Available online at www.sciencedirect.com

SCIENCE DIRECT®

Optics Communications 258 (2006) 30–34

Optics Communications

www.elsevier.com/locate/optcom

Adiabatic three-waveguide directional coupler

Emmanuel Paspalakis

Department of Materials Science, School of Natural Sciences, University of Patras, Rio, Patras 265 04, Greece

Received 31 January 2005; received in revised form 21 July 2005; accepted 25 July 2005

Abstract

We propose a three-waveguide directional coupler based on adiabatic evolution of a single normal mode of the system and analyze its switching properties using coupled mode theory. In our scheme the propagation coefficients of the waveguides are constant and the coupling coefficients are variable. This device works in the case that the propagation coefficients of the two outer waveguides are identical and that the coupling coefficients are designed to act in a counterintuitive order.

PACS: 42.79.Gn; 42.82.Et; 42.81.Qb

Keywords: Three-waveguide directional coupler; Variable coupling coefficient; Adiabatic evolution; Counterintuitive coupling sequence

Optical waveguide directional couplers and their switching properties have attracted a lot of research interest in integrated optics [1–3]. A particular set of schemes in this area involves two- [4–6] and three-waveguide [7,8] directional couplers with variable (tapered) coupling coefficients and variable propagation coefficients. The switching properties of these schemes are based on proper choice of coupling coefficients and propagation coefficients that ensure adiabatic (slow) evolution of a single normal mode (or eigenmode) of the system. The advantage of the schemes based on adiabatic evolution of a single mode over the conventional schemes is that the switching properties of adiabatic schemes are tolerant to small to moderate variations of the system's parameters (coupling coefficients and propagation coefficients).

In this work we study optical switching based on adiabatic evolution of a single normal mode of a three-waveguide directional coupler. We consider a waveguide structure with three waveguides in a linear coupling configuration. The waveguides are placed close to each other so they are optically coupled. In our scheme the propagation coefficients of the waveguides are constant and the

E-mail address: paspalak@upatras.gr.

0030-4018/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2005.07.060

coupling coefficients are variable. We also consider the case that the two outer waveguides have identical propagation coefficients that could be different from the propagation coefficient of the center waveguide. In the case that the variable coupling coefficients are designed such that they act in a counterintuitive order and the evolution of the system is adiabatic, efficient optical switching is achieved.

We note that the basic idea of the device studied in this paper is similar to those of [13,14] where grating-assisted waveguide directional couplers were studied. Here, we extend the basic idea of that papers beyond complete light transfer between two waveguides and present also results for controlled optical power division between two waveguides, an important process in several optoelectronics applications. In addition, we present results for complete light return to the initially excited waveguide.

For the theoretical analysis of the system we use coupled mode theory which has been applied with a lot of success in the description of weakly coupled three-waveguide directional couplers with constant [9–11] and variable [7,8,12] coupling coefficients. We are interested in the behaviour of the system under continuous wave excitation. We denote with 1,3 the two outer waveguides and 2 the center waveguide. As it is usual in the linear coupling configuration the two outer waveguides are not coupled to each other.

In the slowly varying envelope approximation the spatial evolution of the amplitudes of the optical fields, $a_n(z)$, with $n = 1, 2, 3$, is described by the following set of coupled differential equations:

$$-\mathrm{i}\frac{\mathrm{d}a_1}{\mathrm{d}z} = \beta_1 a_1(z) + k_{12}(z)a_2(z), \tag{1}$$

$$-\mathrm{i}\frac{\mathrm{d}a_2}{\mathrm{d}z} = \beta_2 a_2(z) + k_{21}(z)a_1(z) + k_{23}(z)a_3(z), \tag{2}$$

$$-\mathrm{i}\frac{\mathrm{d}a_3}{\mathrm{d}z} = \beta_3 a_3(z) + k_{32}(z)a_2(z). \tag{3}$$

Here, β_n with $n = 1,2,3$, is the constant propagation coefficient of the nth waveguide. Also, $k_{nm}(z)$, with $n,m = 1, 2, 3$ is the variable coupling coefficient between the waveguides n and m. Without the loss of generality we take the coupling coefficients to be real and positive, so $k_{nm}(z) = k_{mn}(z)$.

