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Radiation-field guiding in integrated-optic waveguides

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Because of short distances of propagation in integrated-optic waveguide circuits not only the guided-mode field, but also the radiation field is confined in the waveguide guiding region. This may influence the performance of nonlinear guides in comparison with usual guided-mode analysis results. In this paper, for the first time the radiation field guiding in optical waveguides is proved and studied by means of Beam-Propagation Method (BPM) simulation.

1. Theory and notation

The optical field propagating in a waveguide may differ from waveguide guided modes, what means that only a part of the field can be expressed as a superposition of guided modes. We introduce an idea of guided field, and an idea of radiation field. Guided field denotes the part of the optical beam in the waveguide that is a superposition of guided modes, and the remainder of the beam constitutes the radiation field.

Thus, in a single-mode waveguide an optical beam with any field distribution can be expressed as

$$E_{\mathrm{total}} = E_{\mathrm{guided}} + E_{\mathrm{radiation}}. \tag{1}$$

Therefore, the radiation part of the beam is

$$E_{\mathrm{radiation}} = E_{\mathrm{total}} - E_{\mathrm{guided}}. \tag{2}$$

Guided part of the beam is a guided mode Ψ_0 with some complex amplitude α

$$E_{\mathrm{guided}} = \alpha \Psi_0 \tag{3}$$

where we assume guided mode field Ψ_0 normalized to unity power

$$\iint |\Psi_0|^2 dx dy = 1. \tag{4}$$

The above integral is taken on the waveguide cross-section and propagation along the z-axis is assumed.

It follows from (3) and (4) that guided mode power P_0 in the total field is equal to square modulus of α

$$P_0 = \iint |E_{\mathrm{guided}}|^2 dx dy = |\alpha|^2. \tag{5}$$

Since for the guided mode the phase is constant across the waveguide and of physical interest is the amplitude distribution only, it is sufficient to determine the modulus of α. This may be done by substituting (5) to the orthogonality relation [1]

$$P_0 = |\iint E_{\text{total}} \Psi_0^* dxdy|^2. \tag{6}$$

The guided part of the field propagates down the waveguide without any distortion. On the contrary, the radiation field behaviour is not so obvious. The guiding region of the waveguide, with higher index of refraction, produces focusing effects on this field. Moreover, the radiation field can be converted back to the guided field at points of waveguide imperfections such as junctions, corner bends, *etc.* [2].

Obviously, the radiation field when excited at the input of an ideal guide may be radiated far from the guiding region and eventually disappear at the infinity, but not immediately, of course. The question is: at what distance of propagation?

The aim of this paper is to answer to this question.

2. Numerical results

To prove the radiation field guiding, we have used the simplest planar waveguide case and a Gaussian initial beam. The idea is as follows:

a) the Gaussian beam is decomposed into guided and radiation parts,

b) the radiation part is propagated down the waveguide with the BPM.

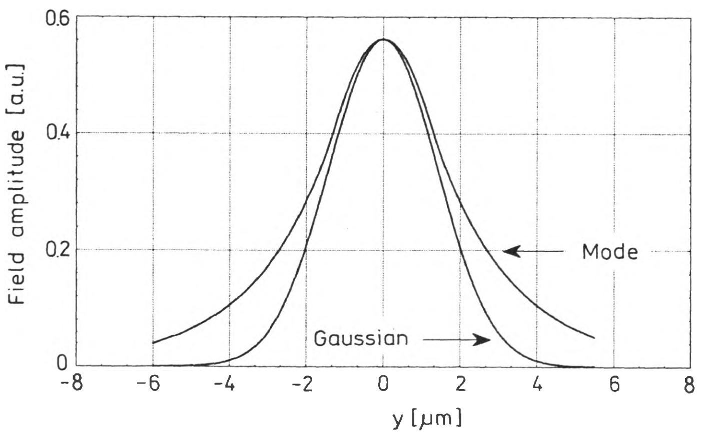

Fig. 1. Symmetric Gaussian input beam and normalized modal field

The chosen example is a single-mode planar guide with index values $n = 1.491$ in the inner (guiding) layer, and $n = 1.479$ in the outer layers. The guiding layer has a width of 4.6 μm. An excitation with symmetrically (Figs. 1–4) or asymmetrically (Figs. 5–8) launched Gaussian beam of TE polarized light at 1.53 μm wavelength is assumed. The Gaussian beam has a peak value equal to peak value of a normalized to unity power guided mode (about 0.56 $\mu m^{-1/2}$), and $1/e$ peak amplitude width of

