Photon scanning tunneling optical microscopy with a three-dimensional multiheight imaging mode

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A photon scanning tunneling microscope with a three-dimensional multiheight mode has been developed for the mapping of optical field distributions in integrated optical waveguide structures. The optical field is measured at different heights above the waveguide surface. The multiheight measurements also contain the optical information gathered with the commonly used constant gap measurements in addition to the topography of the waveguide surface. With the multiheight method, the decay length of the evanescent field is readily determined as function of the in-plane coordinate. Moreover, the evanescent light can be distinguished from scattered light. © *2000 American Institute of Physics.* [S0003-6951(01)02101-5]

Nowadays, the mapping of the optical field distribution of integrated optical waveguide structures with the so-called constant gap mode of a photon scanning tunneling microscope (PSTM) has become routine.[1–7] Yet, an additional imaging mode, of the PSTM the multiheight imaging mode, for the mapping of the optical field as a function of heights above the waveguide surface would yield important extra information. First of all, the scattered light will be more easily distinguished from the evanescent light, which is a crucial demand for the investigation and the development of low-dimensional photonic crystals.[2,4,5,7] Second, the decay length of the evanescent field can be determined by measuring the light intensity at one in-plane position for different heights.[8] Third, the mapping of the optical field distribution at different heights will unravel the interplay of various modes with a different slab order. In the latter case, the optical field decay as function of the height is not constant, due to the different decay lengths of the slab modes.

The optical field above a waveguide has previously been measured with a PSTM at different heights using the constant intensity mode.[9] A serious drawback of the constant intensity mode however is that the fiber probe can come in contact with the waveguide surface during the scan, due to the lack of a height regulation when the intensity becomes too low. PSTM based on an apertureless metallic probe with electron tunneling height regulation has also been applied to multiheight imaging.[10] However, tunneling regulation cannot be applied to optical waveguides because the metal layer, required for the electrical conduction, influences the optical field of the waveguide. Furthermore, the possibility of measuring both with a constant gap mode and a constant height mode has been shown for a near-field scanning optical microscope[11] in the transmission mode, but not yet for the investigation of optical waveguide devices with a PSTM. Recently, van der Rhodes[3] mapped the evanescent decay of the optical field of a waveguide at different heights using a PSTM based on tuning fork height regulation.

In this letter, we report the mapping of the optical field distribution of integrated waveguide structures by means of a PSTM with a three-dimensional (3D) multiheight mode. Both constant gap and multiheight mapping of the optical field simultaneously with the mapping of the topography of the waveguide surface are presented. The decay length of the optical modes in the vertical direction is determined as function of position. Moreover, we show that evanescent and scattered fields can be distinguished.

The optical field of a waveguide is probed with a PSTM by locally frustrating the evanescent field at the waveguide–air interface with an uncoated tapered optical fiber probe.[1–9] The probed light is coupled into the fiber and then detected. The optical field can either be mapped with the conventional constant gap mode or with the multiheight mode (Fig. 1) presented here. For the conventional constant gap mode, the

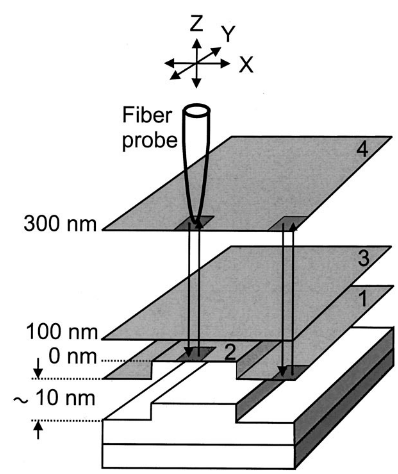

FIG. 1. Scanning sequence of the constant gap and multiheight mode. The probe is raster scanned over the waveguide surface, with a constant gap of around 10 nm between the probe and the waveguide surface, to image with the conventional constant gap mode (planes 1 and 2). By lifting the probe down and up for every measuring position during the raster scan a multiheight map is obtained (planes 1–4). The gap between the probe and the waveguide for the constant gap mode corresponds with the height of the turning point during the lifting of the probe for the multiheight mode. The height of plane 1 above the waveguide ridge is indicated as the 0 mm level. Two planes (3 and 4) are depicted at a constant height of 100 nm and 300 nm, respectively.