We study a waveguide structure with $\beta_1 = \beta_3 = \beta$. Then, if $a_n(z) = b_n(z)\exp(\mathrm{i}\beta z)$, with $n = 1, 2, 3$, Eqs. (1)–(3) become

$$-\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}z}\boldsymbol{b}(z) = \boldsymbol{M}(z)\boldsymbol{b}(z). \tag{4}$$

Here,

$$\boldsymbol{M}(z) = \begin{bmatrix} 0 & k_{12}(z) & 0 \\ k_{12}(z) & \Delta\beta & k_{23}(z) \\ 0 & k_{23}(z) & 0 \end{bmatrix}, \tag{5}$$

$\mathbf{b}(z) = [b_1(z), b_2(z), b_3(z)]^{\mathrm{T}}$ and $\Delta\beta = \beta_2 - \beta$. The propagation matrix $\boldsymbol{M}(z)$ has a zero eigenvalue with normalized eigenstate

$$|\psi_{\text{dark}}(z)\rangle = \frac{1}{\sqrt{k_{12}^2(z) + k_{23}^2(z)}} \begin{bmatrix} k_{23}(z) \\ 0 \\ -k_{12}(z) \end{bmatrix}. \tag{6}$$

This can be also written as

$$|\psi_{\text{dark}}(z)\rangle = \cos[\Theta(z)]|1\rangle - \sin[\Theta(z)]|3\rangle, \tag{7}$$

where $\tan[\Theta(z)] = k_{12}(z)/k_{23}(z)$, and $|1\rangle = (1, 0, 0)^{\mathrm{T}}$, $|2\rangle = (0, 1, 0)^{\mathrm{T}}$, $|3\rangle = (0, 0, 1)^{\mathrm{T}}$. This eigenstate is called a dark state of the system. Such states exist in laser-driven multi-level systems as well and have led to several interesting effects [15].

In all the cases, we study waveguide 1 is initially excited. If the two variable coupling coefficients, $k_{12}(z)$ and $k_{23}(z)$, are applied in a counterintuitive sequence, such that the coupling coefficient $k_{23}(z)$ precedes the coupling coefficient $k_{12}(z)$, then at short distances $k_{12}(z) \ll k_{23}(z)$ so that $\cos[\Theta(z)] \approx 1$ and the system is then in state $|\psi_{\text{dark}}\rangle \approx |1\rangle$. If the evolution of the system is adiabatic, so that the change of the variable coupling coefficients is slow, the system will remain at all distances in the dark state. Then, several switching cases can be achieved by proper design of the coupling coefficients.

If $k_{23}(z)$ is switched off prior to $k_{12}(z)$, then at long distances $k_{23}(z) \ll k_{12}(z)$ so that $\sin[\Theta(z)] \approx 1$ and $|\psi_{\text{dark}}\rangle \approx -|3\rangle$. So, with the above procedure complete light transfer from waveguide 1 to waveguide 3, i.e. creation of a cross state, is achieved. We note that during the light transfer from waveguides 1 to 3, waveguide 2 is never been excited. In addition, if the coupling coefficients are applied initially in a counterintuitive sequence and are switched off simultaneously, then a coherent superposition of states $|1\rangle$ and $|3\rangle$ can be created. So, power division is realized in waveguides 1 and 3. Finally, if $k_{12}(z)$ is switched off prior to $k_{23}(z)$ complete return of light to waveguide 1, i.e. creation of a bar state, occurs.

An example of light transfer with Gaussian coupling coefficients is shown in Fig. 1. The results of Fig. 1(b) are obtained by solving numerically Eq. (4). The coupling coefficients used in this case have the form

