Optical waveguide focusing system with short free-working distance

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In photonics, light usually diffracts in all directions when it emerges from a planar optical waveguide. Besides this fact, in this letter we show that a waveguide with a rectangular cross section can be turned to a focusing system by using three-dimensional self-imaging technique. We obtained a configuration where the focus of the field lies outside the waveguide, in air, with a spot size of approximately the resolution limit of half a wavelength. This type of waveguide could be used as a coupling element in integrated optics or in high numerical aperture optical systems. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1631063]

Diffraction effects within submicron-sized apertures have gained considerable interest because of their importance in optics and semiconductor technology.[1,2] In this letter we present a focusing device, based on self-imaging techniques, using a multimode rectangular waveguide. Inspection of the intensity and phase distributions of the focused field outside the waveguide reveals that the quality of a diffraction-limited spot can be achieved. This compact focusing system is quite simple to be fabricated or extended to arrays, and could be used in integrated optical waveguide systems.

Self-imaging in a homogeneous planar optical waveguide was first suggested by Bryngdahl[3] and extended to strip waveguides by Ulrich.[4,5] Self-imaging within a rectangular waveguide was first studied by Voges, Ulrich, and Simon.[6,7] The structure of our focusing system is a single-mode rectangular waveguide connected with a multimode rectangular waveguide as is shown in Fig. 1. The material of the guide and cladding layers and their refractive indices n_1 and n_2 are SiN ($n_1 = 2.05$) and SiO$_2$ ($n_2 = 1.47$), respectively. The thickness of the cladding (guide) layers are 1100(800) nm for the multimode waveguide and 1120(160) nm for the single-mode guide. The length of the multimode waveguide is 3.4 μm (0.6 μm shorter than the self-imaging length). We modeled it with a particular application in mind, i.e., optical data storage at the wavelength of 400 nm. However, for other applications such as interconnection devices or general focusing systems, similar results can be obtained by just adapting the parameters.

In the design shown here, the width and thickness of the rectangular waveguide are equal. The width corresponds to the effective width, including the penetration depth. We excite the structure with the TE mode (electric field vector parallel to the interface of guide layer and cladding layer) of the single-mode waveguide. The self-imaging effect of the field in the rectangular waveguide can be analyzed in the x and y directions separately. For a step-index multimode waveguide with widths W_x and W_y in the x and y directions, the effective widths W_{xe} and W_{ye} are given by[6]

$$W_{xe} = W_x + \left(\frac{\lambda}{\pi}\right)\left(\frac{n_0}{n_r}\right)^2 * \frac{1}{NA_x}$$

and

$$W_{ye} = W_y + \left(\frac{\lambda}{\pi}\right) * \frac{1}{NA_y}, \tag{1}$$

where n_0 and n_r are the refractive indices of air and guide layer, respectively, and λ is the free-space wavelength. The quantities NA_x and NA_y are defined as

$$NA_x = \sqrt{n_r^2 - n_0^2} \text{ and } NA_y = \sqrt{n_r^2 - n_c^2}, \tag{2}$$

where n_c is the refractive index of the cladding layer. If we require that $W_{xe} = W_{ye} = W_e$, we obtain

$$W_x = W_y + \left(\frac{\lambda}{\pi}\right) * \frac{1}{NA_y} - \left(\frac{\lambda}{\pi}\right)\left(\frac{n_0}{n_r}\right)^2 * \frac{1}{NA_x}. \tag{3}$$

For the specific example shown in this letter, the input field is the zeroth order TE mode field of a single-mode waveguide which excites only the even symmetric modes of the multimode waveguide since the input field is centered on the symmetry axis. The first self-image of the input field is obtained at a length $L_1' = n_r W_e^2 / \lambda$ of the multimode waveguide.[8]

In order to calculate the field outside the waveguide, we first analyze the aberration caused by the coating layer. Since the self-imaging lengths in the x and y directions are equal,
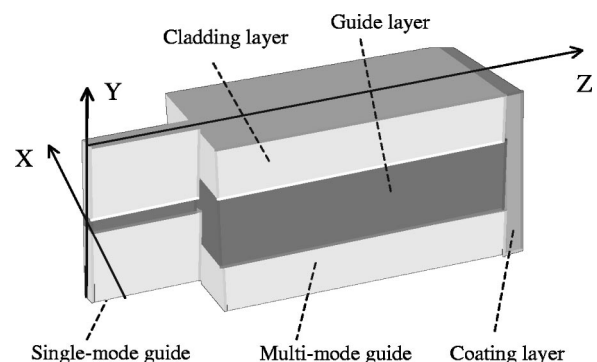

FIG. 1. Structure of the waveguide system used to model the focusing system.
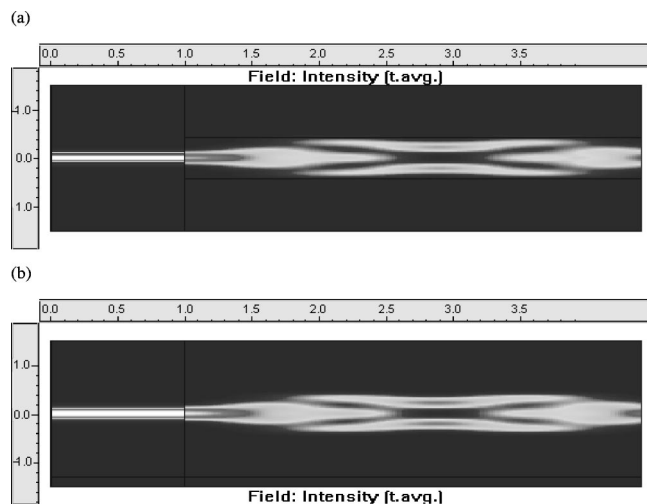
(a)

