Directional Couplers Made of Nonidentical Asymmetric Slabs. Part I: Synchronous Couplers

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***Abstract*—We discuss TE and TM mode directional couplers made of nonidentical asymmetric slab waveguides. Approximate expressions are provided for the coupling coefficients of synchronous (no grating) couplers and their accuracy is checked by comparison with exact solutions that are based on solving the guided mode problem of the total structure consisting of the two slabs considered to be a single waveguide.**

Introduction

DIRECTIONAL couplers are important for many applications in integrated optics [1]. Sometimes it is desirable to make directional couplers of two nonidentical asymmetric slab (or thin-film) waveguides. Without diffraction gratings the two waveguides can exchange energy efficiently whenever they are in synchronism; that is, when in the absence of coupling, both of them have the same propagation constants. We speak of "accidental degeneracy" when the propagation constants of the two waveguides are not equal due to a symmetry of the structure.

Waveguides that are not in synchronism can be coupled by providing a diffraction grating whose period is equal to the beat wavelength between the two nonsynchronous waveguides. Grating-assisted directional couplers will be discussed in the second part of this paper.

Synchronous directional couplers, the subject of the first part of this paper, can be analyzed in different ways. An exact treatment begins by computing the compound modes of the combined structure consisting of the two slabs [2]. For synchronous slabs there are always two solutions of the compound mode problem that have propagation constants that are nearly identical with those of the two modes of the isolated slabs. These two modes of the compound structure would have even and odd symmetry if both slabs were identical. However, even for nonidentical synchronous slabs the two modes can be superimposed so that at the input end of the coupler their fields nearly cancel in one slab while they reinforce each other in the opposite slab. This field pattern represents the initial launching condition where light is inserted predominantly into only one waveguide. Since both modes have slightly different propagation constants β_1 and β_2, their relative phases will reverse at a distance $L = \pi/(\beta_2 - \beta_1)$. At this point the mode fields reinforce each other in the opposite sense, accounting for the exchange of light power between the two waveguides of the coupler.

An alternate, approximate method for treating directional couplers uses two coupled first order differential equations for the amplitudes of the two coupled modes, one in each slab [3]. The coupling coefficient entering these equations can approximately be expressed as an overlap integral [4]. This approach is much simpler to use and works for directional couplers with and without diffraction gratings.

Compound Modes of the Asymmetric Slab Coupler

The directional coupler consisting of two asymmetric slab waveguides placed in close proximity to each other is schematically shown in Fig. 1. The two slabs have dielectric core regions of thickness d_2 and d_4 with refractive index n_2 and n_4. It is assumed that $n_2 > n_1$, n_3 and $n_4 > n_3$, n_5. The spacing between the slab cores is $2S_3$.

We describe TE and TM modes of the compound structure consisting of the five dielectric media by introducing a field function F which represents the E_y component of the electric field for TE modes and the H_y component of the magnetic field for TM modes. In the five regions of space, F is defined as follows:

$$\begin{aligned} F &= A_1 \exp\left[-\gamma_1(x - S_3 - d_2)\right], \qquad \text{for } x \geq S_3 + d_2 \\ &= A_2 \cos\left[\kappa_2\left(x - S_3 - \frac{d_2}{2}\right)\right] + A_3 \sin\left[\kappa_2\left(x - S_3 - \frac{d_2}{2}\right)\right], \qquad \text{for } S_3 + d_2 \geq x \geq S_3 \\ &= A_4 \exp(-\gamma_3 x) + A_5 \exp(\gamma_3 x), \qquad \text{for } -S_3 \leq x \leq S_3 \\ &= A_6 \cos\left[\kappa_4\left(x + S_3 + \frac{d_4}{2}\right)\right] + A_7 \sin\left[\kappa_4\left(x + S_3 + \frac{d_4}{2}\right)\right], \qquad \text{for } -S_3 \leq x \leq -S_3 - d_4 \\ &= A_8 \exp\left[\gamma_5(x + S_3 + d_4)\right], \qquad \text{for } x \leq -(S_3 + d_4). \end{aligned} \tag{1}$$

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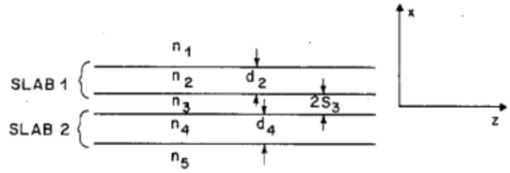

Fig. 1. Schematic of slab directional coupler.