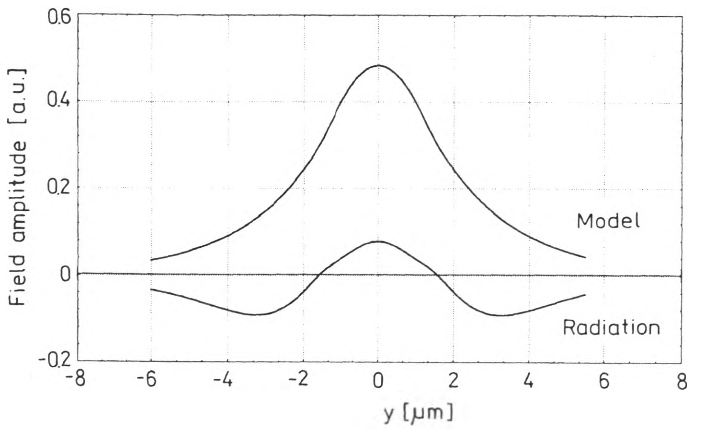

Fig. 2. Modal and radiation parts of Gaussian beam from Fig. 1

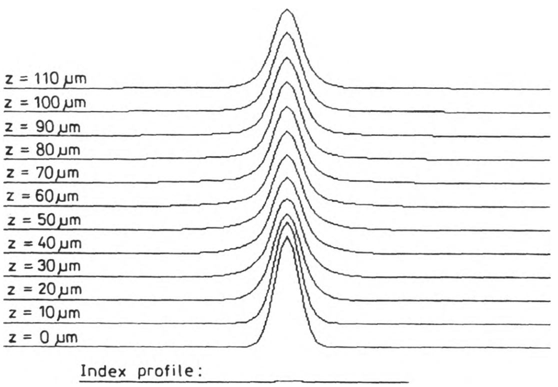

Fig. 3. Propagation of symmetric Gaussian input beam from Fig. 1 — intensity plot

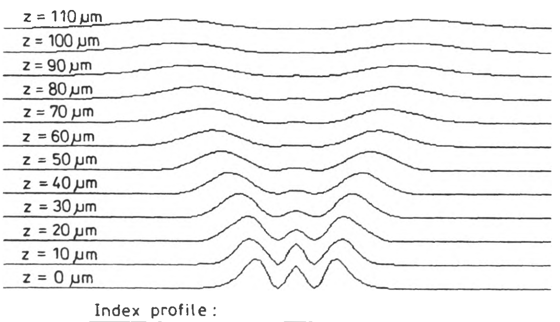

Fig. 4. Propagation of radiation part from Fig. 2 — intensity plot

2 μm. It is centred in the guiding layer when excitation is symmetric, or left-shifted by 1 μm when excitation is asymmetric.

The figures show the plots in arbitrary units (a.u.) of:

a) field amplitudes of the input Gaussian and normalized modal beams,

b) field amplitudes of the modal and radiation parts of the Gaussian input,

c) field intensity (square modulus of amplitude) of the total field propagating in the guide,

d) field intensity of the radiation part of the field.

The values of the radiation part intensity (d) have been magnified by a factor of 10 in comparison with the plots of the total field (c).

Figure 1 shows plots of normalized modal field and symmetric Gaussian excitation. This Gaussian input is decomposed into guided and radiation parts in Fig. 2 with modal field peak value of about 0.48 $\mu m^{-1/2}$. Figure 3 shows the plots of the total Gaussian input propagating in the guide (in terms of intensity) versus propagation distance z, with some radiation beams outgoing from the guiding region. In Figure 4, only the radiation part propagation is simulated; it is obvious

