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Looking into Photonic Structures with a Photon Scanning Tunnelling Microscope

Abstract

We present our first photon scanning tunnelling measurements of optical fields around tailor-made subwavelength structures. A new way to produce low-dimensional photonic crystals based on ion beam milling is also introduced.

1 Introduction

Already more than 50 years ago Purcell [1] realized that spontaneous emission from an atom could be strongly influenced by placing the atom in a cavity with dimensions of the order of the optical wavelength. Photonic crystals, by their nature, consist of building blocks of that dimension (see e.g. [2] (1D) and [3] (3D)) and also act as perfect mirrors in the direction of each stop gap. Thus, they are ideal candidates for gaining a high degree of control over spontaneous emission [4]. With the continued increase of possibilities for the production of submicron structures, it is therefore not surprising that photonic crystals for visible light have seen a tremendous research activity over the last few years. Here, we present focused ion beam (FIB) sputtering as a possible new tool for the production of the photonic structures.

Despite some notable exceptions [5, 6] most of the investigations of photonic materials are carried out with input-output measurements. In other words, light emerging from the material is monitored as a function of parameters of the incoming light (polarisation, wavelength, ...). The results are subsequently compared to theory. Here, we present our first steps to investigate light inside low-dimensional photonic crystals with a photon scanning tunnelling microscope (PSTM). Local studies have the distinct advantage over input-output investigations because they can directly determine the influence of heterogeneities on the optical field propagation.

2 Focused ion beam production of subwavelength photonic structures

Channel waveguides form the basis for our photonic structures. They consist of a Si_3N_4 ridge (height 22 nm & width 1.4 (m) on top of a 33 nm layer of Si_3N_4 on SiO_2. For a wavelength of 632.8 nm in air the only supported mode is the so-called TE_{00} mode with an in-plane

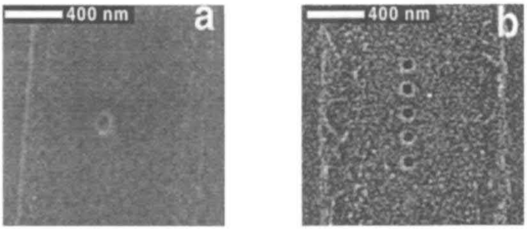

Figure 1: FIB image of subwavelength structures produced by FIB sputtering. A single air rod (a) and a periodic array of 5 air rods (b) have been fabricated in a channel waveguide.

polarisation. The effective index of refraction of this mode is 1.46, as calculated with the effective index method [7].

We have modified the waveguides by means of FIB sputtering. Figure 1a shows a FIB image of an air rod sputtered in a Si_3N_4 channel waveguide. The diameter of the rod is 110 nm. We have produced rods with diameters down to 30 nm. The minimally attainable diameter is not determined by the size of the focal spot ($\sim$ 10 nm) but by charging of the nonconducting Si_3N_4 during the sputter process. As a consequence, the diameter increases with increasing exposure. Separate measurements have confirmed that air rods produced with the FIB are perpendicular to the waveguide surface. As yet, we have not been able to establish the depth of the holes.

Figure 1b shows a FIB image of a periodic array of 5 air rods, each with a diameter of 90 nm. The diameter of the holes is the same for all holes to within the accuracy of the measurements from the FIB images ($\pm 5\%$). The distance between the centres of the air rods is 215 nm. The distance between the holes varies by less than 10 nm.

3 Photon scanning tunnelling microscopy of photonic structures

Figure 2 schematically depicts measurement with a PSTM on a waveguide structure. In the optical ray description light propagates through the waveguide by repeated total internal reflections. As a result an evanescent field is present above the waveguide surface. In the PSTM measurement a subwavelength aperture probe is held at a constant height above the sample surface. The height of the probe is such that it frustrates the evanescent field which, as a result, is transformed into a propagating wave. The output of the probe is monitored with a photomultiplier tube (PMT). As the probe is raster scanned over the surface an image can be constructed of the optical fields in the sample (see e.g. [8] and [9]). A topographic image is simultaneously obtained with the optical image from the height adjustments necessary to keep the height constant. The probe is fabricated from a single mode fibre by standard fibre pulling in order to obtain a sharp apex. In order to minimize stray light entering the probe it is covered with Al. The definition and throughput of the resulting probe is then further improved by sputtering its end face with a focused ion beam (FIB) [10].