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probe is raster scanned over the waveguide surface. A height feedback system based on piezoelectric tuning forks is used both to probe the evanescent field at a constant height above the waveguide and to prevent contact between the probe and the waveguide surface during the scanning.[12] The setpoint of the feedback loop determines the distance between the fiber and the waveguide surface, which is in the range of 2–20 nm. The feedback signal needed to keep the height constant yields a topographic image that is simultaneously measured with the two-dimensional (2D) mapping of the optical field. The multiheight imaging mode is based on a sawtooth voltage applied to the z element of the xyz scanner. By combining the sawtooth movement in the z direction with the raster scanning of the probe in the lateral direction, a 3D multiheight measurement is obtained. The setpoint of the height feedback system is still operational and determines the height at which the fiber is turned around during the downward movement of the fiber. Thus, it prevents the fiber from coming into contact with the waveguide surface. The field distribution at a specific height can be obtained from the 3D multiheight map by constructing an optical image from the intensities measured at that height. The decay length of the evanescent field at a specific lateral position is determined from the measured intensities as a function of the height. The topographical map of the waveguide surface is constructed from the turning points of the fiber as a function of the lateral position. Note that the optical intensity at these heights is the same as that obtained with the constant gap mode.

A constant gap and a multiheight measurement of a Si_3N_4 channel waveguide (monomodal and multimodal in the height and lateral direction, respectively) are presented in Fig. 2. Linear transverse magnetic (TM) polarized 632.8 nm light has been coupled in the waveguide to excite the TM modes of the multimodal waveguide. The topographic map and the simultaneously obtained optical field distribution of the channel waveguide with the constant gap mode are shown in Figs. 2(a) and 2(b), respectively. The scan speed of the constant gap mode is limited by the response time of the height feedback system based on 32.8 kHz tuning forks. For a line scan in the constant gap mode the fiber is raster scanned in the lateral direction from left to right and back. The maximum pixel frequency of around 150 Hz is determined by the quality factor of the tuning fork ($\sim$200). The mode profile with three maxima in Fig. 2(b) indicates the excitation of the TM_{02} mode. The observation of a mode-beat pattern reveals the additional excitation of lower order TM modes. The corresponding 3D multiheight measurement of the same waveguide has been carried out for 64 by 64 pixels in the lateral direction and 1000 pixels in the height direction. Figure 2(c) shows the topographic map of the channel waveguide, as constructed from the multiheight data set at a height of 0 nm (10 nm above the waveguide surface). Figure 2(d) shows the corresponding optical field distribution.

Due to the sawtooth movement of the fiber probe in the height direction for the multiheight mode the measurement time increases. The sawtooth voltage has only been applied when the fiber is raster scanned in the lateral direction from the left-hand side to the right-hand side and not on the way back, to decrease the scan time by a factor of 2. A sawtooth

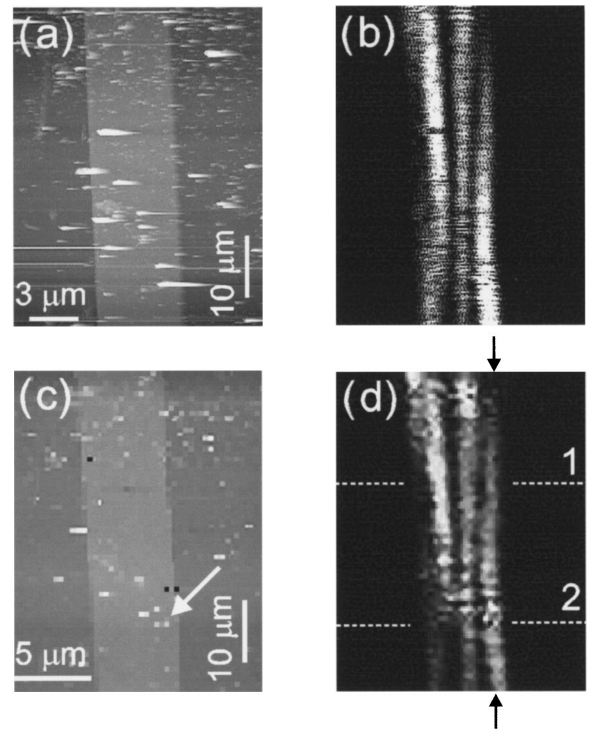

FIG. 2. Constant gap mode and multiheight mode images of a multimodal channel waveguide. TM polarized modes have been excited at a wavelength of 632.8 nm. (a) Topography of the multimodal Si_3N_4 channel waveguide on a SiO_2 substrate detected with the constant gap mode. The designed guided layer thickness, the measured width and height is 100 nm, 5.0 ± 5 μm and 11 ± 2 nm, respectively. The number of pixels is 200 by 200. (b) Photon tunneling image of the optical field of the channel waveguide measured with the constant gap mode and recorded simultaneously with topography shown in (a). (c) Topography of the channel waveguide detected with the multiheight mode. The number of pixels is 64 by 64. The arrow indicates a scattering point. (d) Photon tunneling images of the optical field of the channel waveguide measured with the multiheight mode for a height of 0 nm (plane 2 in Fig. 1) and recorded simultaneously with the topography (c).

frequency of around 3.0 Hz is used for the z modulation. The maximum frequency is determined by the response time of the tuning fork feedback system as to prevent probe crashes. As a result, for each in-plane coordinate, with 1000 pixels in the height direction, the pixel frequency for the multiheight mode is around 3 kHz. The field distribution of the modes measured with the constant gap mode [Fig. 2(b)] and the multiheight mode [Fig. 2(d)] at around 10 nm above the waveguide surface are identical. This shows the proper operation of the multiheight mode compared to the constant gap mode.