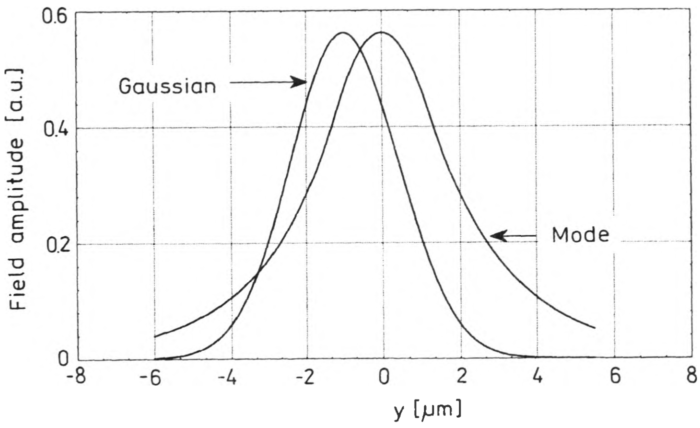

Fig. 5. Asymmetric Gaussian input beam and normalized modal field

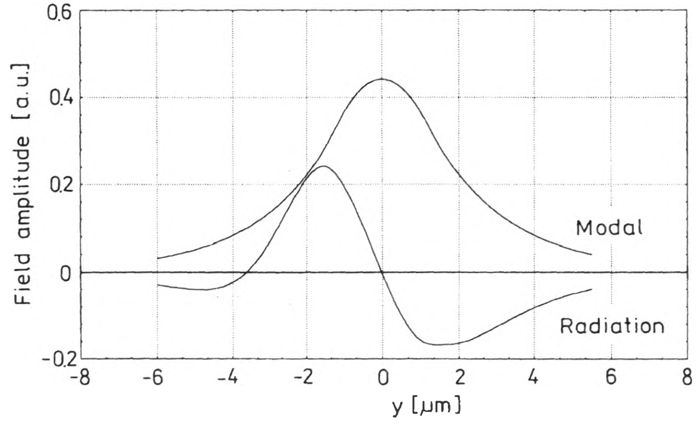

Fig. 6. Modal and radiation parts of Gaussian beam from Fig. 5

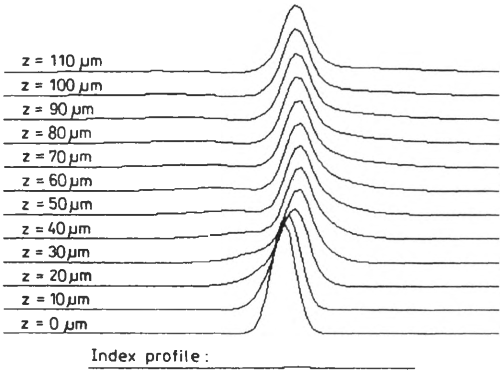

Fig. 7. Propagation of asymmetric Gaussian input beam from Fig. 5 – intensity plot

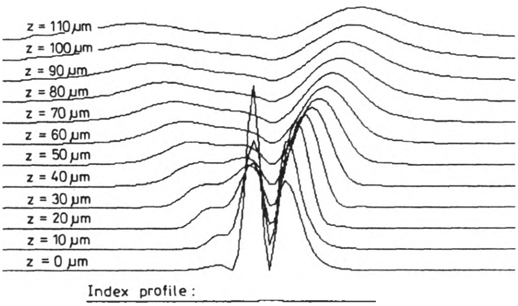

Fig. 8. Propagation of radiation part from Fig. 6 – intensity plot

that the radiation field remains in the guiding region up to a hundred of micrometers of propagation.

Figure 5 shows the plots of normalized modal field and asymmetric Gaussian excitation. This Gaussian input is decomposed into guided and radiation parts in Fig. 6, where the modal field peak value is less – about 0.44 $\mu m^{-1/2}$. Radiation part of the field is asymmetric and larger in this case. Figure 7 shows the plot of the total asymmetric Gaussian input intensity propagating in the guide. A greater part of the field is radiated in this case, and the field exhibits some oscillations transverse to the direction of propagation. In Figure 8, the propagation of the radiation part is simulated. The radiation occurs to the right-side rather, and greater part of the field is in the proximity of the guiding region.

These results show that a non-negligible part of the radiation field is guided in the waveguide at tens of micrometers from the point of excitation. This may be very important in nonlinear waveguides with intensity-dependent index of refraction, where the radiation part does not necessarily tend to radiate at long distances of propagation. As it modifies the index distribution, it also modifies the modal fields and part of it may constitute the guided field of a modified waveguide.

3. Conclusions

We have proved the occurrence of the radiation field guiding in optical waveguides for propagation distances of tens of micrometers.

The influence of the radiation field guiding on the performance of nonlinear guides is currently under study. Nevertheless, in view of the presented results it is obvious that finding an intensity-dependent guided mode in a nonlinear waveguide is sufficient for determining the devices performance only if it is excited with this mode. If not, the radiation part of the field has to be taken into account.

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