$$k_{12}(z) = k_1 \mathrm{e}^{-(z-z_1)^2/\zeta_1^2}, \tag{8}$$

$$k_{23}(z) = k_2 \mathrm{e}^{-(z-z_2)^2/\zeta_2^2}. \tag{9}$$

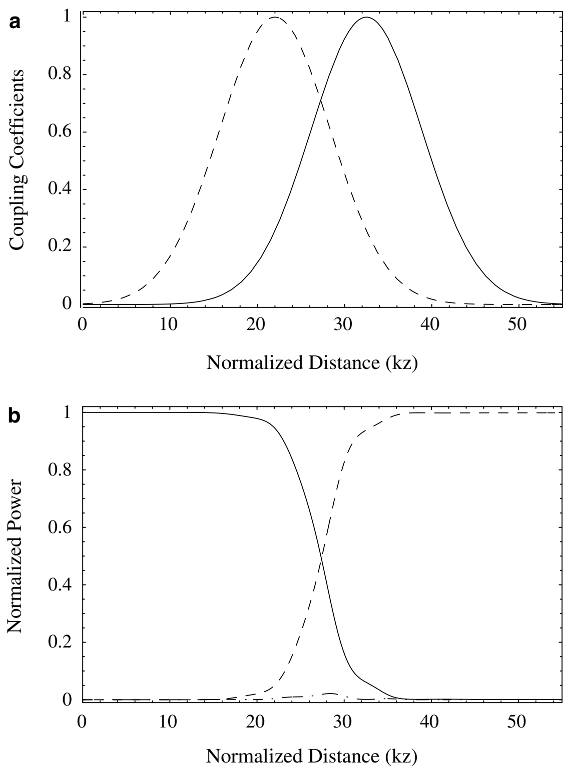

Fig. 1. In (a) we present the variable coupling coefficients of Eqs. (8) and (9), in units of k, as a function of normalized distance for $k_1 = k_2 = k$, $\Delta\beta = 0$, $z_1 = 32.5/k$, $z_2 = 22/k$, $\zeta_1 = \zeta_2 = 9/k$. In (b) the spatial evolution of the normalized light power, $|b_n(z)|^2/P_0$, with $n = 1,2,3$, in waveguide 1 (solid curve), waveguide 2 (dot-dashed curve) and waveguide 3 (dashed curve) is shown. The initial conditions in this figure are $b_1(0) = \sqrt{P_0}$ and $b_2(0) = b_3(0) = 0$.

Here, k_1 and k_2 are the maximum values of the coupling coefficients, z_1 and z_2 are the central distances of the coupling coefficients and ζ_1 and ζ_2 are the widths of the coupling coefficients $k_{12}(z)$ and $k_{23}(z)$, respectively.

We next illustrate a case of power division in Fig. 2. The coupling coefficients are taken as

$$k_{12}(z) = k \sin\theta\, \mathrm{e}^{-(z-z_1)^2/\zeta^2}, \tag{10}$$

$$k_{23}(z) = k\left[\mathrm{e}^{-(z-z_2)^2/\zeta^2} + \cos\theta\, \mathrm{e}^{-(z-z_1)^2/\zeta^2}\right] \tag{11}$$

and the evolution of light power in each waveguide, obtained once again by solving numerically Eq. (4), is displayed in Fig. 2(b) for $\theta = \pi/4$. In this case, the light is divided equally in the two outer waveguides. Finally results of complete light return to the initially excited waveguide is shown in Fig. 3. We have chosen the coupling coefficients

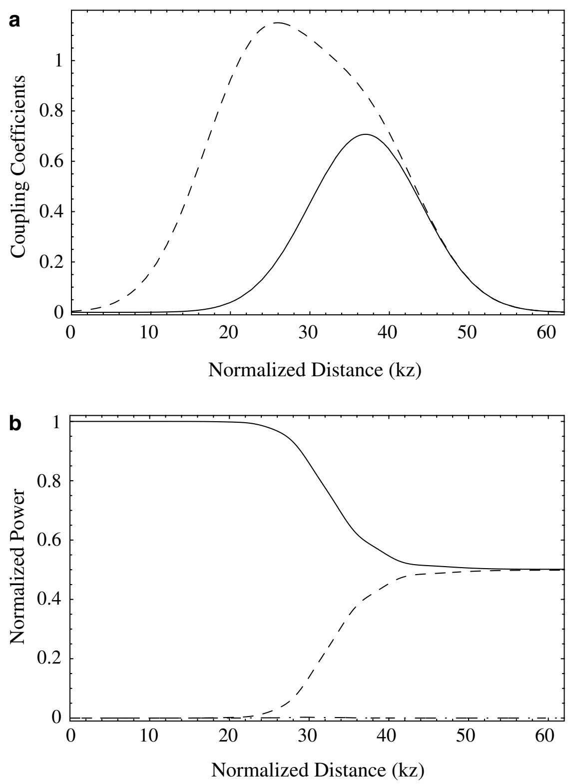

Fig. 2. The same as in Fig. 1 but with the coupling coefficients given by Eqs. (10) and (11). The parameters for this figure are $\Delta\beta = 0$, $z_1 = 37/k$, $z_2 = 23.5/k$, $\zeta = 10/k$ and $\theta = \pi/4$.

