ORIGINAL ARTICLE

Nonlinear planar coupler waveguides system in the medium kerr optics

H. Harsoyono

Abstract

H. Harsoyono

Nonlinear planar coupler waveguides system in the medium kerr optics

Songklanakarin J. Sci. Technol., 2005, 27(2) : 385-391

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 patern 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

Ph.D.(Nonlinear Optics), Department of Engineering Physics, Sepuluh Nopember Institute of Technology, Kampus ITS Sukolio, Surabaya 60111, Indonesia
E-mail: harsoyono@yahoo.com

Received, 9 June 2004 Accepted, 1 September 2004

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 resent 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 α_i is related to the third order susceptibility tensor $\chi^{(3)}$ of the material concerned by $\alpha_i = 3\chi_i^{(3)}$., 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

$$da_2(z)/dz = iK_2.a_4(z) + i\,(Q_1|a_2(z)|^2+2Q_2|a_4(z)|^2)a_2(z) \quad (1)$$

$$da_4(z)/dz = iK_2.a_2(z) + i\,(Q_1|a_4(z)|^2 + 2Q_2|a_2(z)|^2)a_4(z) \quad (2)$$

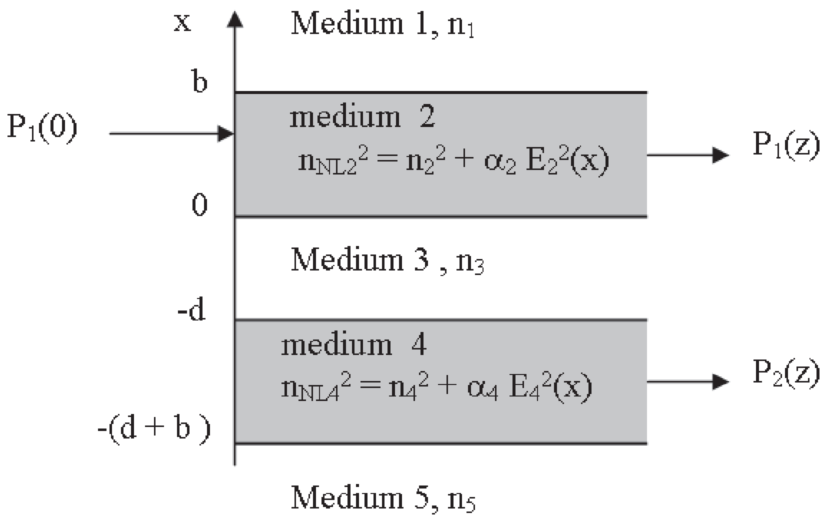

Figure 1. Structure of a planar nonlinear directional coupler, with P_i (0) and P_i (z) denoting respectively the input and transmitted power of the i th waveguide. ($n_1 = n_5 = 2.56$; $n_2 = n_4 = 2.589$; $n_3 = 2.585$)

where $a_2(z)$ and $a_4(z)$ are the wave envelope defined by corresponding mode fields according to $E_i(x,z) = E_i(x)\ a_i(z)\ \exp\ [-i\ \beta_i\ z]$, and the symmetric coupling coefficients are determined by

$$K_1 = (\omega\varepsilon_0/4) \int E_2(x).\ \Delta n_2^2\ E_2(x)\ dx \qquad (3)$$

$$K_2 = (\omega\varepsilon_0/4) \int E_2(x).\ \Delta n_2^2\ E_4(x)\ dx \qquad (4)$$

$$Q_1 = \omega\alpha n_0\varepsilon_0 \int E_2^4(x)\ dx \qquad (5)$$

$$Q_2 = \omega\alpha n_0\varepsilon_0 \int E_2^2(x)\ E_4^2(x)\ dx \qquad (6)$$

with $\Delta n_2^2 = n_3^2 - n_2^2$; $\Delta n_1^2 = n_3^2 - n_1^2$. The transverse field distribution $E_2(x)$'s are to be found by solving to the nonlinear equations

$$\frac{d^2E_i(x)}{dx^2} - k_0^2[\tilde{n}_i^2 - \alpha_i E_i^2(x)]E_i(x) = 0, \quad i = 2,4 \qquad (7)$$

subject to the boundary conditions at x =0, b, and an additional one at -(l+d), where ($\tilde{n}_i^2 = N^2 - n_i^2$ with N denoting the effective refractive index of the individual guide.

