

Quasi interference of perpendicularly polarized guided modes observed with a photon scanning tunneling microscope

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The simultaneous detection of TE- as well as TM-polarized light with a photon scanning tunneling microscope leads to a quasi-interference pattern of these mutually perpendicular polarized fields. This interference pattern has been observed in the optical field distribution as a function of both position and wavelength. Comparison of experimental data with simulations confirms the interference of mutually orthogonal fields. This quasi interference is caused by conversion of the linearly polarized light of both modes into elliptically polarized light by a fiber probe. © 2000 Optical Society of America

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Perpendicularly polarized modes in integrated optical waveguide structures do not interfere. It is known that both perpendicularly polarized TE and TM modes can be probed with a photon scanning tunneling microscope (PSTM).^{1–8} However, it is still not expected that interference will occur when the optical intensity of perpendicularly polarized modes is probed simultaneously. A determination of the relative phase between perpendicularly polarized modes would, however, provide a better understanding of the operation of, for example, polarization converters and mode splitters, the operation of which depends critically on the polarization of the light. We report the observation of quasi interference between TE- and TM-polarized light in an integrated optical waveguide with a PSTM. As a result of this quasi interference the phase difference between the perpendicular polarizations becomes accessible.

The principle of photon tunneling is based on the local frustration of the evanescent field at the waveguide-air interface by a near-field optical fiber probe.^{1–8} As a result, the evanescent wave is locally converted into a propagating wave, which is coupled into the fiber and guided through the fiber toward a detector. By raster scanning of the probe over the waveguide surface, an image of the optical field distribution is constructed. The evanescent field in the near field of the waveguide surface is probed by implementation of a height-feedback mechanism based on shear-force interaction, which keeps the probe height at approximately 10 nm.⁹ This height feedback yields a topographic image that is obtained simultaneously with the optical field distribution.

With the fiber probe it is possible to detect TE- and TM-polarized light. Figure 1A shows a topographical map of a Si₃N₄ channel waveguide. Linearly polarized

light is coupled in a controlled way into the channel waveguide to excite only a TE₀₀ mode (Fig. 1B) or only a TM₀₀ mode (Fig. 1D). In both cases the result is a single-mode light field that is continuous in the propagation direction. For an incoupling polarization angle (Φ) of 45°, both the TM₀₀ and the TE₀₀ modes are simultaneously excited (Fig. 1C). In this case we

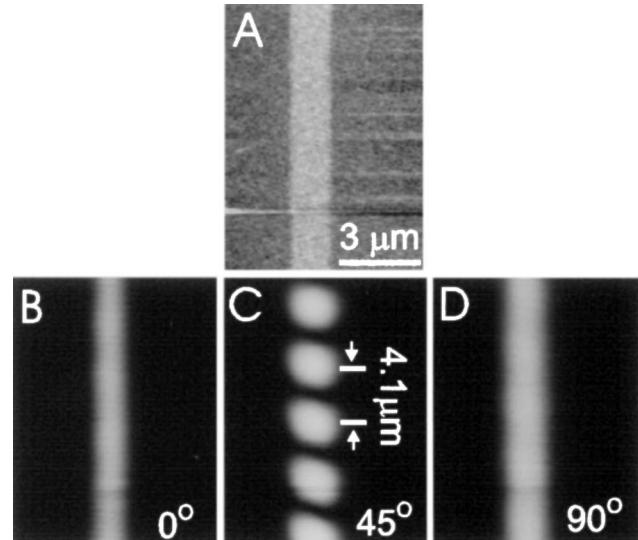


Fig. 1. PSTM maps (7.5 μm by 10 μm) of a Si₃N₄ channel waveguide on a SiO₂ substrate: A, Topography of the channel waveguide with a width of 2.5 μm and a ridge height of 2 nm. The thickness of the guiding layer (not measured with the PSTM) is 120 nm. B, Optical field distribution of a single TE₀₀ mode (incoupling polarization angle $\Phi = 0^\circ$). C, Optical field distribution of both a TM₀₀ mode and a TE₀₀ mode ($\Phi = 45^\circ$). The mode beat length is 4.1(1) μm . D, Optical field distribution of a single TM₀₀ mode ($\Phi = 90^\circ$).

observe an unexpected interference pattern with a period of $4.1(1)\mu\text{m}$.

