similar to a scanning electron microscope. This system has demonstrated spot sizes of a few tens of nanometres at beam energies from 500 eV to 5 keV, and beam currents of a few picamperes. In this work, the operating ion energy was kept at 3.9 keV and the beam current was ≈1 pA. The ion beam radius and the average implantation depth were ≈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 the SE signal. The implantation depth profile was calculated from Monte Carlo simulations using SRIM software. SRIM was also used to calculate the ion trajectories shown in Fig. 1c.

**Optical modelling.** 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, where \( r, \phi \) and \( z \) are the radial, azimuthal and axial coordinates, and \( m \) and \( n \) are the azimuthal and radial modal order numbers. For a fixed azimuthal order \( m = 0, 1, 2, \ldots \), a variety of modes with radial order \( n \) and eigenfrequency \( \omega_n \) were obtained. The refractive index of silicon was considered to be \( n_{Si} = 3.48 \), 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 \( \text{TM}_{n,m} \), with the major magnetic field component parallel to the disk plane. Families of modes of the same radial order have a distinct free spectral range (FSR) and radial field distribution. The FSRS calculated from the model were 15.8 nm, 16.8 nm and 17.9 nm for the zero, first and second radial order modes, respectively (considering only the modes in the relevant range of 1,520 nm to 1,570 nm). The corresponding FSRS of the assigned modes in the experimental spectrum (Fig. 2a) were ≈15.2 nm, ≈16.1 nm and ≈17.3 nm, indicating good agreement between the simulated and observed spectra. 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 was tens of nanometres at most, and considerably smaller than the wavelength. We expect that this omission causes negligible perturbations (much smaller than our measurement error) to the calculated mode shapes.

**References**

32. Knaffman, B., Steele, A. V., Orloff, J. & McClelland, J. J. Nanoscale focused ion beam from laser-cooled lithium atoms. New J. Phys. 13, 103035 (2011).
33. Ziegler, J., Biersack, J. & Ziegler, M. SRIM—The Stopping and Range of Ions in Matter (SRIM Co., 2008); www.srim.org.