

Crosstalk in a Lossy Directional Coupler Switch

V. R. Chinni, T. C. Huang, P. -K. A. Wai, C. R. Menyuk, *Senior Member, IEEE*, and G. J. Simonis

Abstract— Crosstalk due to material absorption in a two-waveguide, symmetric directional coupler switch is investigated. In a material with absorption, it is not possible to completely eliminate the crosstalk by adjusting the coupling length. The coupling length for minimum crosstalk differs from that of lossless systems. Theoretical limits of the lowest achievable crosstalk and the corresponding coupling lengths are calculated. The results show that the effect of absorption on crosstalk is more severe when the devices are designed for low crosstalk. The increase in crosstalk due to absorption can be as high as 20 dB. The material absorption is thus a critical parameter in designing low crosstalk devices.

I. INTRODUCTION

DIRECTIONAL couplers are important guided-wave components in integrated optics. They have been used to implement switching, modulation, wavelength demultiplexing, and power splitting [1]. Crosstalk in a directional coupler is defined as the ratio of light power in the unwanted output port to the power in the desired output port. In a directional coupler, it is desirable to have all the input power coupled to the other waveguide for a cross state and no coupling at all for a bar state. However, a small amount of power always remains in the input waveguide for a cross state and couples to the other waveguide for a bar state, resulting in undesirable crosstalk. Crosstalk imposes limits on system design, especially in large switching fabrics in which the crosstalk adds. Many sources of crosstalk in directional couplers and their effects have been evaluated [2]–[10]. Crosstalk has been attributed to asymmetry of the waveguides [3], absorption loss [4], nonoptimal coupling length [1], unequal excitation of the symmetric and antisymmetric modes at the input [5], coupling of radiation modes to output, or fabrication variations [6]. Most of the analysis to date has considered lossless waveguide couplers. A notable exception is [4] in which Marcuse has shown that the losses in the surrounding medium are unsuitable to decrease the crosstalk between two dielectric waveguides as they also increase mode loss to unacceptably high levels. In this paper, we provide a detailed analysis of the effects of absorption on crosstalk in a symmetric directional coupler switch and

show that absorption is a critical parameter in designing low crosstalk devices. Through a numerical example, we show that the increase in crosstalk due to absorption can be as high as 20 dB in practical directional coupler switches.

In reality, all materials exhibit finite absorption. It is generally assumed that crosstalk due to material absorption can be compensated by simply choosing the correct length for the coupling region. In this paper we show that material absorption in general leads to crosstalk in a directional coupler because the two lowest order modes, one even and one odd, have different power distributions. Ideally, these two modes beat with each other to produce a complete power transfer between the two waveguides, but, due to the different power distributions, the even and odd modes experience different amounts of absorption in a waveguide system with nonuniform absorption. Consequently, the two modes, even when excited equally, will have unequal amounts of power along the length of the coupler. So they will never be able to completely cancel each other, even when they are completely out of phase, leading to crosstalk that cannot be compensated. Consequently, switching is incomplete.

We use first order eigenmode theory to evaluate the crosstalk in a directional coupler switch. The formalism includes the effects of mode mismatch at the input and output of the coupling region. We calculate the effect of material absorption on the crosstalk and establish limits on the best achievable performance. As an example, we evaluate the crosstalk of a field-induced waveguide directional coupler switch [11]. We calculate the minimum achievable crosstalk with different waveguide spacings for different guide refractive indices. The effect of absorption on these devices is measured and the increase in the crosstalk is evaluated. Initially we will consider devices where the radiation field plays a negligible role. In Section IV, we compare the calculated results with numerical simulations using a finite difference beam propagation method [12] that models the entire field, avoiding this approximation and show that the theoretical results agree with numerical simulations. The waveguides studied in this work exhibit modal losses which not only can influence the crosstalk exhibited by the device but also can significantly perturb the modal fields. We have used effective index method and a waveguide numerical analysis that is applicable for lossy waveguides to evaluate the mode fields and complex propagation constants [13].

II. ANALYSIS

A typical two-waveguide symmetric directional coupler is shown in Fig. 1. The indices of refraction of the guiding and cladding regions are n_g and n_c respectively. The width of

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V. R. Chinni was with the Department of Electrical Engineering, University of Maryland, Baltimore, MD 21228-5398 USA. He is now with AT&T Bell Laboratories, Holmdel, NJ 07733 USA.

C. R. Menyuk is with the Department of Electrical Engineering, University of Maryland, Baltimore, MD 21228-5398 USA.

P. K. A. Wai is with the Department of Electrical Engineering, University of Maryland, Baltimore, MD 21228-5398. He is also at Institute of Plasma Research, University of Maryland, College Park, MD 20742 USA.

