

Integrated optical waveguide as a focussing system

Haifeng Wang

Department of Physics and Astronomy, Free University Amsterdam,
The Netherlands

F.H. Groen, S.F. Pereira, J.J.M. Braat

Optics Research Group, Faculty of Applied Sciences, Delft University of Technology
Lorentzweg 1, 2628 CJ Delft, The Netherlands

We present a study of the focussing and general imaging capabilities of a combined multi- and single-mode waveguide system. Some of the imaging characteristics of this system can be compared to with those of a conventional lens system with the advantage that it can be made very small and that its fabrication is relatively simple.

Introduction

The problem of realizing extremely compact focussing or imaging systems has attracted much interest regarding their use in photonics, optical data storage and optical computing. Some approaches to treat this problem are based on surface plasmons effects^[1-3], but the fabrication of the required subwavelength structures is rather difficult.

The system that we present here, namely a specially designed dual waveguide, could be seen as a possible solution to the compact imaging problem. The design of the system is based upon the self-imaging properties of multi-mode waveguides.^[4-6] It is well known that, given a certain input field at the entrance of a multi-mode waveguide (defined here as the field from a single mode waveguide), self-imaging of the input field is obtained after a certain propagation distance L . In our system, we make the length of the multi-mode waveguide slightly shorter than L and calculate the field that freely propagates in air at distances of the order of a few wavelengths. We show that the field outside the multi-mode waveguide first is focussed before it spreads out at large angles towards the far field. Analysis of the on-axis and off-axis imaging characteristics of this micron-sized optical waveguide lens shows that the behavior of our proposed system resembles that of a conventional lens system. This kind of imaging system is simple to be fabricated and can be easily extended to an array geometry.

Simulations

The structure of our imaging system is a multi-mode rectangular waveguide. We modeled it based on 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 imaging 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^[7-8]. The width corresponds to the effective width, including the penetration depth. We excite the multi-mode waveguide with the TE mode (electric field vector parallel to the interface of guide layer and cladding layer) of a single-mode waveguide and the distance between the two waveguides can be varied. The propagation of the field in the single mode waveguide to free space, from free space into the multi-mode

waveguide, and the propagation within the multi-mode waveguide are calculated using the software FIMMWAVE^[9]; the field outside the multi-mode waveguide is calculated with the spectrum propagation method^[10].

The structure we modeled is shown in Fig.1. The material of the guiding layer is SiN and that of the cladding layer is SiO₂. The thickness of the cladding (guiding) layers are 1100(800) nm for the multi-mode waveguide and 1120(160) nm for the single-mode guide. The length of the multi-mode waveguide is 13.6 μm . Given that the size of the guide layer of the single-mode waveguide is much smaller than one wavelength, the field exiting from the single-mode waveguide can be taken as that of a point source. The X-Y-Z positions of the single-mode waveguide with respect to the multi-mode waveguide can be changed in order to make an analysis of the imaging system.

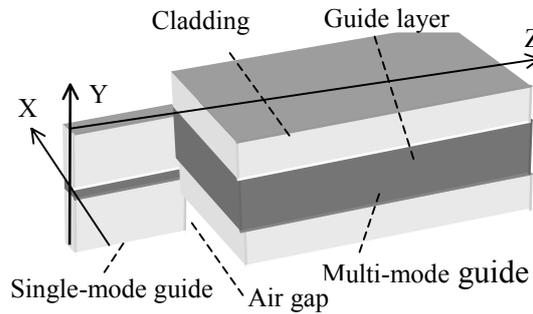


Figure 1: Structure of the imaging system.