We have found, the expressions for $E_2(x)$ as follows

$$E_2(x) = E_{b1} \exp[-k_0\ \tilde{n}_1\ (x-b)], \qquad ; x \geq b$$

$$= q_2E_{01}\frac{q_2cn(q_2x|m_2) + k_3Gsn(q_2x|m_2)dn(q_2x|m_2)}{q_2^2dn^2(q_2x|m_2) + k_0^2\alpha_2E_{01}^2/2sn^2(q_2x|m_2)} \qquad ; 0 \leq x \leq b \qquad (8)$$

$$= \{E_{01} \sinh[k_0\tilde{n}_3(d+x)] - E_{02} \sinh(k_0\tilde{n}_3\ x)\}/\sinh(k_0\tilde{n}_3\ d) \qquad ; -d \leq x \leq 0$$

where G is given by $G = \coth(k_0\tilde{n}_3 d) - \eta\ \mathrm{cosech}(k_0\tilde{n}_3 d)$ with the parameter $\eta = E_{0,2}^2/E_{0,1}^2$ characterizing the asymmetry of the field pattern clearly $G\rightarrow 1$ for $d\rightarrow$. In Eq. (8) all the fields are given as real quantities with E_{01} and E_{02} denoting the values of the electric fields at the lower and upper boundaries of the 3th layer respectively, and E_{b1} the field value at the upper boundary of the 2nd layer, as indicated in Figure 1. Further, the symbols sn, cn, dn represent the specific Jacobian elliptic functions as commonly defined [10] with the modulus given by $m_2 = (q_2^2 + \tilde{n}_2^2)/2\ q_2^2$, and $k_i = k_0 n_i$, $q_2^2 = (\tilde{n}_2^4 + 2\alpha_2 C_2/k_0^2)^{1/2}$, where C_2 is the first integration constant of Eq. (8) determined by the continuity conditions at the boundaries (x = b, 0, -d).

The total guided wave power per-unit length along the y axis is obtained as usual by integrating the Poynting vector over the cross-sectional area of the waveguide system. The resulted expression for the total power distribution in the system is given by

$$P_{total} = \Re\{(N/\tilde{n}_3)(\alpha_2 E_{01}^2/2) \int_{-k_3d}^{0} \frac{1}{\sinh^2 k_3 d}[\sinh\{k_3(d+x)\} - \eta\sinh\{k_3x\}]^2 d(k_3x)$$

$$+(N/\tilde{n}_1)(\alpha_2 E_{b1}^2/2) + 2N(\alpha_2 E_0^2/2)\tilde{q}_2^2 \int_0^{k_0b}\left[\frac{\tilde{q}_2cn(\tilde{q}_2X) + \tilde{n}_3Gsn(\tilde{q}_2X)dn(\tilde{q}_2X)}{\tilde{q}_2^2dn^2(\tilde{q}_2X) + \alpha_2E_0^2/2sn^2(\tilde{q}_2X)}\right]^2 d(x) \qquad (9)$$

where $\Re = (c^2\ \varepsilon_o)/(\omega\alpha_2)$ [W/m], $X = k_0\ x$ and $\tilde{q}_2 = q_2/k_0$. 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 $E_2(x)$ for $n_3 = 2.585$, $n_2 = n_4 = 2.589$, $\alpha_2 = 3.10^{-11}$ (m^2/W) are depicted in Figure 1. With d = 3 µm there is a very good agreement which implies either a relatively large separation between the guides (d), or relatively sharp decay of the evanescent fields beyond the guide boundaries and according to Eqs.3 and 4 for Ref. (Harsoyono *et al.*, 2001). The linear and nonlinear coupling coefficient K's and Q's can be calculated from Eqs. (3)-(6) 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_o 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

$$P_1(K_2\, z) = P_1(0)\{1 + cn(2K_2\, z|M)\}/2 \qquad (10)$$

where P_1 (z) = A_2(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 $P_1(0) \leq P_{Cr}$. 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 µm 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 µm, and P(0)'s = 0.9, 1.1 W/m for the guide width b = 2 µm. With b = d = 3 µm 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