The time and z-dependence of the modes is given by the common factor $\exp\,[i(\omega_t - \beta_z)]$. The parameters κ_j and γ_j appearing in (1) are defined as

$$\kappa_j = \sqrt{n_j^2 k^2 - \beta^2}, \qquad j = 2, 4 \tag{2}$$

$$\gamma_j = \sqrt{\beta^2 - n_j^2 k^2}, \qquad j = 1, 3, 5 \tag{3}$$

with the free-space propagation constant $k = 2\pi/\lambda$.

With no field variation in y-direction the slab modes have three nonvanishing field components. The y-components of the electric and magnetic fields for TE and TM modes are given by (1). The other nonvanishing field components are obtained by differentiation [5]. For TE modes:

$$H_x = -\frac{i}{\omega\mu_0}\frac{\partial E_y}{\partial z} \qquad H_z = \frac{i}{\omega\mu_0}\frac{\partial E_y}{\partial x} \tag{4}$$

and for TM modes:

$$E_x = \frac{i}{n_j^2\omega\epsilon_0}\frac{\partial H_y}{\partial z} \qquad E_z = -\frac{i}{n^2\omega\epsilon_0}\frac{\partial H_y}{\partial x}. \tag{5}$$

Seven of the eight amplitude coefficients A_j appearing in (1) and the propagation constant β are obtained from eight homogeneous equations that result from the boundary conditions requiring continuity of the y and z directed field components. In matrix notation the boundary conditions lead to the equation system

$$CA = 0 \quad \text{or} \quad \sum_{\mu=1}^{8} c_{\nu\mu} A_\mu = 0, \qquad \nu = 1, 2 \cdots 8. \tag{6}$$

The nonvanishing matrix elements are

$$c_{11} = 1,\ -c_{12} = c_{32} = \cos\left(\kappa_2 \frac{d_2}{2}\right),\ c_{13} = c_{33} =$$
$$-\sin\left(\kappa_2 \frac{d_2}{2}\right),\ c_{21} = -\gamma_2/m_1,\ c_{22} = c_{42} = \frac{\kappa_2}{m_2}\sin\left(\kappa_2 \frac{d_2}{2}\right)$$
$$-c_{23} = c_{43} = \frac{\kappa_2}{m_2}\cos\left(\kappa_2 \frac{d_2}{2}\right),\ -c_{34} = c_{55} = e^{-\gamma_3 S_3}$$
$$-c_{35} = c_{54} = e^{\gamma_3 S_3},\ c_{44} = c_{65} = \frac{\gamma_3}{m_3}e^{-\gamma_3 S_3}$$
$$c_{45} = c_{64} = -\frac{\gamma_3}{m_3}e^{\gamma_3 S_3},\ -c_{56} = c_{76} = \cos\left(\kappa_4 \frac{d_4}{2}\right)$$
$$c_{57} = c_{77} = -\sin\left(\kappa_4 \frac{d_2}{2}\right),\ c_{66} = c_{86} = \frac{\kappa_4}{m_4}\sin\left(\kappa_4 \frac{d_4}{2}\right)$$
$$-c_{67} = c_{87} = \frac{\kappa_4}{m_4}\cos\left(\kappa_4 \frac{d_4}{2}\right),\ c_{78} = -1,\ c_{88} = -\frac{\gamma_5}{m_5} \tag{7}$$

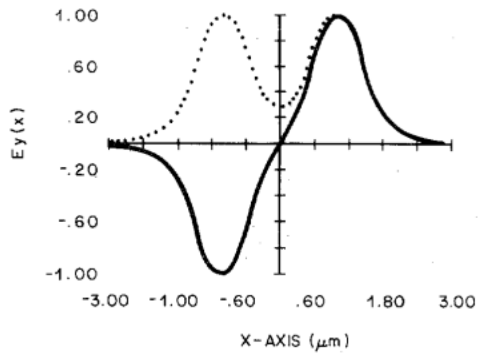

Fig. 2. Even and odd TE modes of a symmetrical directional coupler with $n_1 = n_3 = n_5 = 3.2$, $n_2 = n_4 = 3.3$, $d_2 = d_4 = 1\ \mu$m, $\lambda = 1.5\ \mu$m.

with $m_j = 1$ ($j = 1$–5) for TE modes and $m_j = n_j^2$ for TM modes.