The on-axis imaging characteristics are tested by setting the single-mode waveguide at the center of the multi-mode waveguide in the X-Y plane and by changing the distance between them in the X-Z plane. This simulates the change of the object distance in a lens system. In Fig.2a, we show the intensity distribution on propagation from the single-mode waveguide towards the multi-mode waveguide and inside the multimode waveguide in the X-Z plane. The distance between the single-mode and multi-mode waveguides is 0.6 μm . The field outside the multi-mode waveguide for this distance is shown in Fig.2b. Note that in this case the maximum intensity position, i.e., the intensity focal plane is located at a distance of 0.65λ in air, measured from the exit surface of the multi-mode waveguide. The phase focal plane, i.e., the position where the phase front is plane, can also be calculated and it is not coincident with the intensity focal plane but slightly further away at a distance of 0.85λ . The axial intensity profile as a function of the propagation distance is shown in Fig.2c for other object distances. From this figure one sees that the closer the object is to the multi-mode waveguide the farther away is the image; this the same behavior as for a conventional imaging lens.

The paraxial behavior is studied by shifting the object off-axis, i.e., by keeping the distance between the two waveguides constant and shifting their relative position in the X-Y plane. Fig.3a shows the intensity distribution in the X-Z plane from a single-mode to a multi-mode waveguide for the shifted case, where the distance between the waveguides is equal to 0.6 μm and the shift in the X-Y plane is equal to 0.05 μm ($1/8 \lambda$) in the X-direction. The intensity distribution in the X-Z plane outside the multi-mode waveguide is shown in Fig.3b. The intensity profile in the intensity focal plane for other shifts in the X-direction is shown in Fig.3c. From this figure one sees that as the lateral object shift increases, the maximum in the intensity also shifts off-axis but in the opposite direction.

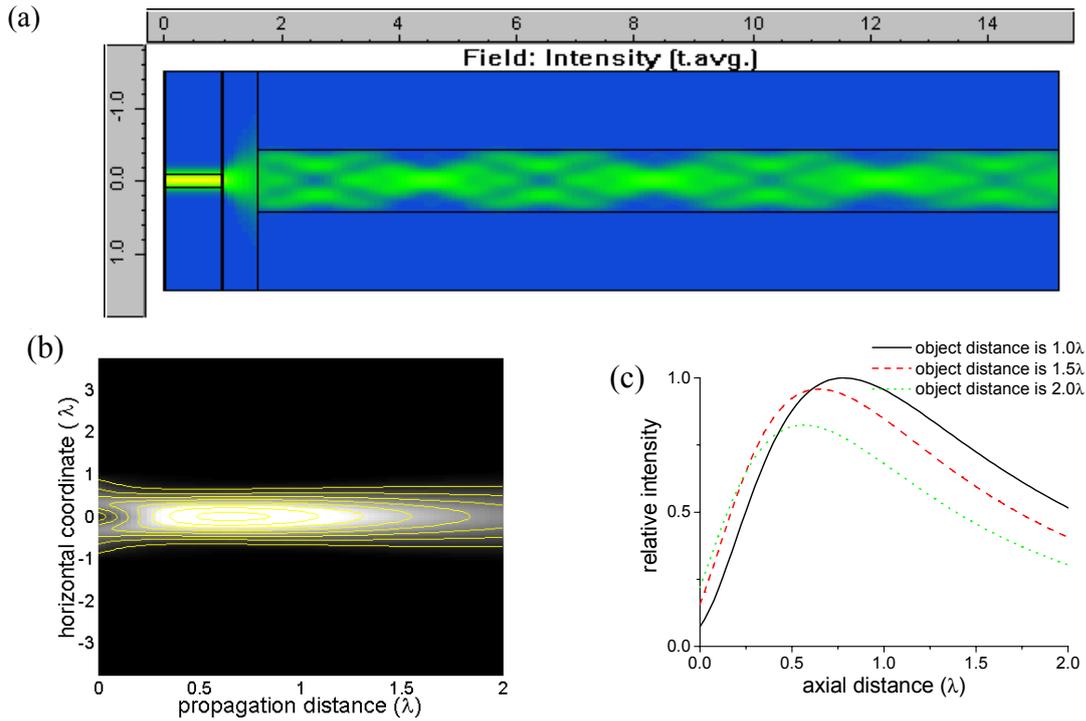


Figure 2:(a) Intensity distribution on propagating from the single to the multi-mode waveguide and inside the multi-mode guide (b) Intensity distribution outside the multi-mode waveguide when the distance between the waveguides is 1.5λ . (c) Axial intensity distribution after the waveguide exit face for various object distances.

