Nonlinear planar coupler waveguides system in the medium kerr optics

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Abstract

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A study of coupling characteristics between two optically nonlinear planar waveguides has been performed in terms of their individual analytical solutions. It is shown that with an appropriate choice of guide widths and proper redefinition of effective propagation constants, the commonly adopted dual waveguide coupled equations can be formally retained even when the optical nonlinearity in each guide is fully taken into account. A specific numerical illustration of the power flow pattern was given on the basis of its analytical expression derived from the coupled equations. The result describes the detailed coupling characteristics and its variation with respect to input optical power, demonstrating its viability for active optical device applications.

Key words : nonlinear optics, directional coupler, all-optical switching

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The coupling behaviors of two-nonlinear-waveguide system in planar structure have been a subject of continuing research owing to its expected novel applications for optically operated devices (Nobrega et al., 1999; Stegeman and Wright, 1990; Chi-Chong Yang and Alexander, 1992; Jensen, 1982). Most of the studies following Jensen's basic formulation were focussed on numerical treatments and their applications for device simulation. While a number of works on nonlinear waveguide have been devoted to analytic solutions for the mode fields, most of them are short of carrying the results over to the study of coupling behavior of a nonlinear coupled system. A combination of the two approaches will be desirable for better understanding of the physical mechanism underlying the coupling characteristics.

In our first study on the nonlinearly coupled planar waveguide system, the nonlinear intensity dependent refractive index (IDRI) effect was restricted to the coupling coefficients only (Harsoyono et al., 2001). In a more recent study on the coupling behavior of two identical nonlinear planar waveguide (Harsoyono et al., 1999; Harsoyono, 2000; Harsoyono et al., 2001), we have taken into account the full effect of IDRI in the individual waveguide following the method introduced by Boordman and Egan (EB) (Allan and Egan, 1985; Allan and Egan, 1986). This analytic solution of the single guide was further extended to include a 4 layer system, which allows the study of the coupling behavior for different guide separation in addition varied guide widths. In this report, the previous result of analytical study are examined numerically, and illustrated for specific models.

Summary of analytical result

We have considered in our previous works (Harsoyono et al., 1999; Harsoyono et al., 2001), a symmetric planar waveguide system described in Figure 1, where $\alpha_i$ is related to the third order susceptibility tensor $\chi^{(3)}$ of the material concerned by $\alpha_i = 3\chi^{(3)}$, $i = 2, 4$. Restricting ourselves to the fundamental mode in each guide, the wave propagation in the system is governed by the following coupled mode equations

\[
\frac{da_i(z)}{dz} = iK_i a_i(z) + i (Q_{i1} |a_i(z)|^2 + 2Q_{i2} |a_{i-1}(z)|^2)a_i(z)
\]

\[
\frac{da_i(z)}{dz} = iK_{i-1} a_i(z) + i (Q_{i1} |a_i(z)|^2 + 2Q_{i2} |a_{i+1}(z)|^2)a_i(z)
\]

Figure 1. Structure of a planar nonlinear directional coupler, with $P_i(0)$ and $P_i(z)$ denoting respectively the input and transmitted power of the $i$th waveguide. ($n_1 = n_5 = 2.56; n_2 = n_4 = 2.589; n_3 = 2.585$)
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\[ P_{\text{total}} = \Re[(N/\tilde{n}_3)(\alpha E_{\mu 2}^2/2) \int_{-\gamma, d} 1 \sinh^{-1} k_3 d(k_3 x) + (N/\tilde{n}_1)(\alpha E_{\mu 1}^2/2) + 2N(\alpha E_{\mu 2}^2/2)\tilde{q}_1^{-1} \int_0^{k_3 b} \left[ \frac{q_2 \cos(q_2 x) + \tilde{n}_3 G\sin(q_2 x) \cos(q_2 x) \sin(q_2 X)}{q_2 \cos(q_2 x) + \alpha E_{\mu 2}^2/2\tilde{q}_2^{-1} \sin(q_2 X)} \right]^2 d(x) \]  

where \( \Re = (c^2 \varepsilon_0)/(\omega \varepsilon_0) \) [W/m], \( X = k_\alpha x \) and \( \tilde{q}_1 = q_1/k_\alpha \). The first, second and third terms in Eq.(9) represent respectively the power flows in the first, third and the guiding layers while power flow in the 4th layer is not included as it is of no interest to us in this work.