The homogeneous equation system has solutions only when its system determinant vanishes $|C| = 0$. It is customary to expand the determinant so that an explicit eigenvalue equation can be written down. However, this 8×8 determinant does not yield a simple expansion, even though 36 of its 64 elements are zero. Thus it is actually easier to obtain numerical solutions directly by searching for zeros of the unexpanded determinant, particularly if a determinant evaluation routine is available on the computer system. Once the eigenvalues β have been found from $|C| = 0$, we may set $A_1 = 1$ and omit the eighth equation in (6). (Instead of A_1 any other amplitude coefficient can be set to unity and any other equation can be omitted from (6)). With the help of numerical matrix routines, the remaining inhomogeneous equation system can now easily be solved for A_j with $j = 2$ through 8.

One word of caution is in order. If, for example, $n_4 > n_2$, it can happen that κ_2 of (2) becomes imaginary. In that case, the cosine and sine functions with argument $\kappa_2 d_2/2$, appearing in (1) and (7), convert to hyperbolic functions. Overall, the field expressions and β remain real, but this possibility must be anticipated when writing the computer program. If β becomes so small that either γ_1 or γ_5 can no longer be real, there are no longer any real solutions of β so that the modal fields become leaky (that is lossy) modes. The synchronous directional coupler shown in Fig. 1 would not function in this case.

Discussion of Numerical Examples

It is interesting to see the field distributions of compound modes of the slab directional coupler. As a first example we consider a symmetrical structure with $n_1 = n_3 = n_5 = 3.2$ and $n_2 = n_4 = 3.3$. $d_2 = d_4 = 1\ \mu$m, $\lambda = 1.5\ \mu$m and a spacing between the two slabs of $2S_3 = 1\ \mu$m. The E_y components of two TE modes of the compound structure are shown in Fig. 2. The dotted line represents the symmetric, the solid line the antisymmetric solution of this symmetric structure. The two modes can be superimposed to yield an initial excitation of the slab on the left, as shown in Fig. 3(a). One exchange length further down the structure, at $z = L$ with

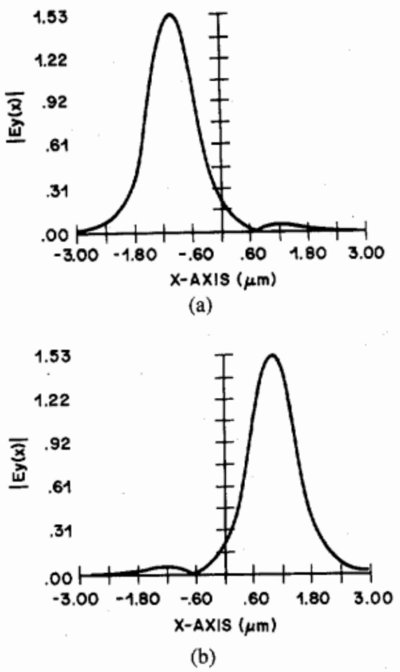

Fig. 3. (a) The modes shown in Fig. 2 have been superimposed to cancel each other on the right slab and reinforce each other on the left. (b) The field distribution at the power exchange length $z = L$.

$$L = \frac{\pi}{|\beta_2 - \beta_1|} \tag{8}$$

(β_1 and β_2 are the propagation constants of the two compound modes), the power has been coupled over to the other slab so that Fig. 3(b) results. It is apparent that almost complete exchange of light energy is possible. However, Fig. 3(a) and (b) also makes it clear that the superposition of the two guided modes of lowest order is not sufficient for an exact representation of an input field illuminating only one of the two slabs. To cancel out the small amount of residual energy existing in the opposite slab would require adding radiation modes to the superposition of guided modes. The radiation modes would carry away some of the light energy. Thus, some power is lost in the attempt of exciting just one of the two slabs at $z = 0$.

