Local Observations of Phase Singularities in Optical Fields in Waveguide Structures

M. L. M. Balistreri, J. P. Korterik, L. Kuipers, and N. F. van Hulst
Applied Optics Group, MESA$^+$ Research Institute and Department of Applied Physics, University of Twente,
P.O. Box 217, 7500 AE Enschede, The Netherlands

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The phase evolution of light in an optical waveguide structure has for the first time been visualized with subwavelength resolution using a novel heterodyne interferometric photon scanning tunneling microscope. Phase singularities in the optical field of the waveguide have been observed. The phase singularities of charge one appear at locations where the modal field amplitude vanishes, due to the interference of various modes in the waveguide. Excellent agreement of the data with calculations has been obtained.

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Many optical wave fields in modern optics display interesting phase discontinuities and anomalies. A focused electromagnetic beam will acquire an additional axial 180° phase shift, the Gouy phase shift, compared to an unfocused plane wave as it envolves through its focus [1]. Furthermore, it is well known that uniform illumination of a positive lens leads to points of zero intensity on the optical axis and zero intensity Airy rings in the focal plane. These intensity minima have been recognized as phase singularities [2]. The recently observed closely packed optical vortices, being phase singularities, in the emitted beam of vertical-cavity semiconductor lasers are of fundamental interest and could have applications in a variety of areas such as optical data-storage, -distribution, and -processing, as well as laser cooling [3]. Phase singularities of an emitted beam are usually visualized by inducing interference of the beam with a plane reference beam. The interference pattern then exhibits the appearance or disappearance of a number of fringes $|m|$, dependent on the topological charge $|m|$ of the singularity [3]. The same visualization method has been used to observe optical wave front dislocations created by laser beam diffraction on computer-synthesized gratings [4].

Recently, the phase of a propagating wave field emitted by a cleaved fiber [5,6] and the phase of an evanescent wave at the base of a prism [6] have been measured with a fiber probe by use of a scanning optical interferometer. In this Letter we present, for the first time, the local observation of phase singularities in the optical field within an optical waveguide using a heterodyne interferometric photon scanning tunneling microscope (PSTM). The phase singularities are observed at fixed positions along the light path.

The working principle of the PSTM is based on the probing of the evanescent field at the waveguide-air interface by a near-field optical fiber probe [7–9]. The evanescent wave is locally converted into a propagating wave, which is coupled into the fiber, guided through the fiber, and detected. This is schematically shown in Fig. 1. With a height feedback mechanism, one can image the surface topography by raster scanning the probe while simultaneously visualizing the optical field distribution in the near field of the waveguide surface [10].

Maps of the relative phase of the optical field have been recorded by including the PSTM and waveguide sample in one branch of a Mach-Zehnder type interferometric setup (Fig. 1). The laser light is split in a part that is coupled into the waveguide and a part that forms the reference branch.

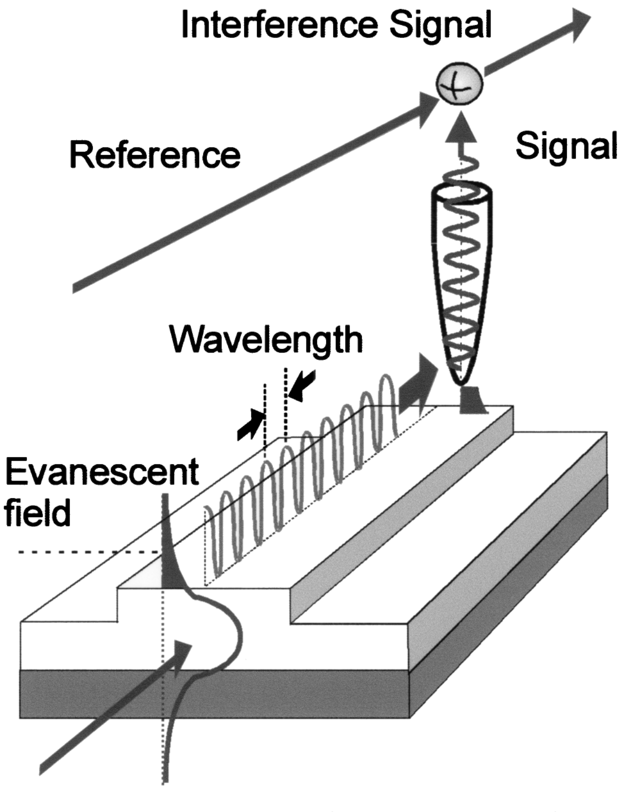

FIG. 1. Schematic illustration of the heterodyne interferometric PSTM. A part of the laser light is coupled in the waveguide and subsequently detected with the PSTM. The other part forms the reference branch. The two signals are brought together in a coupler. The resulting interference signal, which contains both phase and amplitude information, is detected. Furthermore, the principle of photon tunneling and a wave propagating through a channel waveguide is shown.