The intensity as a function of the height and the lateral position along the dashed line 1 in Fig. 2(a) is shown in Fig. 3(a). The decay of the evanescent field of TM polarized modes (slab order 0) is observed. Figure 3(b) shows the intensity as a function of the height along the line indicated with the two arrows in Fig. 3(a). The intensity exhibits an exponential decay, as expected. The measured curve has been fit with a exponential decay function to determine the measured decay length and is found to be 39 ± 5 nm, which corresponds well (within the experimental accuracy) with the calculated decay length of 41 ± 2 nm of the zero order slab mode. The intensity as a function of the height and the lateral position along the dashed line 2 in Fig. 2(d) is shown in Fig. 3(c). The light path of the scattered light due to a scattering

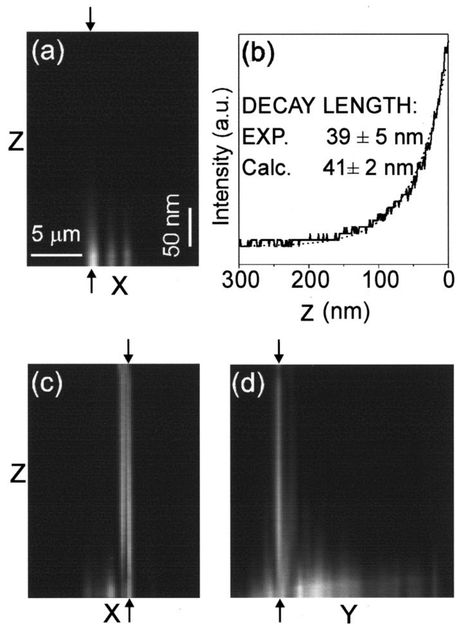

FIG. 3. 2D *XZ* and 2D *YZ* maps of the optical field as obtained with the multiheight mode. The intensity has been measured as function of the height from 300 nm down to 0 nm. The height of the turning point is indicated as the 0 nm height level, as explained in Fig. 1(a). The light intensity measured in the *XZ* plane through the dashed line 1 in Fig. 2(d). The intensity of the evanescent field decays exponentially. (b) The light intensity measured as a function of height along the line indicated with the two arrows in (a). The dashed curve is the fit of the measured curve with an exponential decay function. The calculated and the experimentally determined decay length of the modes are 41±2 nm and 39±5 nm, respectively. (c) The light intensity in the *XZ* plane through the dashed line 2 in Fig. 2(d). The scattered light, observed in the *XZ* plane due to the scatter point, propagates in the vertical direction. The scatter point is indicated with an arrow in the topographical image of Fig. 2(c). (d) The light intensity in the *YZ* plane indicated with the two arrows in Fig. 2(d). This line crosses the dashed line 2 in Fig. 2(d) at the scatter point. In the *YZ* plane the scattered light also propagates in the vertical direction.

point is observed. The scattered light shows up as an intensity that hardly decays with height [bright vertical stripes, Fig. 3(c)]. The scatter point is indicated with an arrow in the topographical map of Fig. 2(c). The intensity as a function of the height and the lateral position along the line indicated with the two arrows in Fig. 2(d) is shown in Fig. 3(d). This plane crosses the scattered light due to the scatter point indicated in Fig. 3(c). Again, the scattered light appears as bright vertical stripes. It is surprising that the existence of this scattering point remains hidden in the intensity map of Fig. 2(b) and 2(d). This observation illustrates the power of the multiheight mode to distinguish the evanescent light from the scattered light in their different height dependence.

In conclusion, a photon scanning tunneling optical microscope with a multiheight mode for the mapping of the optical field distribution in optical waveguide devices has been shown. The 3D multiheight images of the optical field contain more information than images obtained with a 2D constant gap mode. The decay length of the evanescent field can be determined for all scanned positions and the evanescent light can be distinguished from the scattered light. It is anticipated that the multiheight mode of the PSTM will be used in the future for the development and the investigation of low-dimensional photonic crystals, for which it is important to distinguish the studied evanescent light from the scattered light.

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