As a second example we consider a structure consisting of two nonidentical slabs with $n_1 = n_3 = n_5 = 3.2$, $n_2 = 3.3$, $n_4 = 3.35$, and $d_2 = 1$ μm. To achieve synchronism of the two slabs at the wavelength $\lambda = 1.5$ μm requires that $d_4 = 0.4734$ μm for TE modes ($d_4 = 0.49474$ μm for TM modes). The slab separation is once more $2S = 1$ μm.

The E_y field components of TE modes of the compound structure are shown in Fig. 4. Again, we see two modes which, even though they lack perfect symmetry, resemble symmetric and antisymmetric functions. These two modes can be superimposed to yield an excitation of predominantly the left slab, as shown in Fig. 5(a). Compared to Fig. 3(a), the cancellation of light energy on the right slab is somewhat poorer in this example. But, as Fig. 5(b)

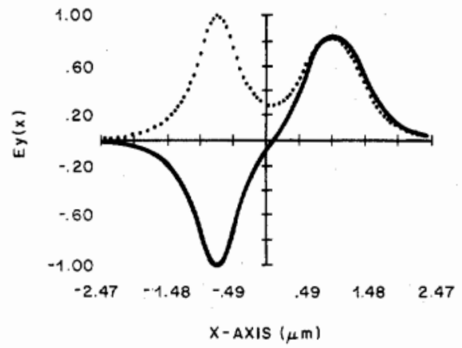

Fig. 4. TE modes of a coupler made of two nonidentical slabs with $n_1 = n_3 = n_5 = 3.2$, $n_2 = 3.3$, $n_4 = 3.35$, $d_2 = 1$ μm, $d_4 = 0.4734$ μm, $\lambda = 1.5$ μm.

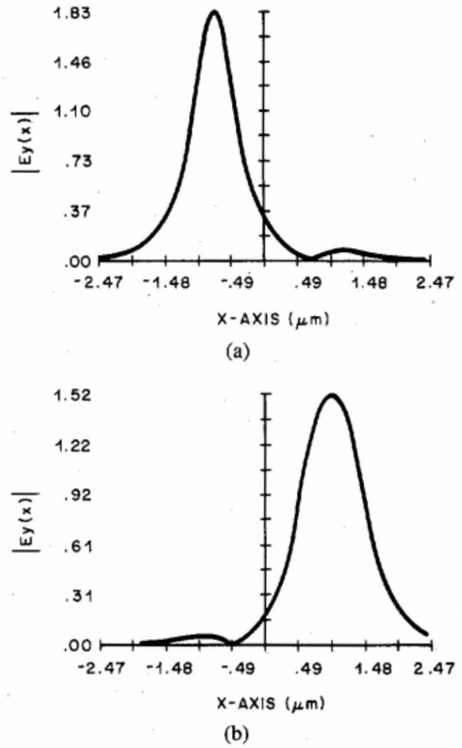

Fig. 5. (a) Superposition of the modes of Fig. 4 to yield excitation of the left slab. (b) Field distribution at $z = L$.

shows, after traversing one half beat wavelength $L = 200$ μm, almost all the light energy is once more coupled over to the right slab.

Finally, we consider two slabs whose fundamental modes are not synchronous. Fig. 6 shows the two fundamental modes of the asymmetrical compound structure for $n_1 = 1$, $n_3 = n_5 = 3.2$, $n_2 = 3.3$, $n_4 = 3.5$, $d_2 = 1$ μm, and $d_4 = 0.3$ μm. Fig. 6 shows that each of the two modes favors one of the two slabs. Thus, each mode is more nearly equal to the mode of one or the other slab taken in isolation. Whereas the solid line has a slight relative extremum in the region of the core of slab 2, the mode represented by the dotted line lacks this feature, because κ_2 is imaginary so that the mode remains evanescent within the core of slab 1. Superposition of the two modes again makes it possible to represent field excitation of the left slab as shown in Fig. 7(a). However, at $z = \pi/(\beta_2 -$

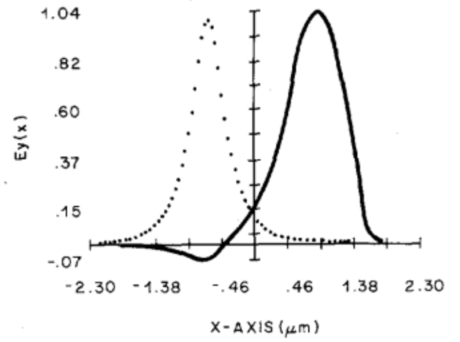

Fig. 6. The TE modes of two nonsynchronous slabs with $n_1 = 1$, $n_3 = n_5 = 3.2$, $n_2 = 3.3$, $n_4 = 3.5$, $d_2 = 1$ μm, $d_4 = 0.3$ μm, $\lambda = 1.5$ μm. Note that each mode resembles the corresponding mode of an isolated slab.