The photon-tunneling signal and the reference signal recombine in a 50/50 fiber coupler, and the interference signal is detected with a photon multiplier tube (PMT). Acousto-optic modulation of the reference beam with a frequency of 40 kHz is used to allow heterodyne interferometric detection of the photon-tunneling signal. A lock-in amplifier is used to measure the signal. The detected signal is proportional to the photon-tunneling signal, the reference signal, and the cosine of the relative phase in the waveguide. Two outputs of the lock-in amplifier, with a phase delay of 90° compared to each other, have been used to extract both phase and amplitude of the local optical field.

A phase measurement on a planar waveguide channel is presented in Fig. 2. Linearly polarized light has been coupled into the waveguide such that only the TM_{00} mode of the waveguide is excited. The topography of the 4 nm high waveguide is shown in Fig. 2(a). Figures 2(b) and 2(c) depict the measured optical amplitude and cosine of the phase in the waveguide, respectively. The amplitude image shows the Gaussian-like mode profile of the TM_{00} mode. The cosine of the phase shows parallel stripes that indicate the propagation of a plane wave with a well-defined wavelength. It is clear that the lateral resolution for the phase determination is easily subwavelength. The fact that the observed wave fronts are straight and highly parallel shows the high degree of stability of the interferometric setup. A Fourier transform of the phase image directly yields the wavelength of the light in the waveguide and thus the effective index of refraction associated with the mode. In this way, and by varying the input polarization, we obtain effective indices of 1.67 ± 0.05 and 1.52 ± 0.05 for TE_{00} and TM_{00} modes, respectively. Within the experimental accuracy these values correspond well to the calculated values of 1.61 ± 0.03 and 1.47 ± 0.03.

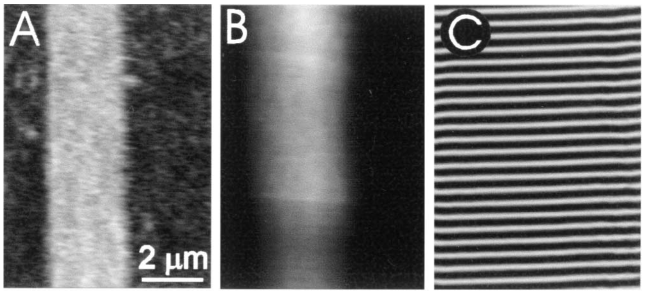

FIG. 2. Interference PSTM measurement of a Si_3N_4 channel waveguide for a scan range of $9 \times 6.7\ \mu m^2$. The width and the height step of the waveguide are 2.86 ± 0.09 μm and 4.2 ± 0.3 nm, respectively. The waveguide is monomodal for TM-polarized light (TM_{00} mode) and bimodal for TE-polarized light (TE_{00} and TE_{01} mode). Linearly polarized light has been coupled in a controlled way in the channel waveguide to excite only the TM_{00} mode. (A) The measured topography. (B) The measured amplitude of the optical field of the excited TM_{00} mode inside the waveguide. (C) The measured phase evolution of the optical field. The cosine of the phase is shown.

When two polarizations are coupled into the waveguide simultaneously, the measured optical images change drastically. Figure 3 depicts the optical parameters as measured for copropagating modes. The amplitude image [Fig. 3(a)] shows a clear beating pattern as a function of position along the propagation direction. This beating is easily explained by the fact that the different modes have different wavelengths. It is visible that the beating pattern is not fully mirror symmetric with respect to the propagation direction. This symmetry breaking indicates that higher order modes play a role in the observed interference pattern. It turns out (see below) that the observed pattern is the result of beating between three modes: TE_{00}, TE_{01}, and TM_{00}. The main beating feature (beat length 4.3 ± 0.1 μm) is attributed to interference of TE_{00} and TM_{00} modes. Ordinarily, these modes would not be able to interfere due to their perpendicular polarization. However, the simultaneous detection of TE- and TM-polarized light with a PSTM and the subsequent coupling in the detection fiber, leads to a quasi-interference of the mutually perpendicular fields [11].

