Visualizing the whispering gallery modes in a cylindrical optical microcavity

M. L. M. Balistreri

Applied Optics Group, MESA+ Research Institute and Department of Applied Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

D. J. W. Klunder, F. C. Blom, A. Driessen, and H. W. J. M. Hoekstra

Lightwave Device Group, MESA+ Research Institute and Department of Applied Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

J. P. Korterik, L. Kuipers, and N. F. van Hulst

Applied Optics Group, MESA+ Research Institute and Department of Applied Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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Whispering gallery modes in cylindrical integrated optics microcavities have, for what is to our knowledge the first time, been mapped with a photon scanning tunneling microscope. Optical images were obtained with a spatial resolution of 50 nm. By combination of information on the spatial optical distributions with wavelength-dependent measurements, an unexpectedly rich variety of intracavity phenomena, such as polarization conversion and interference of copropagating and counterpropagating modes, could be directly observed. A quantitative comparison of the experimental data with computer simulations results in a comprehensive understanding of the various whispering gallery modes inside the microcavity.

The rapidly increasing bandwidth demand of communication systems has resulted in an immense drive toward all-optical networks in which, besides data transport, routing and switching are also performed in the optical domain. As the trend is to employ a large number of densely spaced wavelengths (more than 100) at high speed (tens of gigabits per second), the realization of the network nodes requires very reliable and complex optical structures. Similar to the case of miniaturization in electronics, these advanced optical structures can be realized only by use of integrated circuitry. For integrated electronic circuitry, efforts over the past 30–40 years have led to a substantial scientific and technological infrastructure, which is still largely missing for photonic structures.

In this Letter we report an important step in the development of optical waveguide technology. For what is to our knowledge the first time, the optical field inside a nontrivial integrated optics device, a cylindrical microcavity, has been experimentally determined with unprecedentedly high spatial and spectral resolution. This approach contrasts with conventional experimental methods that mostly have been restricted either to a black-box-like characterization with respect to the functional behavior or to coarse, diffraction-limited imaging techniques.

In our case, looking directly into the microcavity by means of a photon scanning tunneling microscope (PSTM) with a spatial resolution of 50 nm revealed a variety of unexpected phenomena. In the case of microspheres, the bulk-optics equivalent of the resonators presented here, Knight et al. have successfully measured the whispering gallery modes (WGM’s) at the surface by photon tunneling.

Integrated optical microcavities recently attracted broad interest, as they can be applied as compact filter elements in dense wavelength-division multiplexing networks, microlasers, all-optical switches, and more generally as all-optical data processing elements. The cylindrical microcavity that we investigated in this study is shown schematically in Fig. 1.

The straight waveguide is present for the excitation of the WGM’s. The light in the WGM’s circles around by repeated total internal reflection at the cavity boundary. As a result, the WGM’s form a collection of concentric rings close to the rim of the cavity.

The principle of photon tunneling is based on the local frustration of the evanescent field with a decay length of 40 nm at the cavity–air interface by a near-field optical fiber probe with a 50-nm aperture (Fig. 1). As a result, the evanescent wave is locally converted into a propagating wave that is coupled into the aperture and guided through the fiber toward a detector. Scanning the probe over the microcavity surface allows one to construct an image of the optical field distribution, with a resolution given by the size of the aperture rather than by the wavelength of light.
Fig. 1. Schematic overview of WGM’s in a cylindrical microcavity, which are probed with a PSTM. The cylindrical Si$_3$N$_4$ microcavity (radius, 64 $\mu$m; height, 115 nm) and a straight Si$_3$N$_4$ channel waveguide (step height 9 nm) are fabricated in a Si$_3$N$_4$–SiO$_2$ layer system on a Si substrate.$^{13}$

surface, while staying well within the evanescent field. A height feedback mechanism based on shear force interaction is implemented that keeps the probe height at $\sim$10 nm.$^{13}$ Importantly, the force feedback yields a high-resolution topographic image that is simultaneously obtained with the optical field distribution.

Topographical and optical maps of the microcavity are shown in Figs. 2A and 2B, respectively. In the topographical image the cylindrical shape of the microcavity, with a radius of 64 $\mu$m and a height of 115 nm, can be clearly seen. The flat facet on the left-hand side of Fig. 2A is caused by the processing of the adjacent straight waveguide that is used to excite the WGM’s. The WGM’s were excited with TE-polarized light from a tunable dye laser. The microcavity is brought into resonance at a wavelength near 674 nm. As expected, the optical image (Fig. 2B) clearly shows a light distribution that is confined to the outer rim of the microcavity. Actually, one really can see the propagation of the light both in the adjacent waveguide and in the microcavity. Unexpectedly, however, an interference pattern, rather than the expected perfect rings, is observed in the optical field distribution. Such a pattern indicates that several WGM’s are simultaneously excited in the microcavity. Moreover, this pattern means that the various allowed modes interfere with one another. By zooming in (Fig. 2C), we find a period of the order of 8 $\mu$m for the so-called mode-beat pattern. Closer examination (Fig. 2D) reveals yet another interference pattern, with a periodicity near 190 nm. This periodicity is surprisingly small and can only be the result of interference between two modes, one propagating clockwise and the other counterclockwise. This observation unmistakably shows the power of the PSTM, as this subwavelength feature would have remained hidden from conventional imaging techniques.$^{2}$

