ANALYSIS OF A NONLINEAR 2X3 INTERSECTING WAVEGUIDE BY A FINITE DIFFERENCE METHOD

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Summary A novel 2x3 intersecting waveguide which consists of a nonlinear two-waveguide asymmetric confluence in the input section and a nonlinear symmetric trifurcation in the output section, both being embedded in homogeneous linear medium, is proposed and analyzed by means of FD-BPM(Finite Different Beam Propagation Method). The characteristics of the output power are calculated as a function of input power. It is shown that the proposed waveguide has the advantage of potential applications in a wide variety of all-optical devices for integrated optics such as intensity-dependent optical switches, optical power distributors, etc.

1.Introduction

Nonlinear waveguides have recently received considerable attention owing to their potential applications to ultrafast all-optical signal processing. The intensity-dependent change in refractive index presents interesting phenomena such as self-focusing and bistability, bringing about unusual waveguiding behaviour which can never be observed in linear waveguides. More recently, directional couplers composed of two waveguides as well as three, Y-branching waveguides and X-crossing waveguides have been investigated extensively and a lot of theoretical and experimental proposals for novel optical devices have been reported. Some of schemes for all-optical switching devices utilizing intersecting waveguides are particularly interesting[1]-[6].

In the present paper, we propose a new 2x3(two-input-port and three-output-port) intersecting structure, partly consisting of nonlinear material, for optical wave guidance. Numerical results of output power obtained as a function of input power reveal that the present waveguiding structure will be unquestionably applicable to three-channel switches or distributors of optical waves. Accurate analysis of waveguiding structures such as intersecting, branching or coupling waveguides is essential for the effective designing of photonic integrated circuits. We here employ FD-BPM which has been successfully applied to the analysis of wave propagation in many practical waveguiding structures containing nonlinear material. Calculations in radiation losses also indicate that FD-BPM is more efficient and stable compared to FFT-BPM(Fast Fourie Transformation BPM)[7],[8].

2.Waveguide structure and basic principles

The schematic structure of the present 2x3 intersecting waveguide is shown in Fig.1 together with the coordinate system used in our analysis. It is composed of two single-mode waveguides differing in film thickness in the input section and three single-mode waveguides having an identical film thickness in the output section, with the both sections being connected to each other through a multi-mode waveguide having a length of l_2. The whole waveguiding structure, being assumed to be consisting of Kerr-like nonlinear material, is embedded in homogeneous linear medium. Branching angles between the waveguides are θ_{in} in the input section and θ_{out} in the output section. To be sure that the input and output ports are sufficiently isolated, both sections should have some appropriate lengths, which are designated by l_1 and l_3, respectively. The relative permittivities of composing materials are assumed to be ϵ_c in the surrounding region and $\epsilon_f + \alpha\,|E|^2$ in the film, where α is the nonlinear coefficient and $|E|^2$ the intensity of electric fields. It is also assumed that the geometry is uniform in the y direction, hence $\partial/\partial y = 0$.

We intend to examine the propagation properties of TE waves, thus exciting the TE_0 mode in the thinner waveguide of the input section. In waveguides partly containing nonlinear material, the refractive index changes depending upon light intensity of propagating waves. The more intensive, the higher refractive index when α is positive. The input section of our structure has the exciting port slightly thinner than the other. Hence its effective refractive index is lower when input power is small. As it increases, differences in the effective refractive index between two branches decrease and eventually the reverse situation arises. Accordingly, the field distribution at $z = l_1$, which is mainly composed of superposition in terms of possible guided modes of the multi-mode waveguide in some appropriate mixing ratio, varies depending upon input power. After the propagation of finite distance through the multi-mode waveguide following the input section, also varies the field distribution just at the entrance of the output section. Consequently, the ratio of output power from the three output ports changes depending upon input power. The quantitative characteristics will be discussed in detail in the following.