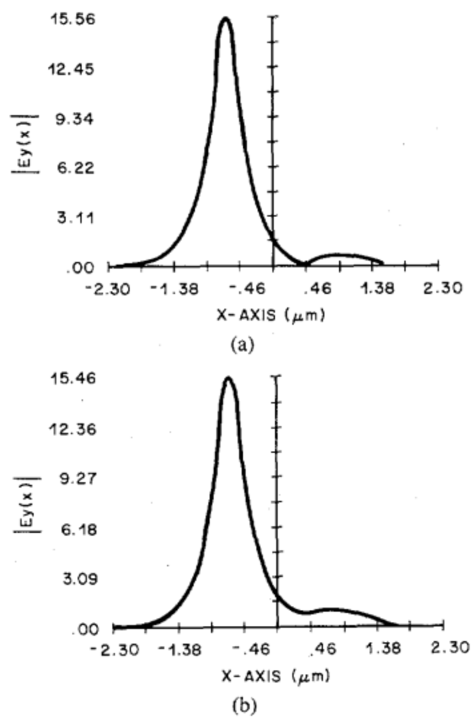

Fig. 7. (a) The modes of Fig. 6 have been superimposed to yield excitation of the left slab. (b) Field distribution at $z = L$.

β_1) the light energy still resides mostly on the left slab, as shown in Fig. 7(b). No substantial exchange of light energy is taking place when the two slabs lack phase synchronism.

Coupling Coefficients of Asymmetric Slab Coupler

The exact solutions of the compound modes of the directional coupler yield the energy exchange length L of (8) as the (inverse) difference of the propagation constants of two modes. This result is exact but its evaluation requires relatively complicated computations. For this reason we present approximate, yet highly accurate coupling coefficients which yield the same information.

Since essentially only two guided modes are involved in describing the exchange of energy on a directional coupler, it is possible to write down two simultaneous differential equations for their field amplitudes [3], [4]

$$\frac{da_1}{dz} = -i\hat{\beta} a_1 + c a_2$$

$$\frac{da_2}{dz} = -i\hat{\beta} a_2 - c a_1. \tag{9}$$

This equation system holds for the two synchronous modes of a directional coupler without a diffraction grating. The coupling coefficient c appearing in (9) is defined as [4]

$$c = -\frac{\omega \epsilon_0}{4P} \left\{ \int_{S_3}^{S_3 + d_2} (n_2^2 - n_3^2)\, \vec{E}_1 \cdot \vec{E}_2 \, dx + \int_{S_3 + d_2}^{\infty} (n_1^2 - n_3^2)\, \vec{E}_1 \cdot \vec{E}_2 \, dx \right\}. \tag{10}$$

In this formula ϵ_0 is the electric permittivity of vacuum, ω is the circular frequency of the light, P is a normalization constant which represents the unit of power. The actual power carried on slab j is given as $|a_j|^2 P$. $\vec{E}_1$ and $\vec{E}_2$ are the electric field vectors of the modes of slab 1 and slab 2, respectively. Thus, we are now dealing with modes of the isolated slabs instead of with compound modes of the whole system. The interaction between the two slabs is mediated by the coupling process incorporated into the equations (9). The expressions for the modal fields of isolated slabs can be found in [5]. The eigenvalue equations for the isolated slabs can conveniently be written in the form [5]

$$\kappa_2 = \frac{1}{d_2} \left\{ N\pi + \arctan\left(\frac{m_2}{m_3} \frac{\gamma_3}{\kappa_2} \right) + \arctan\left(\frac{m_2}{m_1} \frac{\gamma_1}{\kappa_2} \right) \right\}. \tag{11}$$