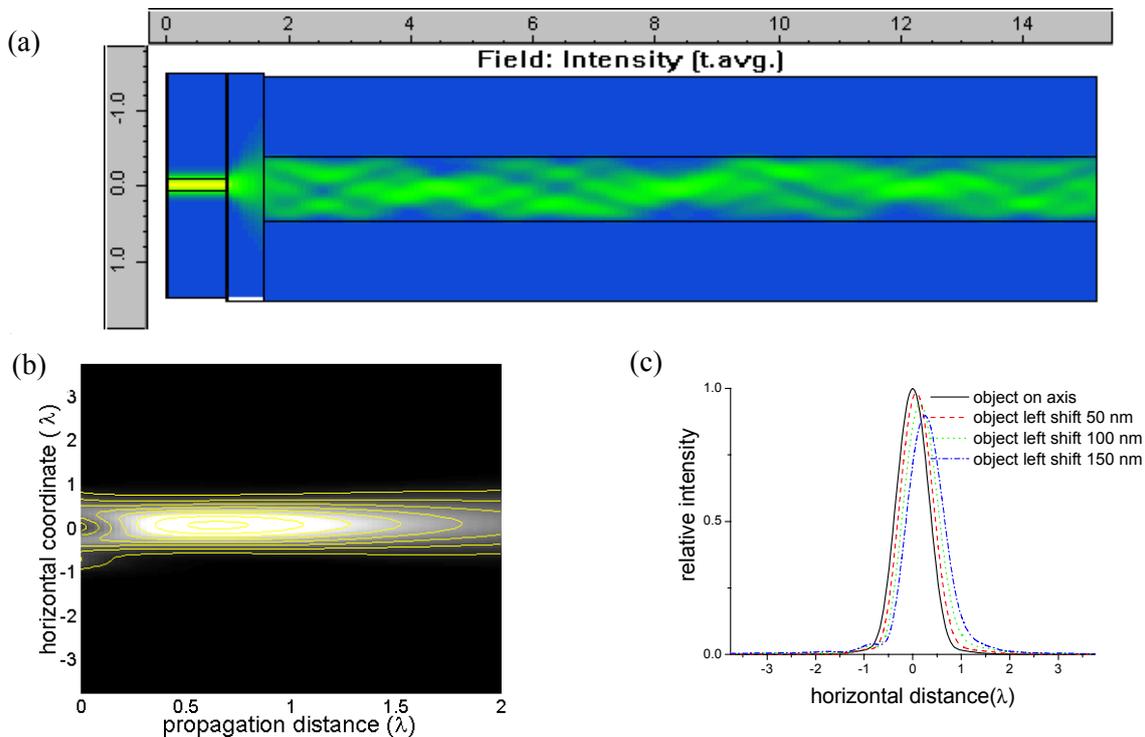


Figure 3: Intensity distributions (a) within and (b) outside the multimode waveguide when the air gap between the single- and multi-mode waveguides is 1.5λ and the single-mode waveguide is shifted in the +Y-direction over a distance of $1/8 \lambda$. (c) Horizontal profile outside the multi-mode waveguide for different off-axis shifts of the single-mode waveguide.

In conclusion, we have analyzed a combined single- and multi-mode rectangular waveguide system that can be used as an focussing device. Both the paraxial and axial behavior of this system resembles that of a conventional lens system. It is also found that the field outside the waveguide in air is focused at a distance that is well beyond the near field. We believe that this result can set a bridge between many optics-related fields and semiconductor technology. The size of this imaging system can be made at micron-scale, becoming a promising candidate for interconnection devices, high-capacity free-space switching systems by MEMS or liquid crystals, for optical tomography, optical computing and parallel optical data storage. This system can be fabricated in relatively simple ways and extended to array structures on a photonic integrated circuit (PIC).

Acknowledgements

The authors would like to thank Prof. Taco D. Visser for helpful discussions. This work is supported by the European project IST-2000-26479 (“Super Laser Array Memory”).

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