3.Numerical Results

The fixed parameters used are the wavelength $\lambda = 1.064\mu\text{m}$, refractive indices $\sqrt{\epsilon_f} = 1.54$ and $\sqrt{\epsilon_c} = 1.53$, nonlinear coefficient α=6.377 x 10^{-12} m^2/V^2, film thicknesses $w_a + w_b = 6.0$ μm and $w_1 = w_2 = w_3 = 2.0$ μm, waveguide lengths $l_1 = l_3 = 1000$ μm, and branching angles in the input and output sections $\theta_{in} = 0.435^o$ and $\theta_{out} = 0.229^o$, respectively. The propagation constant of the fundamental TE_0 mode in the input port is given by $\beta/k_0 = 1.5361$(k_0 : free space wave number) when $w_a = 2.8$ μm and $\alpha = 0$. We proceed our BPM analysis in the region of $|x| < x_{max}$, where $x_{max} = 20\mu$m.

Figure 2 shows the transverse field distributions in terms of light intensity just at the confluence of the input section, that is at $z = 1000$ μm, as the input power is varied. When it is small, the field is focused mainly on the right side of the waveguide, which means that in the multi-mode waveguide the TE_1 mode dominates over the TE_0 mode. On the contrary, the TE_0 mode dominates the field profile more and more as the input power is increased. Its contribution to the field distribution seems conspicuous especially when the input power is about 10 W/m or more. The contributions from either one of two modes are not negligible for middle input powers. This suggests that the characteristics of output power would strongly depend on the intensity of light waves which propagate through the waveguiding structure.

Figure 3 shows the transverse field distributions in terms of intensity with input power as a parameter after the propagation through the multi-mode waveguide having a length of 100 μm for (a) and 230 μm for (b). It is worth noting that two profiles (a) and (b) of the field distributions in Fig.3 appear almost reflectively symmetric to each other. Hence we can easily guess that the output characteristics to be obtained for both cases should be of reflective symmetry as well.

Figure 4 shows output powers from the output ports 1, 2, and 3 as a function of input power, where l_2=100μm for (a) and 230μm for (b). The output power is evaluated with the following integral:

$$P_i = (\beta/k_o)\sqrt{\epsilon_o/\mu_o}\int_{x_{i-1}}^{x_i} |E(x)|^2 dx, i = 1,2,3 \quad (1)$$

where ϵ_0 and μ_0 are the permittivity and permeability of vacuum and $E(x)$ is the field distribution obtained by FD-BPM. The integrals should be carried out over the regions which are defined by $x_0 = -x_{max}$, $x_1 = -(w_2 + w_4)/2$, $x_2 = (w_2 + w_5)/2$, and $x_3 = x_{max}$. Normalizing by the input power P_{in} gives the simple expression for radiation losses, that is $P_l = 1 - \sum_{i=1}^{3} P_i / P_{in}$. The extinction ratio is also defined by $R_{ex}^{(i)} = \max\{P_j, P_k\}/P_i$, where $(i,j,k)=(1,2,3)$. As is expected, we have obtained reflective symmetry-like results for the cases of l_2=100μm and 230μm. The maximum extinction ratios from the output ports are $R_{ex}^{(1)} = -16.6$dB at $P_{in} = 4.5$ W/m, $R_{ex}^{(2)} = -10.6$dB at 7.2 W/m, $R_{ex}^{(3)} = -16.1$dB at 8.5 W/m for $l_2 = 100\mu$m and -17.2dB at 8.0 W/m, -11.2dB at 6.9 W/m, and -17.7dB at 4.5 W/m for 230μm. Radiation losses for the corresponding cases are 0.32%, 0.51%, and 0.67% of the input power for $l_2 = 100\mu$m and 0.59%, 0.52%, and 0.30% for $l_2 = 230\mu$m.

4.Conclusions

We have proposed a new 2x3 intersecting waveguide partly composed of Kerr-like nonlinear material and analyzed the intensity-dependent characteristics of output power by means of a finite difference BPM. As a result we have found that the proposed intersecting waveguide definitely provides the function of sharp three-channel switching of optical waves. The optimization of structural parameters would make it possible to achieve further improvement in the switching characteristics.