Figure 2 illustrates the dependence of the interference pattern on Φ . To obtain the results shown in Fig. 2 we scan the fiber probe in the center of the channel waveguide along the propagation direction, and at six instances (arrows) the angle Φ is changed by 15° . When only the TE_{00} mode ($\Phi = 0^\circ$) or only the TM_{00} ($\Phi = 90^\circ$) is excited, no interference pattern is observed. For angles from 0° to 90° an interference pattern is observed, the period of which is always $4.1(1)\mu\text{m}$. However, the modulation depth of the pattern varies with Φ . Because of the dependence of the interference pattern on Φ , we can attribute this variation only to unexpected quasi interference between TE- and TM-polarized light.

Quasi interference can also be observed in measurements as a function of wavelength. The intensity of the optical field is measured at a fixed position while the wavelength of the incident light is varied. In this way the change of the phase difference $\Delta\varphi$ from a TE- to a TM-polarized mode at this fixed position is measured as a function of the wavelength. The phase difference $\Delta\varphi$ is given by

$$\Delta\varphi = \frac{2\pi L}{\lambda} [n_{\text{TM}}(\lambda) - n_{\text{TE}}(\lambda)], \quad (1)$$

where L is the distance from the incoupling facet of the waveguide to the measuring position, λ is the wavelength in vacuum, and n_i is the effective refractive index of mode i . From Eq. (1) it follows that at a fixed position the change of $\Delta\varphi$ when the wavelength λ of the incident light is varied will be proportional to distance L . We have carried out wavelength-dependent measurements at three positions along the waveguide (Fig. 3A). The distances between positions 1 and 2 and between positions 1 and 3 are 1.3 and 2.3 mm, respectively. Figure 3B shows the optical signal when the wavelength is varied from 669 to 673 nm for an incoupling angle Φ of 0° (TE_{00} mode only). As expected, no interference is observed. Figures 3C, 3D, and 3E show the same wavelength measurements for an angle Φ of 10° (TE_{00} and TM_{00} modes) at positions 1, 2, and 3, respectively. In this case, wavelength-dependent interference is observed when both TE- and TM-polarized light are coupled in. The periods of the observed interference in Figs. 3B, 3C, and 3D are $0.57(4)$, $0.81(7)$, and $1.1(2)$ nm, respectively. As expected, the change of $\Delta\varphi$ increases with the distance L to the incoupling facet of the waveguide.

Using calculated effective refractive indices, we have determined the expected interference periodicities. A comparison of the experimental data and the calculations is given in Table 1. The excellent agreement between the measured spatial-mode and the calculated-mode beat lengths for TE_{00} and TM_{00} further corroborates our conclusions concerning the origin of the interference pattern. Interference between lower-order (00) and higher-order modes can be excluded as a cause of the observed pattern, as such interference would lead to a mode beat length that is more than an order of magnitude larger than the observed length (TE_{00} with TE_{01} is given as an example).

An additional check of our conclusion is to use Eq. (1) to calculate the distance between positions 1 and 3 from the observed beating at a fixed position. Here, the calculated index of refraction is assumed to vary little with wavelength, so

$$\frac{d(n_{\text{TE}} - n_{\text{TM}})}{d\lambda} \ll \frac{(n_{\text{TE}} - n_{\text{TM}})}{\lambda}. \quad (2)$$

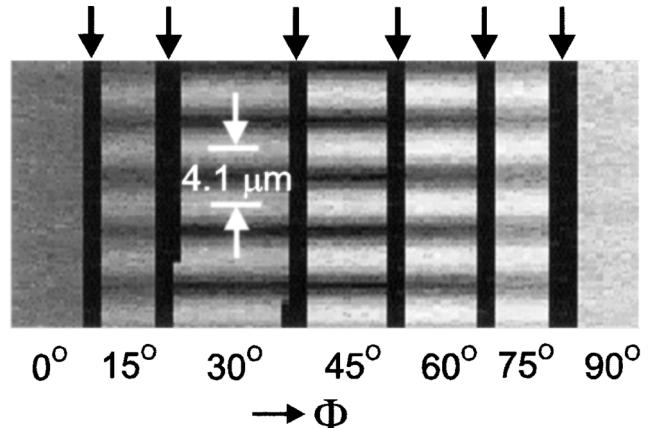


Fig. 2. Dependence of the detected optical intensity on Φ . The fiber probe is scanned in the center of the channel waveguide along the propagation direction. Φ has been changed in discrete steps of 15° from 0° and 90° . Between consecutive changes of Φ the laser beam has been blocked (arrows).