We have again $m_j = 1$ for TE modes and $m_j = n_j^2$ for TM modes. The integer N is the mode number and assumes the values 0, 1, 2, etc., $N = 0$ is the dominant TE or TM mode. The eigenvalue equation was written for the modes of slab 1. The modes of slab 2 follow by replacing $n_1 \rightarrow n_5$, $n_2 \rightarrow n_4$, $d_2 \rightarrow d_4$. The evaluation of (11) is most easily accomplished by iteration. That is we choose a trial value of κ_2 to compute an iterated value by substitution into the right-hand side of the equation. The only tricky part in this procedure is to ensure that none of the γ-parameters becomes imaginary during the iteration process, which can happen when the desired solution belongs to a mode near cutoff.

Evaluation of (10) is straightforward (if a little tedious) and results in the following expression for the coupling coefficient of TE modes

$$c = \frac{-2\kappa_2 \kappa_4 \gamma_3 e^{-2S_3\gamma_3}}{k^2 \hat{\beta} \left\{ (n_2^2 - n_3^2)(n_4^2 - n_3^2)(d_2 + 1/\gamma_1 + 1/\gamma_3)(d_4 + 1/\gamma_5 + 1/\gamma_3) \right\}^{1/2}}. \tag{12}$$

The coupling coefficient for TM modes is far more complicated (TM modes always are!) and is thus presented in the following way

$$c = \frac{-2n_2n_3^2n_4\kappa_2\kappa_4\gamma_3 e^{-2S_3\gamma_3}}{\hat{\beta}\left\{(n_3^4\kappa_2^2 + n_2^4\gamma_3^2)(n_3^4\kappa_4^2 + n_4^4\gamma_3^2)Q_2Q_4\right\}^{1/2}} \quad (13)$$

with

$$Q_2 = d_2 + \frac{n_2^2n_3^2}{\gamma_3}\frac{\kappa_2^2 + \gamma_3^2}{n_3^4\kappa_2^2 + n_2^4\gamma_3^2} + \frac{n_2^2n_1^2}{\gamma_1}\frac{\kappa_2^2 + \gamma_1^2}{n_1^4\kappa_2^2 + n_2^4\gamma_1^2} \quad (14)$$

and

$$Q_4 = d_4 + \frac{n_4^2n_3^2}{\gamma_3}\frac{\kappa_4^2 + \gamma_3^2}{n_3^4\kappa_4^2 + n_4^4\gamma_3^2} + \frac{n_4^2n_5^2}{\gamma_5}\frac{\kappa_4^2 + \gamma_5^2}{n_5^4\kappa_4^2 + n_4^4\gamma_5^2}. \quad (15)$$

Like any system of linear differential equations with constant coefficients, (9) has normal mode solutions

$$\beta_1 = \hat{\beta} - c \quad (16)$$

and

$$\beta_2 = \hat{\beta} + c. \quad (17)$$

These normal modes correspond to the compound modes of the directional coupler. Thus, we see that the difference of the propagation constants of the compound modes is equal to twice the coupling coefficient

$$\beta_2 - \beta_1 = 2c \quad (18)$$

so that the power exchange length (8) becomes

$$L = \frac{\pi}{2c}. \quad (19)$$

To compute the length of the directional coupler required for complete exchange of energy thus involves solving the eigenvalue equation (11) for one slab and using the eigenvalues $\hat{\beta}$, k_j, and γ_j to compute the coupling coefficients from (12) or (13). Since synchronism of the two slabs is required, it is necessary (for nonidentical slabs) to solve (11) for one slab and compute the slab width d_j ($j = 2$ or 4) for the other slab from the corresponding equation solved for d_j. If d_j is already specified, one of the refractive indices must be adjusted to achieve phase synchronism.