Numerical solutions for \( N \) and \( E_1(x) \) for \( n_3 = 2.585, n_1 = n_2 = 2.589, \alpha_2 = 3.10^{11} \) (m/W) are depicted in Figure 1. With \( d = 3 \) \( \mu \)m there is a very good agreement which implies either a relatively large separation between the guides (d), or a non-linear coupling coefficient K's and Q's can be calculated from Eqs. (3) as function of \( N \). (Harsoyono, 2000; Harsoyono et al., 2001)

For some special case of practical applications such as optical switch and power divider, the total power \( P_{\text{total}} \) is initially launched into guide-1.
at \( z = 0 \), namely \( P_1(0) \) and \( P_2(0) = 0 \). In this case the power in guide 1 (\( i = 2 \)) at an arbitrary point \( z \) along the guide can be derived from Eqs.(1) and (2) as given in the following

\[
P_1(K_2 z) = P_1(0)\left\{1 + cn(2K_2 z|M)\right\}/2 \quad (10)
\]

where \( P_1(z) = A_1(z)A_2^*(z) \), and

\[M = \frac{P_1^2(0)}{P_{cr}^2} \]

It is observed that for \( P_1(0) > P_{cr} \), the power will be completely detuned and completely transmitted through guide 1, while a perfect phase matched coupling is achieved for \( P_1(0) < P_{cr} \). The parameter \( P_{cr} \) is the critical power, where \( P_{cr} \) dependent by guide width \( b \)'s is given approximately \( P_{cr} = 3.6, 4.2 \) and \( 6.3 \) watt/m for guide widths 2, 3 and 4 \( \mu m \) respectively, and shown in Figure 2. It is also interesting to note that for certain waveguide length \( L_c \), all input waves with \( K_2 = (2n+1)\pi/L_c \), \( n = 0, 1, ... \) will be totally transferred to guide 2.

**Numerical result and discussion**

The numerical result concerns with the verification of the analytic expression of the transverse field profile given by Eq. (8). The power transfer pattern according to Eq. (9) is plotted as a function of \( z \) for the values of the effective refractive index \( N \) designated by the points A, B, C, D, and E shown in Figure 2. It is clear from Figures 3 and 4 that it is in very good agreement with Figures 2, the device acts as a conventional directional coupler \( L_c = 6.1 \) mm, and \( 5.2 \) mm with complete crossover can occurs for \( P_1(0)'s = 0.9, 1.1, 3 \) W/m respectively for the guide width \( b = 3 \) \( \mu m \), and \( P(0)'s = 0.9, 1.1 \) W/m for the guide width \( b = 2 \) \( \mu m \). With \( b = d = 3 \) \( \mu m \) can be applied for several input power \( P_1(0)'s = 0.9, 1.1, 3 \) W/m and \( L_c = 6.1 \) mm, so that is a very good agreement.

In order to substantiate the above illustration, a full and explicit description of the power and field evolution along the guide for the input power \( P_1(0)'s = 0.9, 1.1, 3.0 \) and 4.2 W/m at the points A, B, C, and D (from Figures 2, 3) is given below as a result of applying the MenuFast numerical program by Hoekstra *et al.* (1995) has been developed. The numerical result according to Figures 3 and 4 can be shown in Figures 5, and 6 further confirm quantitatively the coupling behaviors predicted by our previous analytical study (Hoekstra *et al.*, 1995; Abramowitz and

![Figure 2. Variation of N with respect to P_1(0) for various b's at d = 3 \( \mu m \) from Eq. (9)](image-url)
Stegam, 1965) according to Eqs. 4, 6 and Figure 2. Thus, under phase-matched conditions for low input power, power transfer occurs periodically with $z$ as already. For high input power with $P_1(0) \gg 4.2 \text{ W/m}$, a complete power transfer from guide 1 to guide 2 does not take place or the nonlinear index change detunes the wave guide, and the coupling is blocked, can be shown in Figures 6a, and 6b.

We consider next the case of high input power, specifically $P_1(0) > P_{cr}$ ( $P_{cr} = 4.2 \text{ W/m}$). It is found from the result presented in Figure 6b that a complete power transmission takes place within guide 1. In other words the nonlinear index
Figure 5. Coupling characteristics obtained numerically showing (a), (b), (c), and (d) the power coupling behaviors for the 3-dimensional profile of the field distribution with $d = 3 \, \mu m$, and $b = 3 \, \mu m$, $P_1(0)$ for $d = 0.9, 1.1, 3, \text{ and } 4.2 \, W/m$ respectively.

Figure 6. 3-dimensional of field in nonlinear directional coupler with (a) for low input intensity and (b) for high input intensity. $P_1(0) = 3 \, W/m$, and $5.6 \, W/m$ respectively.
change detunes the waveguides, and the coupling is blocked. This result together with the earlier result for the case $P_i(0) < P_c$ describes the optical switching function of dual waveguide system. At low intensity, the light excited in one guide couplers over to the other waveguides, and at high intensity the nonlinear index change detunes the waveguides. This logic actions are explicitly shown in Figures 6a and 6b, demonstrating the possibility of implementing nonlinear directional coupler which could function either as an optically controlled OR, and AND gates depending only on the input power. Therefore, this result demonstrates the possibility of designing a symmetrical nonlinear directional coupler planar waveguide configuration which could function either as an optical switching depending only on the input powers, the widths of waveguide and guide separations.

**Conclusion**

We have described the result of a numerical study on the coupling behavior of a system of two nonlinear waveguides based on the analytical result obtained previously of the nonlinear effect. The result of the coupling effect for the optical switching and 3 dB power divider of the nonlinear directional coupler incorporate explicitly the influence of the guide widths, guide separations and input powers.

**References**