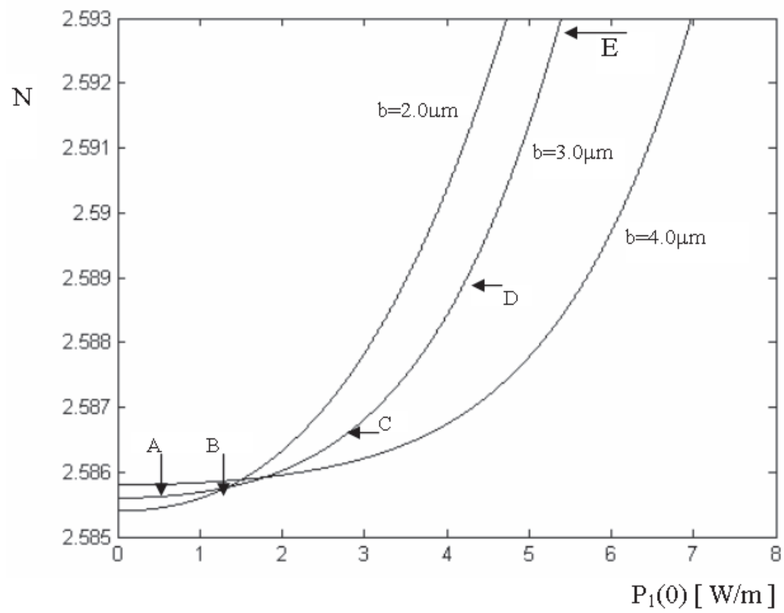

Figure 2. Variation of N with respect to P_1 (0) for various b's at d = 3 µm from Eq. (9)

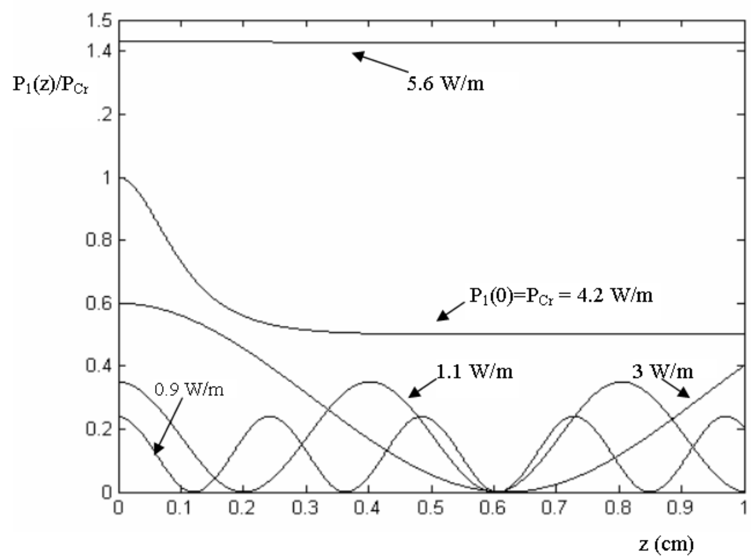

Figure 3. Power propagation in guide 1 as it propagates along the couper for various input powers P_1 (0) for d = 3 μm, and b = 3 μm.