Comparison of Approximate and Exact Power Exchange Lengths

Fig. 8(a) shows the power exchange lengths L (broken lines with scale on left), computed from (8), as functions of the slab separation $2S_3$ for TE and TM modes for the example used in Figs. 4 and 5. Also plotted on the same figure are the relative errors $100 \times \Delta L/L$ (solid lines with scale on right) of the approximate relation (19)—relative to the exact result (8). In this example, the exchange lengths for TE and TM modes are so similar that only one curve is shown, and the approximations (12), (13), and (19) are accurate to better than 1 percent. The difference between TE and TM modes is more apparent in the example shown in Fig. 8(b) with: $n_1 = 1$, $n_3 = n_5 = 3.2$, $n_2 = 3.3$, $n_4 = 3.5$, $d_2 = 1$ μm, $d_4 = 0.1633$ μm for TE modes and $d_4 = 0.1791$ μm for TM modes. We see that in this second example the error stays below 10 percent for TE modes even for extremely close slab spacings, barely exceeding this value for TM modes.

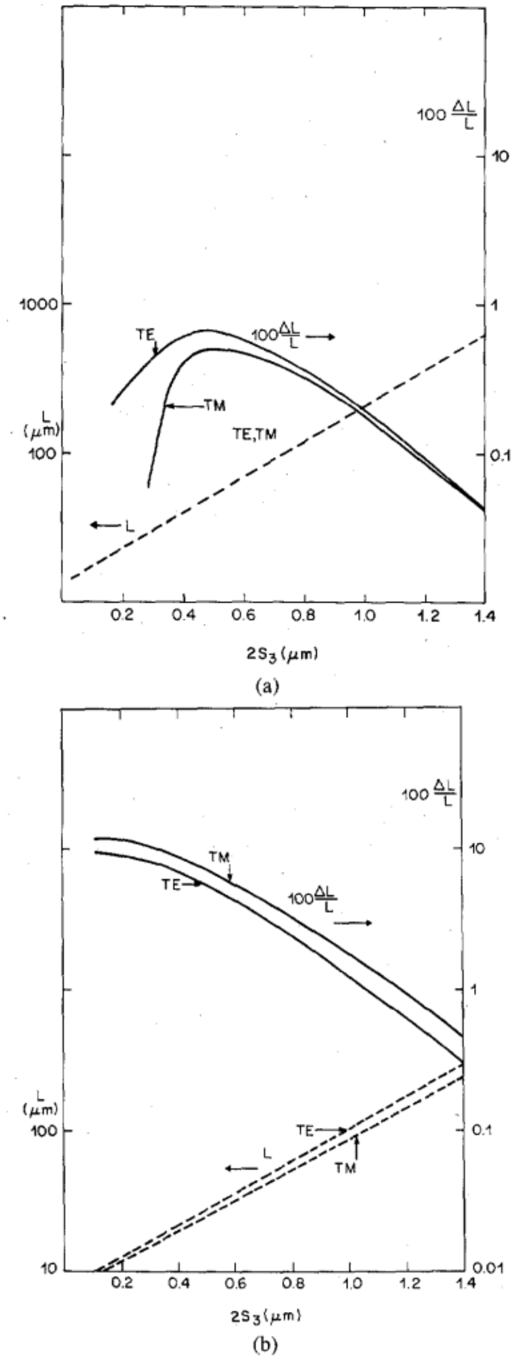

Fig. 8. (a) Power exchange length L (dotted line) and error of approximate coupling formulas (solid lines) as functions of the slab separation for the slab coupler used in Fig. 4. (b) Same as (a) for $n_1 = 1$, $n_3 = n_5 = 3.2$, $n_2 = 3.3$, $n_4 = 3.5$, $d_2 = 1$ μm, $d_4 = 0.1633$ μm, $\lambda = 1.5$ μm.

Coupler Bandwidth

Nonidentical directional couplers can exchange energy only at those wavelengths where the propagation constants of two modes, one on each slab, become identical. That means that these devices are bandpass filters. The (wavelength) full width at half maximum is approximately given by the expression [6], [7]

$$\Delta\lambda = \frac{5}{\left|\frac{d\beta_2}{d\lambda} - \frac{d\beta_1}{d\lambda}\right|} \tag{20}$$

where β_1 and β_2 are the propagation constants of the two coupled modes and L is the power exchange length of the coupler. The wavelength derivatives of the propagation constants can be computed numerically by solving the eigenvalue equation (11) at two closely spaced wavelengths. If the material dispersion of the refractive indices n_j are to be taken into account, this is probably the simplest approach since the eigenvalue equation must be solved at one wavelength anyhow. Ignoring material dispersion ($dn_j/d\lambda = 0$), we can obtain the wavelength derivatives of the propagation constants by differentiating the eigenvalue equation (11). Thus, we obtain for TE modes

