Visualization of mode transformation in a planar waveguide splitter by near-field optical phase imaging

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The gradual transformation of a guided TM_{00} mode into an ''intermediate'' double mode by a splitting junction has been investigated with a phase-sensitive photon scanning tunneling microscope. Field profiles and wave vectors of the modes have been directly determined from the phase information. Via a Fourier analysis of the measured phase and amplitude maps the decay of the TM_{00} mode and buildup of the intermediate mode have been directly visualized. Phase singularities and phase jumps in the transition region underline the mode transformation process. Finally, a partial polarization conversion of the TM modes to TE-polarized modes has been observed. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1394175]

Measurement of the local optical phase of light inside photonic structures in addition to the field amplitude, yields detailed information about the light propagation, as demonstrated recently using a heterodyne interferometric photon scanning tunneling microscope (PSTM).[1] The unique phase information allows the determination of all relevant parameters of the waveguide modes directly: wave vector, mode profile, relative excitation strength, relative phase, and the difference in propagation direction of leaky and guided modes.[1] In this letter we present the gradual shape transformation of a mode as it is split by a planar waveguide splitter. The local optical phase and amplitude detection by heterodyne interferometeric PSTM, allows visualization of the profile and the relative amplitude of both the incoming and the ''intermediate'' double mode independently.

In a PSTM a near-field optical fiber probe is used to probe the evanescent field at the waveguide-air interface.[1–4] The surface topography is imaged by raster scanning the probe, using a height feedback mechanism.[5] In order to measure the phase of the optical field in the waveguide an interferometric method is used: PSTM and waveguide sample are introduced in one branch of a Mach–Zehnder type interferometric setup.[1] The laser light is split in a part that is coupled into the waveguide and a part that forms a reference branch. Combination of the photon-tunneling signal with the reference signal yields the interference signal. Heterodyne interferometric detection is achieved by acousto-optic modulation of the light in the reference branch. The resulting signal, measured with a lock-in amplifier, contains the phase information and is proportional to the field amplitudes of both the local waveguide field and reference signal. The relative phase distribution within the waveguide is measured by scanning the probe over the waveguide surface. The drift of the interferometer during the measurement is negligible.

The investigated waveguide splitter is designed to split light ($\lambda=632.8$ nm) in a channel waveguide into two equal parts in identical channel waveguides. The Si_3N_4 planar waveguide splitter has been realized in a Si_3N_4/SiO_2 layer (indices 2.01 and 1.46, respectively) on a Si substrate.[6] The Si_3N_4 slab thickness is 120 nm, with an additional 4 nm ridge at the channel. The width of the incouple channel waveguide increases slowly from 2.5 to 5.0 μm and separates into two channels, both 2.5 μm wide. A 2.5 μm channel is monomodal for TM- and bimodal for TE-polarized light,[7] where an effective wavelength difference of ~1.3 nm between both TE modes is calculated. A 5.0 μm channel allows two modes for TM and four modes for TE-polarized light, where the maximum effective wavelength difference is ~0.5 and ~2.6 nm for the TM and TE modes, respectively. Furthermore, also leaky modes with slightly longer wavelengths than those of the guided modes are excited in the splitter.[8]

Measurements of the planar waveguide splitter with the heterodyne interferometric PSTM are presented in Fig. 1, with TM polarized light coupled into the input facet of the splitter. The topography of the splitter with a measured height of 4.2±3 nm is shown in Fig. 1(a). The incouple channel waveguide, with a measured width of 8.3±0.1 μm, splits into two channels of 3.5±0.1 μm and 3.0±0.1 μm. The actual dimensions are larger than designed. The amplitude (A) of the optical field is shown in Fig. 1(b). The splitting of the light is clearly visible. Furthermore, an unexpected beating pattern is observed with a modulation depth (along the dashed line) of 0.11±0.02. The mode-beat period is determined by Fourier analysis of the optical amplitude along the dashed line [Fig. 1(c)] and shows a clear peak corresponding to a mode-beat length of 4.4±0.5 μm. This beat length corresponds to the length expected for quasi-interference that can occur between TM- and TE-polarized modes due to the field mixing at the subwavelength probe.[9] The phase of the optical field ($\cos\phi$) is shown in Fig. 1(d). The ''phase image'' is dominated by straight wave fronts associated with a single plane wave. It is clear that any phase development around the splitting point is very gradual. At the positions of the two arrows, unexpected phase jumps and phase singularities[1] appear. Their positions do not correspond with any topographic feature of the splitter.