References

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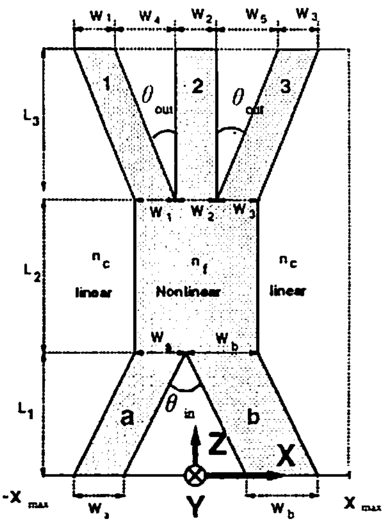


Fig.1 Waveguiding structure

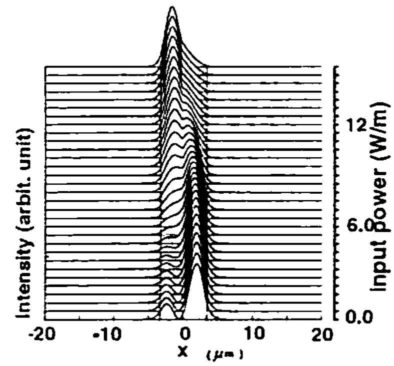
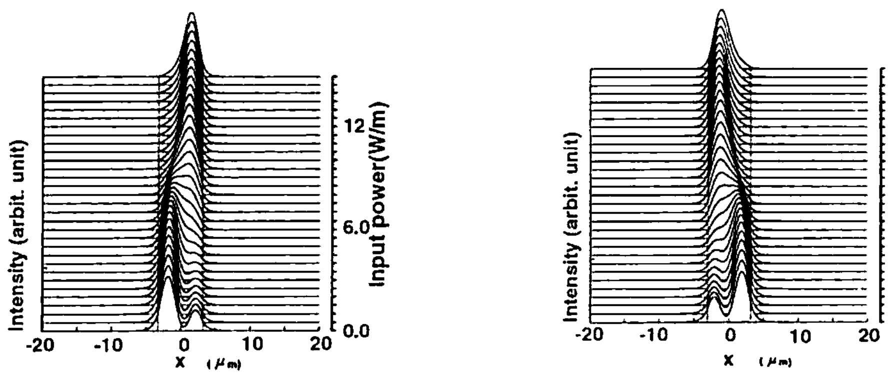
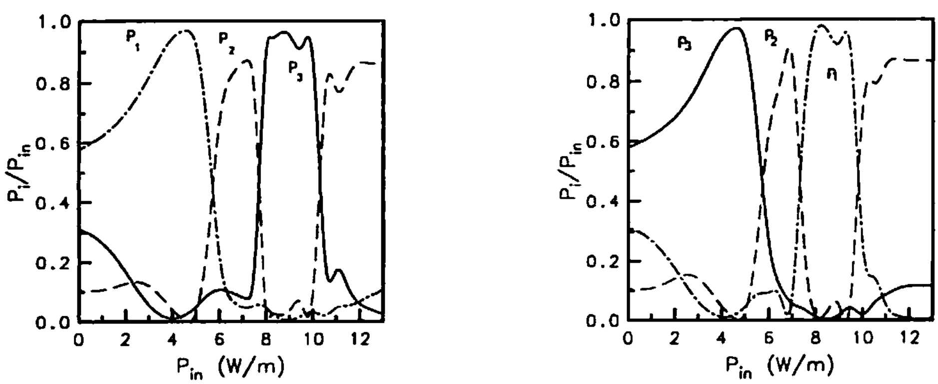


Fig.2 Transverse field distributions at z=1000μm in terms of intensity with input power as a parameter.



(a) (b)

Fig.3 Transverse field distributions in terms of intensity with input power as parameter, where l_2=100μm in (a) and 230μm in (b).



(a) (b)

Fig.4 Output power as a function of input power, where l_2=100μm in (a) and l_2=230μm in (b).