$$\frac{d\beta}{d\lambda} = -\frac{n_2^2k^2d_2 + \beta^2\left(\frac{1}{\gamma_1} + \frac{1}{\gamma_3}\right)}{\lambda\beta\left(d_2 + \frac{1}{\gamma_1} + \frac{1}{\gamma_3}\right)} \tag{21}$$

and

$$\frac{d\beta}{d\lambda} = -\frac{n_2^2k^2\left(d_2 + \frac{1}{\gamma_1} + \frac{1}{\gamma_3}\right)}{\lambda\beta\left[d_2 + \frac{n_2^2k^2}{\beta^2}\left(\frac{1}{\gamma_1} + \frac{1}{\gamma_3}\right)\right]} \tag{22}$$

for TM modes. These equations are written for the slab with core index n_2, the corresponding equation for the other slab is obtained by exchanging $n_1 \rightarrow n_5$, $n_2 \rightarrow n_4$, $n_3 \rightarrow n_3$, and $d_2 \rightarrow d_4$.

The coupler bandwidth is plotted in Fig. 9 as a function of the slab spacing for a coupler with the same refractive index values and core widths as those of Figs. 4, 5, and 8(a) (in the absence of material dispersion). As filters, such directional couplers would have wide bandwidths. Narrower bandwidths can be achieved by making the coupler much longer. An order of magnitude increase in coupler length reduces the bandwidth by one order of magnitude. Making use of material dispersion should also help to reduce the bandwidth.

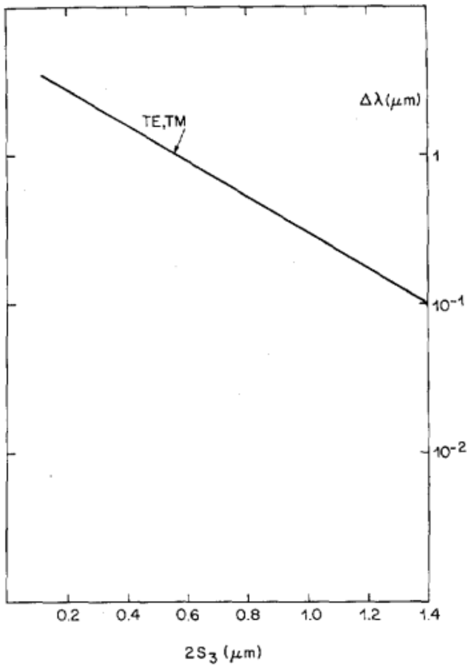

Fig. 9. Bandwidth of the coupler used in Fig. 4 as a function of slab separation.

Conclusions

We have analyzed synchronous directional couplers made with non-identical, asymmetric slab waveguides. We found that the simple coupling theory, using coupling coefficients for modes of the individual (isolated) slabs, yields very satisfactory results. Formulas were presented for the coupling coefficients and for the bandwidth (without material dispersion) for TE and TM modes of slab directional couplers. The approximate results were compared with exact results obtained from modal solutions of the compound structure.

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References

[1] R. G. Hunsperger, *Integrated Optics Theory and Technology*, 2nd ed. Berlin, W. Germany: Springer Verlag, 1984.

[2] E. A. J. Marcatili, "Dielectric rectangular waveguide and directional coupler for integrated optics," *Bell. Syst. Tech. J.*, vol. 48, pp. 2071–2102, 1969.

[3] A. W. Snyder and J. D. Love, *Optical Waveguide Theory*. London: Chapman and Hall, 1983.

[4] D. Marcuse, *Light Transmission Optics*, 2nd ed. New York, 1982.

[5] D. Marcuse, *Theory of Dielectric Optical Waveguides*. New York: Academic, 1974.

[6] R. C. Alferness and R. V. Schmidt, "Tunable optical waveguide directional coupler filters," *Appl. Phys. Lett.*, vol. 33, pp. 161–163, 1978.

[7] D. Marcuse, "Directional coupler filter using dissimilar optical fibres," *Electron. Lett.*, vol. 21, pp. 726–727, 1985.

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