The measured product $A\cos\phi$ is shown in Fig. 1(e), together with the Fourier spectrum along the dashed line in

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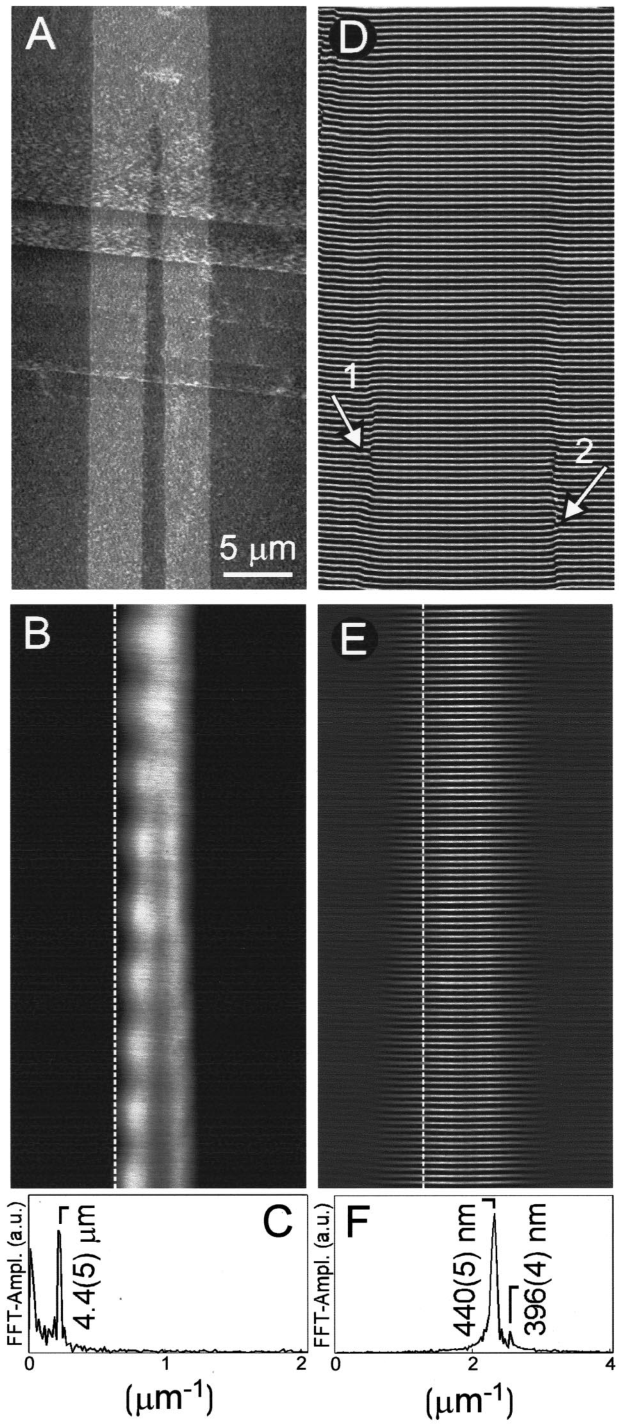

FIG. 1. Interference PSTM images (40×20 μm^2) of a Si_3N_4 waveguide splitter. TM-polarized light has been coupled in and propagates from the top to bottom of the image. (a) The splitter topography. (b) The measured amplitude of the optical field. A mode-beat due to the interference between the TM_{00} and TE_{00} mode is observed in the left part of the *Y* junction. (c) Fourier transform of the measured amplitude along the dashed lines in Fig. 1(b) showing a mode-beat length of 4.4(5) μm, due to TM/TE interference. (d) The measured phase evolution of the optical field. cos ϕ is shown. Phase jumps and singularities are observed (arrows 1 and 2). (e) The measured A cos ϕ of the optical field. (f) Fourier transform of the measured A cos ϕ along the dashed lines in Fig. 1(e) yields wavelengths of the TM_{00} and TE_{00} mode of 440(5) and 396(4) nm, respectively.

Fig. 1(f). The spectrum shows a strong peak corresponding to a periodicity of 440±5 nm and a weaker peak corresponding to 396±4 nm. The periodicities of 440 and 396 nm correspond to the wavelengths of the excited TM- and TE-polarized modes, respectively. With these two experimental values for the wavelength we calculate a TE–TM mode-beat length of 3.96±0.08 μm. As expected, this beat length corresponds well with the value of 4.4±0.5 μm, as determined from the amplitude modulation only [see Fig. 1(c)]. The peak heights of the Fourier spectrum indicate a 1:13±1 amplitude ratio between the TE and TM modes. From this ratio we calculate a modulation depth of 0.15±0.02, in good agreement with the observed modulation depth, which again confirms the TE–TM beating.

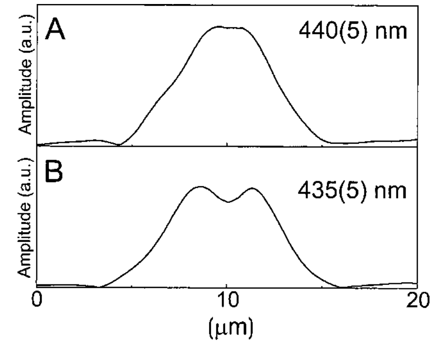

FIG. 2. Field profiles of the different modes excited in the waveguide splitter using a one-dimensional Fourier transform of the measured A cos ϕ map [Fig. 1(e)]. (a) The TM_{00} guided mode at a wavelength of 440(5) nm, and (b) the TM intermediate guided mode at a wavelength of 435(5) nm.