(b)

FIG. 2. Intensity distributions of the field within the multimode waveguide in the (a) *x*- and (b) *y*-directions. Units are in microns.

the image in both directions coincides, i.e., there is no astigmatic aberration. The spherical aberration is calculated according to Ref. 9. We use SiON with refractive index 1.43 and thickness 64.34 nm as the coating layer. To calculate the maximum aberration, we take the convergence angle to be 90°, resulting in an aberration factor of $0.026\lambda = 10.4$ nm, which is negligible. The field inside the waveguide and at the guide–air interface is calculated using the computer program FIMMWAVE[10] and the field at a distance *d* from the waveguide in air is calculated with the spectrum propagation method.[11] The intensity distributions inside and outside the rectangular waveguide for both *x* and *y* directions are shown in Figs. 2(a), 2(b), and 3(a), 3(b), respectively. From Figs. 3(a) and 3(b) one sees that the position of the maximum intensity (intensity focal plane) lies outside the waveguide at a distance of 0.25λ from the guide–air interface. By analyzing the phase of the external field we obtain that the phase focal plane (i.e., where the phase front is a plane) is at 0.4λ distance away from the guide–air interface. The full width at half maximum of the intensity spot in the *x* and *y* directions are 0.77 and 0.5λ, respectively.

In conclusion, we modeled a relay focusing system with an appreciable free-working distance based on a rectangular waveguide. The results shown here can be extended to waveguides with wider dimensions, and the position and width of the focus spot can be adjusted by varying the length of the multimode waveguide. The resolution of the system can be made close to the resolution limit of half a wavelength. Besides its potential use in microscopy and integrated optics, this system can also be beneficial if combined with ideas related to the use of a waveguide as a reading head in optical recording.[12]
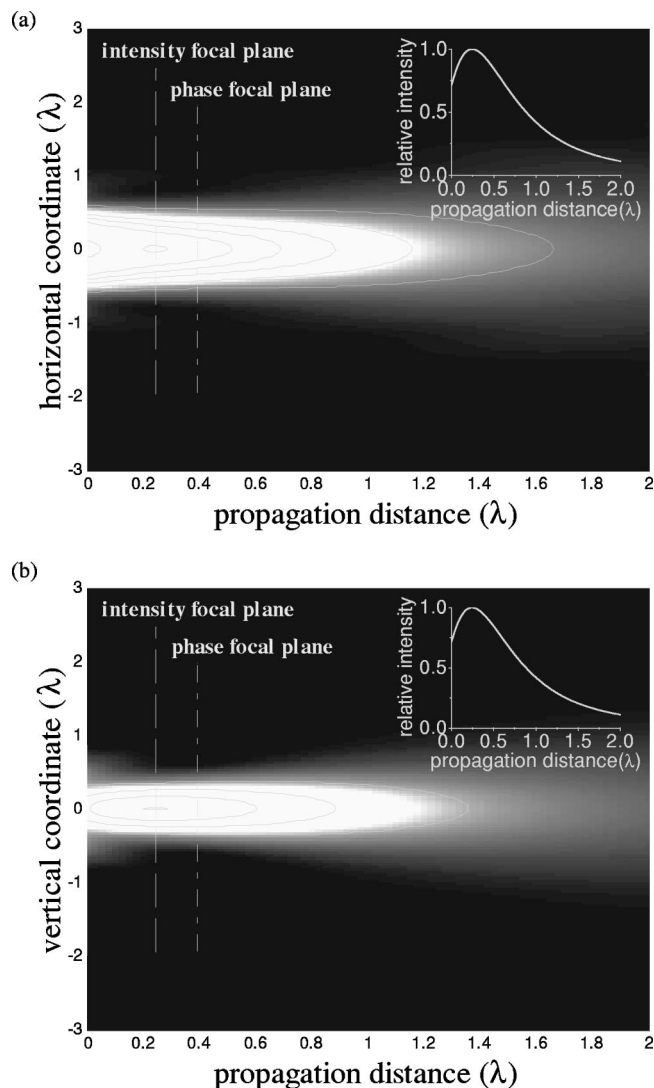
(a)

(b)

FIG. 3. Intensity distribution outside the multimode waveguide in the (a) *x*- and (b) *y*-directions. Top right: the profile of the intensity at the center. Units are in wavelengths.

[1] H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martin-Moreno, F. J. Garcia-Vidal, and T. W. Ebbesen, Science **297**, 820 (2002).

[2] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).

[3] O. Bryngdahl, J. Opt. Soc. Am. A **63**, 416 (1973).

[4] R. Ulrich, Opt. Commun. **13**, 259 (1975).

[5] R. Ulrich, Appl. Phys. Lett. **27**, 337 (1975).

[6] E. Voges and R. Ulrich, *Proceedings of the VIth European Microwave Conference* (Microwave Exhibition, Sevenoaks, 1976), p. 447.

[7] A. Simon and R. Ulrich, Appl. Phys. Lett. **31**, 77 (1977).

[8] J. M. Heaton, R. M. Jenkins, D. R. Wight, J. T. Parker, J. C. H. Birbeck, and K. P. Hilton, Appl. Phys. Lett. **61**, 1754 (1992).

[9] J. J. M. Braat, Appl. Opt. **36**, 8459 (1997).

[10] FIMMWAVE version 4.06, a vectorial waveguide solver, Photon Design, December 2002.

[11] M. Born and E. Wolf, *Principles of Optics*, 4th ed. (Pergamon, Oxford, 1980).

[12] F. Fransoo, D. Van Thourhout, L. Van Landschoot, A. Verbiest, W. Van Parys, P. Vandaele, R. Baets, Proceedings of the 15th Annual Meeting of the IEEE-LEOS (Cat. No. 02CH37369), **2**, 750 (2002).