The cosine of the optical phase as a function of position is depicted in Fig. 3(b). It is clear that the optical phase on the whole corresponds to that of plane waves propagating along the waveguide. However, the pattern contains

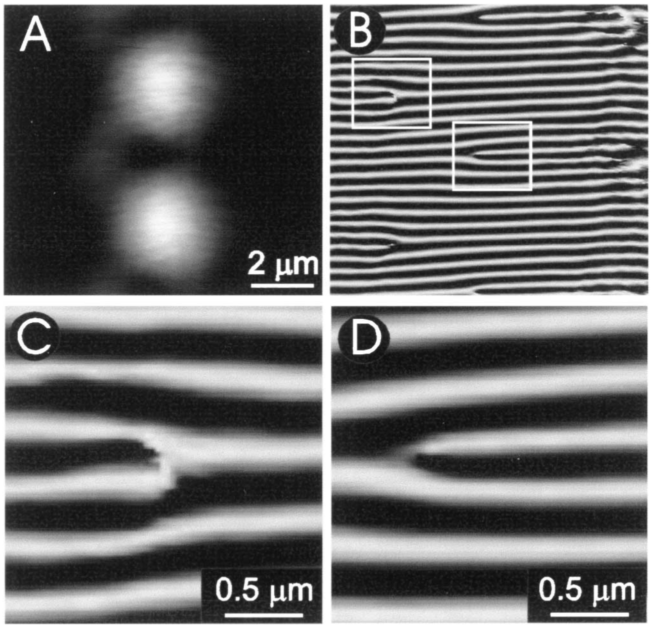

FIG. 3. Interference PSTM measurement of the Si_3N_4 channel waveguide in Fig. 2 for a scan range of $9 \times 10\ \mu m^2$. Linearly polarized light has been coupled in a controlled way in the channel waveguide to excite the TE and TM modes simultaneously. (A) The measured amplitude of the optical field inside the waveguide. A clear beating pattern is observed. (B) The measured phase evolution of the optical field. The cosine of the phase is shown. Several phase singularities are apparent. (C) Zoom in of the left square white box of the measured phase map of (b). The phase singularity has a topological charge +1. (D) Zoom in of the right square white box of the measured phase map of (b). The phase singularity has a topological charge −1.

positions at which wave fronts suddenly disappear or appear. In effect we observe phase singularities. Figures 3(c) and 3(d) depict a closeup of the boxed areas in Fig. 3(b). They clearly show singularities with an opposite topological charge of $+1$ and -1 for Figs. 3(c) and 3(d), respectively. The assignment of the sign of the topological charge for this geometry is rather arbitrary. It is important, though, to note that we observe two lines along the propagation direction containing phase singularities with opposite signs. As a result, the overall topological charge in the waveguide is zero. Furthermore, a change of the shape of the phase singularities along these two lines is observed, with a period of around 120 μm. This periodicity is due to the mode-beat between the TM_{00} mode with the 2 TE modes.

The experimental results have been compared with a calculation of the amplitude and phase of the optical field as they arise from interference of the different modes in the waveguide. In the calculation the TE_{00}, TE_{01}, and TM_{00} modes have been taken into account. Each mode is represented by a mode profile and wave vector. Experimentally determined mode profiles, which correspond well with the calculated mode profiles [12], have been used for the calculation. The wave vectors of the TM_{00} and TE_{00} modes and the relative amplitude of the modes have been determined experimentally using the Fourier transform of the measured phase map [Fig. 3(b)]. The wave vector of the TE_{01} mode is so close to that of the TE_{00} that it could not be distinguished experimentally. Calculations show that a phase measurement of over more than 120 μm would have been needed to resolve TE_{01} with the Fourier analysis. The calculated wave vectors have been used for the calculation of the amplitude and phase of the optical field. The amplitude of the TE_{01} mode has been varied relative to the other two modes. All three modes have been added together to obtain the amplitude of the measured interference pattern [Fig. 4(a)]. An asymmetric mode-beat pattern is observed in the calculated amplitude map [Fig. 4(a)], which is almost identical to the measured mode-beat pattern [Fig. 3(a)]. The relative phases of the modes have been varied in order to find a shape of the calculated phase singularities corresponding with the measured singularities. The calculated phase map of these modes is shown in Fig. 4(b). Excellent agreement of the data with the theory is obtained. The striking phase singularities in the phase map of Fig. 3(b) appear at positions where the summed amplitude of three modes vanishes due to the interference and, consequently, the summed phase is undefined. Thus, the conditions for the occurrence of a phase singularity are fulfilled [4]. The appearance or disappearance of 1 fringe indicates that the topological charge of all the phase singularities is 1 [4]. All phase singularities in Figs. 3(b) and 4(b) with a shape corresponding to the shape of the singularities shown in Figs. 3(c) and 3(d) have a topological charge of $+1$ and -1, respectively. The observed phase singularities have a strong similarity to the singularities found along the optical axis in the focal region of a positive lens [2]. For waveguide structures, the singularities in practical circumstances will never attain higher topological charges than 1 because of the limited differences in wave vector. The phase singularities along the optical axis of a focused beam have been observed experimentally by mapping the intensity of the optical field [2]. However, the phase evolution of these phase singularities has not yet been measured. We measured for the first time not only the phase evolution of the optical field in an optical waveguide, but also the phase evolution of the observed phase singularities.