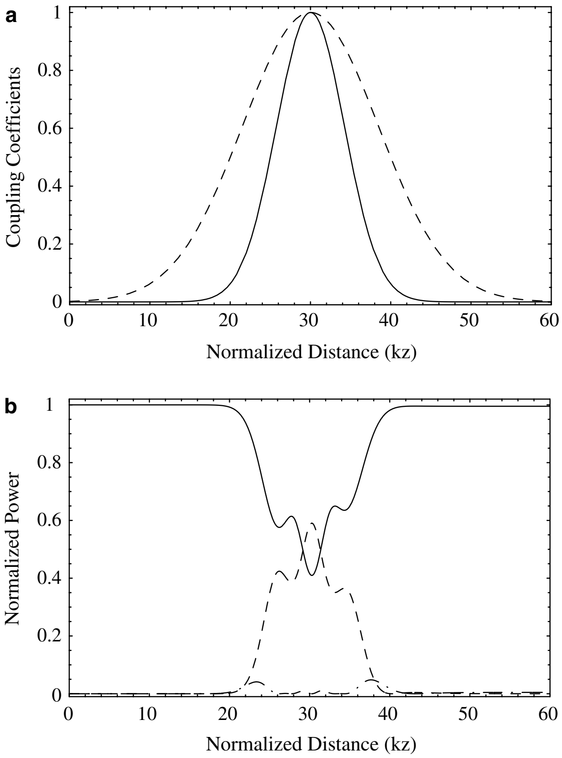

Fig. 3. This is the same as in Fig. 1 with parameters $\Delta\beta = 0$, $z_1 = z_2 = 30/k$, $\zeta_1 = 6/k$ and $\zeta_2 = 12/k$.

to be Gaussian type of the form of Eqs. (8) and (9) with $z_1 = z_2$ and $\zeta_1 < \zeta_2$.

We note that the coupling coefficients used in the adiabatic method described here need not be of a specific shape nor their parameters need to obey specific conditions, in contrast to the conventional coupling approach [10,12]. The choice of Gaussian shaped coefficients in the above two examples was made only for convenience. The coupling coefficients must only be sufficiently wide and overlap significantly in distance so that adiabatic evolution is ensured [14,15]. For Gaussian pulses of the form of Eqs. (8) and (9), in order to realize complete light transfer from waveguide 1 to waveguide 3 we must have $\sqrt{k_1^2 + k_2^2}\Delta z \gg 1$, where Δz is the overlap of the coupling coefficients. Typically, $\sqrt{k_1^2 + k_2^2}\Delta z$ of the order of 10 or larger is sufficient for adiabatic evolution and complete light transfer. For power division the waveguides must be typically longer than for those used for complete light transfer.

In summary, we have proposed an optical switching scheme in a three-coupled waveguide device with variable coupling coefficients that is based on adiabatic evolution of a normal mode of the system. We have also analyzed the switching properties of the system using coupled mode theory. As the proposed device is based on adiabatic evolution of the system's normal mode, it is not constrained by the need for having exact system parameters and is not limited by small to moderate fluctuations of the system parameters. As in the other proposals of adiabatic evolution directional couplers [4–8] the waveguide coupler needs to have increased device length in comparison with conventional three-waveguide directional couplers [9–12] for adiabatic evolution to be succeeded.

Acknowledgement

This work has been supported by the Greek-Hungarian bilateral research program 'Nonlinear and quantum optics in photonic band gap materials: phenomena and methods'.

References

[1] A.W. Snyder, J.D. Love, Optical Waveguide Theory, Chapman and Hall, London, 1983.
[2] R.R.A. Syms, J.R. Cozens, Optical Guided Waves and Devices, McGraw-Hill, London, 1992.
[3] A. Yariv, P. Yeh, Optical Waves in Crystals, Wiley Classics Library, New York, 2003.
[4] R.R.A. Syms, R.G. Peall, Opt. Commun. 69 (1989) 235.
[5] R.R.A. Syms, IEEE Photon. Technol. Lett. 4 (1992) 1135.
[6] A. Syahriar, V.M. Schneider, S. Al-Bader, J. Lightwave Technol. 16 (1998) 1907.
[7] V.M. Schneider, H.T. Hattori, IEEE J. Quant. Electr. 36 (2000) 923.
[8] V.M. Schneider, H.T. Hattori, Opt. Commun. 187 (2001) 129.
[9] H.A. Haus, C.G. Fonstad, IEEE J. Quant. Electron. 17 (1981) 2321.
[10] C.-M. Kim, Y.-J. Im, IEEE J. Sel. Top. Quant. Electr. 6 (2000) 170.

[11] N.K. Efremidis, D.N. Christodoulides, Opt. Commun. 246 (2005) 345.
[12] G.J. Liu, B.M. Liang, Q. Li, G.L. Jin, Opt. Eng. 42 (2003) 2930.
[13] A. Yariv, Opt. Lett. 23 (1998) 1835;
E. Peral, A. Yariv, J. Lightwave Technol. 17 (1999) 942.
[14] A.M. Kenis, I. Vorobeichik, N. Moiseyev, IEEE J. Quant. Electron. 37 (2001) 1321.
[15] K. Bergmann, H. Theuer, B.W. Shore, Rev. Mod. Phys. 70 (1998) 1003;
N.V. Vitanov, M. Fleischhauer, B.W. Shore, K. Bergmann, Adv. Atom. Mol. Opt. Phys. 46 (2001) 55.