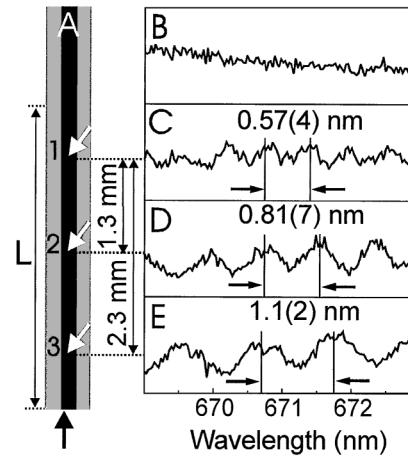


Fig. 3. A, Schematic of the wavelength-dependent measurement of a channel waveguide. The fiber probe is positioned in the middle of the waveguide at a distance L from the incoupling facet of the waveguide. The fiber is not scanned. The wavelength of the incident light is scanned from 669 to 673 nm. The distance between measuring positions 1 and 2 is $1.3(3)$ mm; between measuring positions 1 and 3, $2.3(3)$. The Si_3N_4 channel waveguide on a SiO_2 substrate has a width of $2.5\mu\text{m}$, a height of 9 nm, and a thickness of the guiding layer of 175 nm. B, position 1 for $\Phi = 0^\circ$ (TE_{00} mode only). No interference is observed. C, position 1 for $\Phi = 10^\circ$ (TE_{00} and TM_{00} modes). Spectral interference with a period of $0.57(4)$ nm is observed. D, position 2 for $\Phi = 10^\circ$ (TE_{00} and TM_{00} modes). Spectral interference with a period of $0.81(7)$ nm is observed. E, position 3 for $\Phi = 10^\circ$ (TE_{00} and TM_{00} modes). Spectral interference with a period of $1.1(2)$ nm, is observed.

Table 1. Comparison of the Measured (Exp.) Spatial Interference [Mode Beat Length (μm)] and the Spectral Interference [Distance $L_1 - L_2$ (mm)] with the Calculated (Theory) Spatial and Spectral Interference

Interference	Exp.	Theory	
		$\text{TE}_{00} - \text{TM}_{00}$	$\text{TE}_{00} - \text{TE}_{01}$
Spatial	4.1(1)	4.2(2)	193(8)
Spectral	2.3(3)	2.4(6)	51(2)

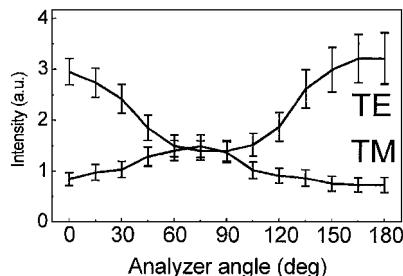


Fig. 4. Polarization of the detected light on the analyzer. The detected light of the fiber probe is analyzed with an analyzer from 0° to 180° in discrete steps of 15° for $\Phi = 0^\circ$ (TE_{00} mode only) and 90° (TM_{00} mode only).

Again, only good agreement is achieved between the measured distance $2.30(3)$ mm and the calculated distance for interference between TE_{00} and TM_{00} .

The question now arises as to how two perpendicularly polarized modes can interfere. We have therefore measured the polarization characteristics of the light emerging from the fiber probe. The polarization of the detected light has been analyzed with an analyzer for an angle Φ of 0° (TE_{00} mode in the waveguide only) and 90° (TM_{00} mode only) (Fig. 4). We observe elliptically polarized light coming out of the fiber probe, when the light in the waveguide is either TE or TM polarized. How the linearly polarized evanescent wave is converted into an elliptically polarized wave is not completely clear. In all probability the polarization conversion occurs both when the light is coupled into the fiber and when the light propagates through the fiber, the curvature of which is known to induce an effective birefringence. As a result, two mutually linearly polarized orthogonal modes in the waveguide, which are not allowed to interfere, yield polarizations with an effective overlap. This overlap results in the detected quasi-interference pattern. It turns out that the shape and the orientation of the

ellipse depend on the length, the tilt, and the bending of the fiber probe. Thus the modulation depth of the quasi interference can be influenced by these parameters.

In conclusion, we have shown that, contrary to intuition, simultaneous detection of mutually perpendicularly polarized fields with a PSTM leads to a quasi-interference pattern. This interference behavior has been observed both in the spatial optical distribution and in wavelength-dependent measurements. A quantitative comparison of the experimental data with theory confirms that the detected interference is caused by quasi interference of mutually perpendicular fields. Conversion of linearly polarized light into elliptically polarized light by the fiber probe causes this quasi interference. The new attribute of the PSTM, measurement of an interference pattern that is due to the presence of TE- as well as TM-polarized light, opens new possibilities for investigating integrated optical waveguide structures, the operation of which depends critically on the polarization of the light.

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