Each mode has a different wave vector and is thus represented by a distinct peak in the Fourier spectrum. As a result the field profile of every mode can be determined independently by plotting the amplitude of the peak in the Fourier spectrum, as a function of the direction perpendicular to the propagation direction. The spectral resolution of the method is proportional to the length of the scan in the propagation direction. The field profile obtained by selecting the peak in the Fourier spectrum at 440 nm [see Fig. 1(f)] is depicted in Fig. 2(a). Because of the limited scan length of 40 μm, this profile is the sum of the profiles of all the TM-polarized modes. For a channel width of 8.3 μm, which allows up to 3 and 5 modes for TM and TE polarization, respectively,[7] an observation length of at least 640 μm would be necessary to separate all the contributions of the various TM modes in the spatial frequency spectrum. Because the overall shape of the profile corresponds with the shape of a single TM_{00} mode, clearly the TM_{00} mode is far more strongly excited than the higher order TM modes. The field profile obtained by selecting the amplitude of the Fourier component at 435 nm is depicted in Fig. 2(b). This field profile contains two maxima. We attribute the field profile to a TM intermediate guided mode that arises as a result of the splitting of the light. The slight increase of the amplitude of the field profiles outside the splitter area in Figs. 2(a) and 2(b) is an indication of the excitation of leaky TM modes.[8]

The development of the different modes excited in the waveguide splitter can be determined as function of position by performing a two-dimensional (2D) Fourier analysis. First, a 2D Fourier transform of the measured A cos ϕ map is calculated. Subsequently, an inverse Fourier transform is calculated of only spatial frequencies in the high and low frequency part of the peak around 440 nm in the Fourier spectrum of Fig. 1(f). The resulting spatial distributions of the

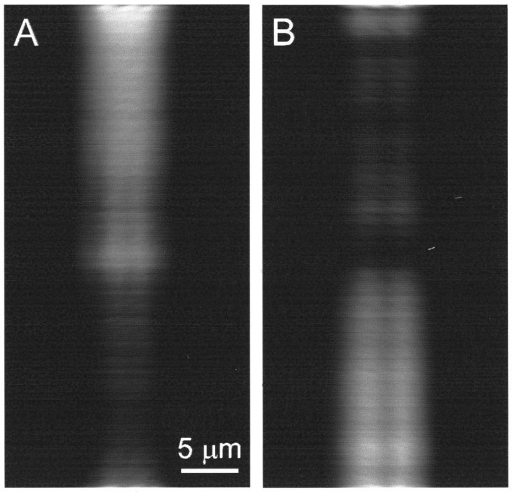

FIG. 3. The development of the different modes excited in the waveguide splitter, determined using a 2D Fourier transform of the measured $A \cos \phi$ map [Fig. 1(e)]. (a) The TM_{00} mode with a measured wavelength of 440(5) nm, obtained by selecting the low frequency part of the peak in the Fourier spectrum of Fig. 1(f). The breakup of the TM_{00} mode in the propagation direction is observed. (b) The TM intermediate guided mode with a measured wavelength of 435(5) nm. The buildup of the mode in the propagation direction is observed.

TM_{00}-mode amplitude (440 nm) and the intermediate mode amplitude (435 nm) are plotted in Figs. 3(a) and 3(b). The peak around 396 nm, corresponding to the excitation of TE-polarized modes, has been filtered out of the inverse transform to eliminate the TE/TM mode beat. Figures 3(a) and 3(b) show the growth of the intermediate mode with distance at the expense of the TM_{00} mode. The gradual change in relative amplitudes and field profiles of the two modes (the Gaussian field profile of TM_{00} mode and the field profile with two maxima of the intermediate mode) illustrates elegantly the splitting of the light by conversion of a mode into another mode. The higher ''frequency'' features in Figs. 3(a) and 3(b) are due to edge effects in the Fourier filtering.

The observed phase singularities and jumps [Fig. 1(d)] underline the buildup of a new guided TM mode at the expense of the original TM_{00} mode with only a small wavelength difference between the two modes.

The presence of the TE-polarized modes is unexpected, because exclusively TM-polarized light has been coupled in. The presence of TE modes indicates a partial polarization conversion of TM- to TE-polarized light. The polarization conversion occurred already before the splitting point as revealed by the mode-beat pattern. Possibly scattering at the surface or a fabrication artifact caused the partial polarization conversion.

In conclusion, the splitting process of the light inside a planar waveguide splitter has been studied as a function of position by measuring both the amplitude and phase of the optical field using a heterodyne interferometric PSTM. A gradual transformation of the incoming mode has been visualized over a length of 40 μm. The interference of guided and leaky modes resulted in the appearance of phase jumps and phase singularities. The development of various modes could be determined independently using the phase information.

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