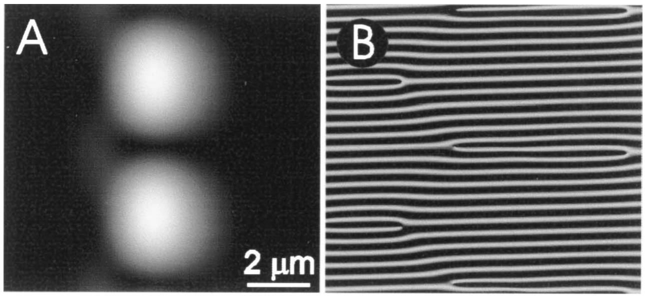

FIG. 4. Calculation of the amplitude and phase of the optical field, corresponding with the measurement of Fig. 3, that arises from interference of the TE_{00}, TE_{01}, and TM_{00} modes in the waveguide. The calculation is carried out for a scan range of $9 \times 10\ \mu\mathrm{m}^2$. (A) The simulated amplitude of the optical field of the 3 modes corresponding with the measured amplitude of the optical field of Fig. 3(a). (B) The simulated phase evolution of the optical field of the 3 modes corresponding with the measured phase evolution of the optical field of Fig. 3(b).

In conclusion, phase singularities in the optical field of an optical channel waveguide have been observed with subwavelength resolution using a heterodyne interferometric PSTM. The experimental phase maps are better understood by comparing the experimental data with calculations of the amplitude and the phase of the optical field. The phase singularities are caused by the interference of various modes and appear at positions where the summed amplitudes of the modes vanish and the phase is undefined.

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[1] A. B. Ruffin, J. V. Rudd, J. F. Whitaker, S. Feng, and H. G. Winful, Phys. Rev. Lett. **83**, 3410 (1999).

[2] G. P. Karman, M. W. Beijersbergen, A. van Duijl, D. Bouwmeester, and J. P. Woerdman, J. Opt. Soc. Am. A **15**, 884 (1998).

[3] J. Scheuer and M. Orenstein, Science **285**, 230 (1999).

[4] I. V. Basistiy, M. S. Soskin, and M. V. Vasnetsov, Opt. Commun. **119**, 604 (1995).
[5] J. N. Walford, K. A. Nugent, A. Roberts, and R. E. Scholten, Appl. Opt. **38**, 3508 (1999).
[6] P. L. Phillips, J. C. Knight, J. M. Pottage, G. Kakarantzas, and P. St. J. Russell, Appl. Phys. Lett. **76**, 541 (2000).
[7] A. G. Choo, H. E. Jackson, U. Thiel, G. N. De Brabander, and J. T. Boyd, Appl. Phys. Lett. **65**, 947 (1994).
[8] Y. Toda and M. Ohtsu, IEEE Photonics Technol. Lett. **7**, 84 (1995).
[9] M. L. M. Balistreri, D. J. W. Klunder, F. C. Blom, A. Driessen, H. W. J. M. Hoekstra, J. P. Korterik, L. Kuipers, and N. F. van Hulst, Opt. Lett. **24**, 1829 (1999).
[10] K. Karrai and R. D. Grober, Appl. Phys. Lett. **66**, 1842 (1995).
[11] M. L. M. Balistreri, J. P. Korterik, A. Driessen, L. Kuipers, and N. F. van Hulst, Opt. Lett. **25**, 637 (2000).
[12] *Integrated Optics*, edited by T. Tamir (Springer-Verlag, Berlin, 1975).