To unravel the interplay of the various modes in the cavity further and thus find the origin of the observed interference patterns we performed spectral scans. An attractive method for combining spectral and spatial scanning works as follows: While we continuously scan one line perpendicular to the rim of the microcavity, the wavelength of the incoming light is varied with time. As a result, we build up a quasi image (Fig. 3A) in which each vertical line represents the optical field distribution in the radial direction for one particular wavelength. Horizontal cuts represent the variation of the optical field as a function of wavelength; i.e., they give the spectrum for one particular radial position. The wavelength scans have one additional advantage, as they allow the determination of the relative phases of the different modes. Figure 3A depicts a wavelength scan for a wavelength range from 648 to 678 nm. Two conclusions are immediately obvious. First, the vertical features in the image that vary rapidly as a function of wavelength indicate

Fig. 2. PSTM images of the microcavity and the generated WGM’s. The dashed and the solid lines indicate the corresponding line profile and cavity edge, respectively. A. Topography of the Si$_3$N$_4$ cavity detected in shear force feedback. The line profile shows the 128-$\mu$m diameter and the average height of 115 nm. The straight coupling channel is positioned at the left-hand side of the cavity. B, Photon tunneling image of a microcavity in resonance at a wavelength of 674 nm, recorded simultaneously with A. The intensity profile shows the confinement of the WGM field close to the cavity edge. C, A close look at the cavity edge (solid curve) reveals modal fields at different radial distances. Moreover, a beat pattern is observed, with a period of approximately 8 $\mu$m (arrows and line profiles). D, High-resolution photon tunneling image of a spatial beat pattern close to the cavity edge. An interference pattern with a 190-nm period is observed. The large modulation depth of the interference fringes (line profile) indicates the unique spatial sensitivity of the near-field optical probe.
that the cavity goes in and out of resonance when the wavelength is varied. Second, the optical fields at the rim exhibit two distinct bands along the edge of the cavity, corresponding to the rings in Fig. 2C. Figure 3B shows two spectra through the outer bands (i.e., for different radial positions). Both spectra show in-resonance and out-of-resonance behavior. It is clear from the dashed vertical lines in Fig. 3B that the resonance behavior at the two radial positions is out of phase as a result of the difference in propagation constants of the WGM’s. In addition to the rapidly varying resonance aspects, the spectra exhibit a slowly varying feature. This feature is attributed to the beating of the various WGM’s, analogous to the observations in the spatial maps (Fig. 2C).

A Fourier analysis of the spectra yields the so-called free spectral ranges (FSR’s) for the various radial WGM’s and the periods corresponding to the spectral mode beat. A detailed scrutiny of the Fourier analysis combined with simulations of the microcavity behavior yields several surprises. First, in addition to the expected FSR of 0.54 nm, which corresponds to the TE-polarized WGM, a FSR of 0.51 nm was observed. The calculations show that this FSR can be attributed only to a TM-polarized mode in the cavity. The existence of this mode is also confirmed by the 8-μm beat length of the interference pattern in Fig. 2C, which can be attributed only to the spatial mode beat of a TE-polarized mode with a TM-polarized mode. The presence of TM-polarized light was unexpected, since only TE-polarized light was coupled into the structure. The second outcome from the analysis is that the observed spectral periods near 1.0 nm correspond to the interference between clockwise- and counterclockwise-propagating modes. This outcome further corroborates our earlier conclusion concerning the 190-nm spatial beat patterns, which was based solely on direct optical imaging (Fig. 2D). We attribute both the polarization conversion and the change in the propagation direction to the coupling of the straight waveguide with the microcavity. Note that, against intuition, TE-as well as TM-polarized light can be simultaneously detected, leading to the observed interference pattern of the mutually orthogonal fields.

In conclusion, it has been demonstrated that a PSTM yields detailed information on the optical field distribution of a nontrivial planar waveguide device as a function of wavelength and position. The information is obtained with a spatial resolution that is unattainable with conventional microscopic methods. Moreover, the measurements allow a quantitative comparison with computer simulations. Including the unexpected PSTM observations in the computer calculations that are based exclusively on geometrical and materials properties of the device results in an excellent simulation of the behavior of the device. It is anticipated that the PSTM will be used for the development of novel high-performance planar waveguide devices, e.g., dense wavelength-division multiplexers, in which demands on the device parameters are extremely high.

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*Present address, Uniphase Netherlands B. V., Prof. Holstlaan 4, Eindhoven, The Netherlands.

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