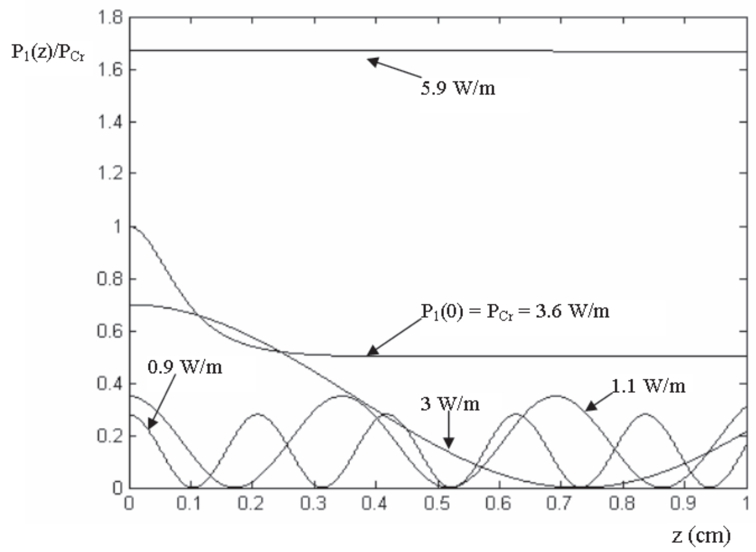

Figure 4. Power propagation in guide 1 as it propagates along the couper for various the input powers P_1 (0) for d = 3 μm, and b = 2 μm.

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 $P_1(0)$ >> 4.2 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 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

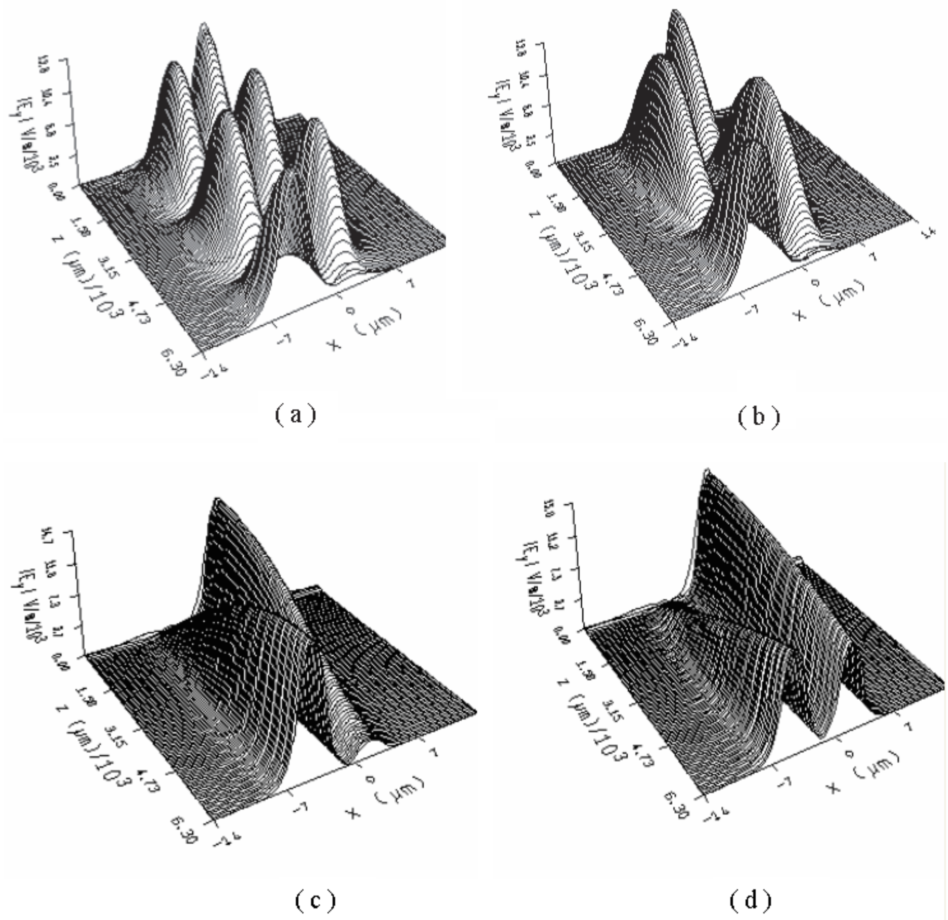

Figure 5. Coupling characteristics obtained numerically showing (a), (b), (c), and (d) the power coupling behaviors for the 3-dimensional profile of the field distribution with d = 3 μm, and b = 3 μm, P_1 (0) for d = 0.9, 1.1, 3, and 4.2 W/m respectively.