Figures 3a and b show a height image (a) and an optical image (b) simultaneously ob-

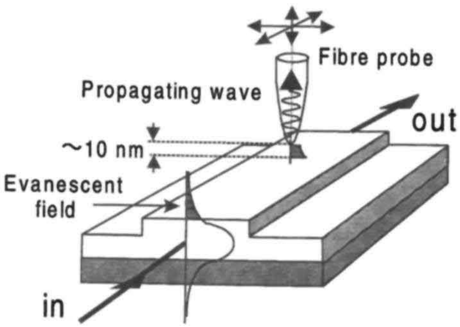

Figure 2: Schematic representation of a PSTM measurement. An aperture probe is raster scanned over the sample while the height above the surface is kept constant at ~ 10 nm. As a result the evanescent field above the sample is frustrated and picked up by the probe.

tained with a PSTM around the hole depicted in fig. 1a. In the topographical image the hole is clearly visible in the centre of the waveguide. Light is coupled into the waveguide structure by means of a microscope objective (the direction of the incoming light is from top to bottom). In the optical image around the hole we observe a pattern attributed to interference of scattered and unscattered light. The fringes have a separation of 217 nm just in front of the hole. Within the experimental accuracy this value is equal to the expected half of the wavelength as determined by the effective index of the channel waveguide ($n_{eff} = 1.46$). Note that other techniques would not be able to resolve this interference pattern. It is clear that the light intensity just in front of the hole is higher than further away. We attribute the increase in intensity close to the hole to light scattered directly out of the waveguide into the aperture probe. The interference pattern is not mirror symmetric with respect to the axis of the waveguide. This asymmetry is probably the direct result of the hole being off-axis by ~ 100 nm.

Figures 3c and 3d show the height image (c) and an optical image (d) obtained with the PSTM of the structure depicted in fig. 1b. Qualitatively the same optical pattern is observed as in the case of a single hole. Here however we observe two pronounced maxima 'followed' by a long ($> 1\mu$m) shadow. The two maxima and the three local maxima inside the shadow region are located at the 'down stream' air- Si_3N_4 interface of the air rods. Again the mirror symmetry is broken even though the array is less than 30 nm off-axis.

Figure 4 (left panel) shows a line trace of the detected optical intensity as a function of the position along the waveguide. It shows the interference fringes mentioned previously with an increased intensity and modulation depth close to the holes. A beating pattern is also just visible. The beating becomes clearer when the boxed area is Fourier transformed. The result of this transform is depicted in the right panel. It shows two distinct peaks: the expected peak at 217 nm and an unexpected peak at 262 nm. We attribute the peak at 262 nm to interference of light propagating inside the waveguide with light propagating above the waveguide.

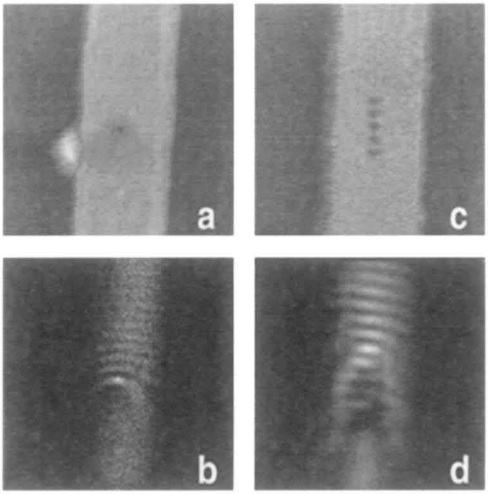

Figure 3: Height (a & c) and optical (b & d) images (4 μm × 4 μm) obtained with a PSTM.

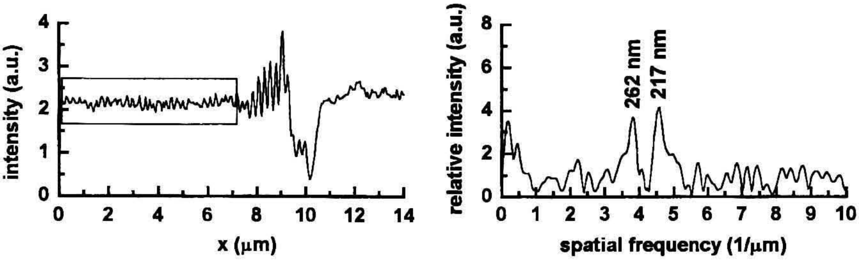

Figure 4: (left panel) Line trace of the optical signal of fig. 3d along the direction of the waveguide. The increased optical intensity due to scattering close to the first air rods (at 9.2 μm) is clearly visible. (right panel) Fourier transform of the boxed array showing two distinct spatial frequencies being present in the interference pattern.

4 Discussion

We have presented our first subwavelength photonic structures produced by focused ion beam sputtering. The technique is shown to have a high flexibility similar to that of electron beam lithography. The fabrication of nonperiodic structures like microcavities with dimensions of $\sim \lambda^3$ seems feasible. The advantage of the technique over e-beam lithography is that no resist is required for structure production.

We have mapped the optical fields around 2 different subwavelength objects (a single air rod and a periodic array of 5 air rods) with a resolution unattainable for other techniques.

Thus, we can observe interference of scattered and unscattered light. The optical images indicate that the production of 1D photonic structures requires a great positioning accuracy of the scatterers with respect to the waveguide structure. In the near future we will perform the same optical mapping as a function of wavelength. In addition, we will map the phase of the light by inserting the PSTM in one of the legs of a Mach-Zehnder interferometer.

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