Summary

Eliane Flück
Ph.D. thesis, June 20, 2003

Photonic crystals are structures with a strong relation between geometry and optical properties. The application of near-field methods is a new and challenging approach to investigate the local optical properties of photonic crystals. The optical signals obtained in crystal structures of various dimensionalities can be directly related to the local geometry of the structure. In contrast to this local probe technique that enables sub-wavelength resolution, far-field approaches return information that is spatially averaged. Reflectivity experiments, for example, reveal the long-range quality of a crystalline structure or the effect of stopgaps on the overall light propagation. By combining the complementary near-field and far-field results, a complete picture of the optical properties in a photonic crystal structure emerges.

A theoretical introduction on photonic crystals is provided in chapter 1. For the infinite one-dimensional case the dispersion relation is introduced. Subsequently, the two specific cases of a photonic crystal slab and a three-dimensional polystyrene opal are discussed in detail. The second part of the chapter deals with the methods used to fabricate the photonic crystal structures investigated in this thesis. To fabricate different sub-wavelength features of any size and in a periodic arrangement, we use a focused ion beam (FIB). High-energy heavy ions locally sputter material away to create a nanoscale arrangement of alternating refractive indices. For the fabrication of a large two-dimensional periodic structure, a holographic method is applied to illuminate photo resist. After lift-off and etching processes a freestanding membrane containing a hexagonal arrangement of air rods is produced. Three-dimensional photonic crystals are made by self-assembly of polystyrene spheres. The close packed face centred cubic lattice crystals (artificial opals) show photonic stopgaps along different crystalline directions.

Different methods, both near-field and far-field, have been used to investigate photonic structures. In the most frequently used methods both the light source and the detector are in the far-field. We have used such far-field methods to determine the stopgaps of the two-dimensional photonic crystal slab and the three-dimensional photonic crystals. Moreover, top reflection measurements on

the two-dimensional freestanding membrane allow so-called resonant modes to be probed. The method is elucidated theoretically in chapter 2. Moreover, the working principle of near-field detection is explained as well as the fabrication process of near-field probes. In this thesis, two different near-field optical instruments are used: a photon scanning tunnelling microscope (PSTM) and a near-field scanning optical microscope (NSOM). In the PSTM the sub-wavelength aperture fibre probe is used as detector, whereas in the NSOM, the probe provides a point-like light source. Both setups can be operated in a three-dimensional (3D) measurement mode, such that retraction and approach curves can be measured. Moreover, the PSTM enables the measurement of the optical phase simultaneously with the local intensity of light and the topography of the structure.

In chapter 3 different one-dimensional photonic structures produced by FIB milling are investigated with the PSTM. The optical field distribution of light around 15 air rods and 15 slits in a waveguide ridge show a standing wave in front of the structure. Inside the arrays themselves, the decay of the optical intensity is measured. The losses of the array are determined from the intensity decay as a function of position. The decay inside the array is found to be wavelength dependent. A faster decay rate for shorter wavelength of light suggests that losses arising from scattering processes produce the decay in intensity. Behind the 15 slit array an unexpected, wavelength-dependent recovery process is observed. The underlying interference is caused by light propagating through the array and light reflected by substrate layers underneath the waveguide. The fact that reflections from underlying substrate layers can find their way back into photonic structures, bypassing photonic crystal regions, may have repercussions for cross-talk in photonic crystal circuits based on, for example, silicon-on-insulator technology. On the 15 air rod structure the phase information of light is analysed as well. In the air rod region, we find indications of a local change in the effective refractive index. Overall, the air rod array produces circularly shaped scattered waves that interfere with the propagating waves. As a result, in a complex interference pattern is built up, which shows a network of phase singularities and phase jumps. These field and phase measurements show that a PSTM can reveal complex local scattering phenomena, which remain hidden in far-field investigations. In the last part of chapter 3 we demonstrate the importance of the three-dimensional measurement mode. Thus, the evanescent fields and propagating scattered light can be separated, as is illustrated on scattering by two slits in a waveguide ridge. The 3D measurement mode also allows evolution of phase singularities in space to be visualized. For a waveguide that contains 4 guided modes, we observe the creation of a pair of phase singularities as the height above the waveguide is increased.

A two-dimensional photonic crystal slab is characterised by far-field reflectivity measurements and the results are discussed in chapter 4. Through these measurements it is possible to investigate the coupling to resonant modes (or leaky modes) of the photonic crystal slab. The excitation of such a mode produces a sharp feature with a dispersive line shape in the reflectivity spectrum. The origin of the sharp features is interference between light propagating along two different pathways: a direct reflection and reflection via the resonant mode. Through a determination of the dispersion of the features part of the band structure, above the light line, of the photonic slab is reconstructed. Excellent agreement with the calculations is found. In the second part of chapter 4, the actual line shape of the resonance features is investigated in more detail. To this end, the theory introduced by Fano, for the description of inelastic scattering of electrons on Helium atoms, is translated to the photonic case to fit the data. We find that the line width of the observed resonaces is extremely narrow, which indicates the high quality of our large photonic crystal. The theory introduces a coupling parameter q that describes the ratio of two transition probabilities. For TM polarised light we observe a reversal in the sign of the coupling parameter q at certain $k_{//}$. This sign reversal signifies a phase change of light in one of the two interference pathways. A possible explanation is that a phase change occurs in the directly reflected light pathway while tuning the incident angle through a Brewster-like angle. It is remarkable that this angle is determined by an effective refractive index of the photonic crystal slab and not by its band structure.

In chapter 5, the transfer of light coming from a point-like light source, which couples to a three-dimensional photonic crystal and subsequently propagates through it, is investigated by using the NSOM. For different normalised frequencies we find a position dependence of the transfer. For high frequencies more light is transmitted through the crystals when the fibre probe is positioned on top of a sphere, whereas less light is transmitted in between the spheres. For low normalised frequencies, the near-field transfer pattern is inverted in intensity, thus more light is transmitted in between the spheres and less light through the spheres. The inclusion of a defect in the <111> surface affects the local coupling of light strongly. For low frequencies (except for a frequency in the first order L-gap) we find a high throughput at the defect. For high frequencies and a frequency in the first order L-gap less light enters through defects. We find that the near-field investigations have the potential to locate defects underneath the first layer of polystyrene spheres. Investigations on approach curves performed at different optical frequencies indicate the effect of the first order stopgap on the near-field coupling. At the stopgap frequency, the decay length associated to evanescent light from the crystal is two times longer than for other frequencies. In addition, a high modulation of Fabry-Perot fringes is found for frequencies near the stopgap. The near-field technique reveals the complex coupling of light at the interface of a three-dimensional photonic crystal.

This thesis describes a rich variety of optical behaviour in photonic crystal structures. Local visualization of light propagation allows the direct determination of losses and refractive indices and the observation of complex interference phenomena like the formation of phase singularity networks. Both local and spatially averaging techniques have been used to investigate the coupling of light to photonic crystals. We find that coupling to resonant modes can exhibit so-called q-reversal. The near-field coupling of light coming from a point-like light source is found to be both position-dependent and frequency dependent. This coupling is strongly influenced by local defects in the crystal.