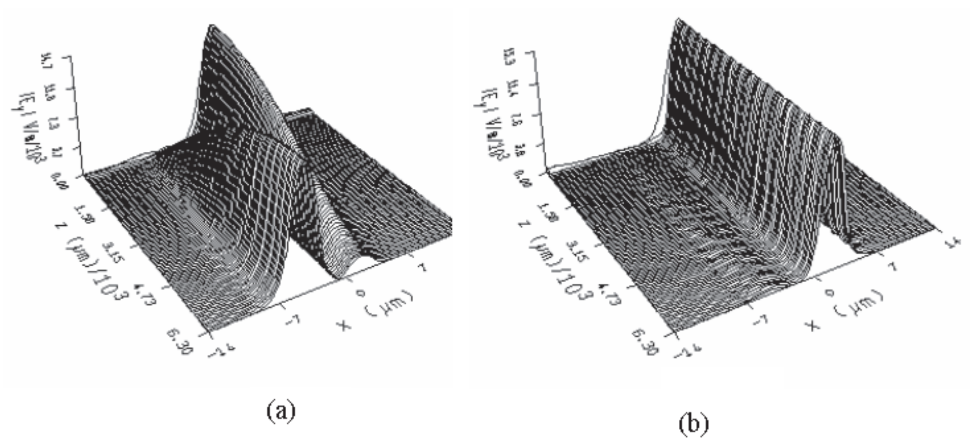

Figure 6. 3-dimensional of field in nonlinear directional coupler with (a) for low input intensity and (b) for high input intensity. $P_1(0)$ = 3 W/m, and 5.6 W/m respectively.

change detunes the waveguides, and the coupling is blocked. This result together with the earlier result for the case $P_1(0) < P_{Cr}$ 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

Abramowitz, M. and Stegam, I.A. 1965. Handbook of Mathematical Functions, NewYork: Dover.

Allan D Boardman and P. Egan. 1985. S-Polarized Waves in a Thin Dielectric Film Asymmetrically Bounded by Optically Nonlinear Media, IEEE-J. Quantum Electronics, QE.21(10): 1701-1713.

Allan D Boardman and Egan, P. 1986. Optically Nonlinear Waves in Thin Films, IEEE J. of Quantum Electronics, QE-22(2): 19-324.

Chi-Chung Yang and Alexander J.S. Wang. 1992. Asymmetric nonlinear coupling and its applications to logic functions, IEEE - J. of Quantum Electronics, 28(2): 479-487.

Harsoyono, H. 2000. Nonlinear TE wave in multiplayer planar waveguide with optically nonlinear medium, Chiang Mai J. Sci. 27(1): 24-32.

Harsoyono, H., Siregar, R.E. and Tjia, M.O. 2001. A Study of Nonlinear Coupling Between Two Identical Planar Waveguide, J. Nonlinear Optical Physics and Material. 10(2): 233-247.

Harsoyono, H., Siregar, R.E., Soehiani, A. and Tjia, M.O. 1999. A numerical study of beam propagation in multilayer plannar waveguide with optically nonlinear medium, proceedings of SPIE. 3896: 585-593.

Hoekstra. H.J.W.M, Krijnen, G.J.W. and Abelmann, L. 1995. MenuFast: A beam propagation method programme, Tranducers and Materials Science, University of Twente - The Netherlands, (1995)

Jensen, S.M. 1982. The Nonlinear Coherent Coupler, IEEE J. of Quantum Electronics, QE-18(10): 1580-1583.

Nobrega, K.Z., M.G da Silva, Sombra, A.S.B. 1999. Optical Multistability on the Asymmetric Nonlinear Directional Coupler, J. Opt. Comm. 20(6): 210-214;

Nobrega, K.Z., M.G da Silva, Sombra, A.S.B. 2000. Multistable all-optical awitching behavior of the asymmetric nonlinear directional coupler, J. Opt. Comm. 173: 413-421.

Stegeman G.I, Wright, E.M. 1990. All- Optical Waveguide Switching, Optical and Quantum Electronics 22: 95-122.