T. C. Huang and G. J. Simonis are with the Army Research Laboratory, Adelphi, MD 20783 USA.

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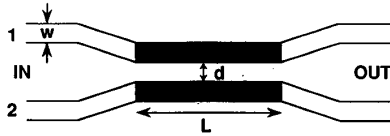


Fig. 1. Schematic diagram of a two-guide symmetric directional coupler. Width of the waveguides is w . Their edge-to-edge separation is d . Length of the coupling region is l .

the waveguide is w and their edge-to-edge separation is d . The transition regions are symmetric and adiabatic. We focus our analysis upon a directional coupler with only two guided modes in the coupling region. Accordingly, we assume that the uncoupled waveguides can only support one mode. The eigenmodes of the coupling region corresponding to the lowest order even and odd modes are ψ_e and ψ_o , and their respective propagation constants are β_e and β_o . The sum of the even and odd modes gives the power distribution across the waveguides. The eigenmodes of the decoupled input waveguides are ϕ_1 and ϕ_2 . The coupling of ϕ_1 to ψ_e and ψ_o depends on the geometry of the transition region. Consider launching ϕ_1 at the input waveguide. The coupling between the input excitation and the modes in the coupling region can be expressed as

$$\begin{aligned}\phi_1 &= a_e \psi_e + a_o \psi_o \\ \phi_2 &= a_e \psi_e - a_o \psi_o\end{aligned}\quad (1)$$

where a_e and a_o are the coupling coefficients. In the simple case of a straight coupler, a_e and a_o are real. The effect of the input bend region is to induce a small phase difference between the excited even and odd modes [5] so that a_e and a_o are complex. This initial phase difference between the even and odd modes can be compensated by properly adjusting the coupling length [9]. In our analysis, we assume a_e and a_o to be purely real. Note that the ratio between a_o and a_e indicates the excitation asymmetry of even and odd modes in the coupling region.

At the end of the coupling region, the modes can be projected onto the output waveguide modes with appropriate phase factors due to the output bend region. Using this approach, the output mode amplitudes can be obtained by a series of matrix multiplications from the input mode amplitudes. If we assume that the output transition region is identical to the input transition region, then by reciprocity the output coupling coefficients can also be found from (1).

After a propagation distance l , the fields at the output waveguides ϕ'_1, ϕ'_2 are given by [5]

$$\begin{aligned}\phi'_1 &= \left[\frac{a_o^2 \exp(-i\beta_e l) + a_e^2 \exp(-i\beta_o l)}{4a_e^2 a_o^2} \right] \phi_1 \\ &+ \left[\frac{a_o^2 \exp(-i\beta_e l) - a_e^2 \exp(-i\beta_o l)}{4a_e^2 a_o^2} \right] \phi_2, \\ \phi'_2 &= \left[\frac{a_o^2 \exp(-i\beta_e l) - a_e^2 \exp(-i\beta_o l)}{4a_e^2 a_o^2} \right] \phi_1 \\ &+ \left[\frac{a_o^2 \exp(-i\beta_e l) + a_e^2 \exp(-i\beta_o l)}{4a_e^2 a_o^2} \right] \phi_2.\end{aligned}\quad (2)$$

From (2), the crosstalk for a propagation distance of l with $\phi_1 = 1$ and $\phi_2 = 0$ is given by

$$C(l) = \left| \frac{a_o^2 \exp(-i\beta_e l) + a_e^2 \exp(-i\beta_o l)}{a_o^2 \exp(-i\beta_e l) - a_e^2 \exp(-i\beta_o l)} \right|^2. \quad (3)$$

We will use (2) and (3) and $dC(l)/dl = 0$ to calculate the minimum possible crosstalk and the corresponding coupling length. We then calculate the best possible power transfer efficiency, and the coupling length required. In our calculations, we treat power transfer efficiency as the ratio between the output power coupled into the desired port to the power at the input.

In our analysis, we neglect the reflections at the beginning of the directional coupler and at the end of the directional coupler. We also do not consider coupling into radiation modes and the interaction between the radiation and the output modes. Reflected power is very small and also it does not affect the crosstalk calculations [5]. The radiation modes excited at the interface between the input transition region and the coupler can couple into the output. For low radiation losses (less than 1%), the influence of radiation modes on crosstalk performance is negligible [9]. The radiation can affect the results obtained for very low crosstalk devices. We have carried out numerical simulations including the effects of radiation for a field-induced waveguide directional coupler switch that we will discuss later. These simulations show that the effect of differential absorption on crosstalk is significant even when radiation is important.

In a lossy material system the propagation constant of a mode is complex, with the imaginary part representing the absorption coefficient associated with the mode. In practical systems, the material absorption is nonuniform. For example, the nonuniformity may be due to different doping concentrations or due to different material regions in the structure. As a result, the absorption associated with each mode can be different; because each mode has a different power distribution, the even and odd modes of the coupled mode structure in a nonuniform absorption system will have different absorption coefficients. In an ideal case of no asymmetry in excitation, the two modes are equally excited at the input. In reality, the excitation is unequal, establishing a floor for the minimum achievable crosstalk. Above and beyond that, due to differential absorption of the modes, each mode will have a different amount of power throughout the length of the coupler. Therefore, even when the two modes are combined in phase in a bar state, or out of phase in a cross state, the switching is not complete. Consequently, the power cannot be completely switched to any of the output waveguides, adding more crosstalk to the device, and leading, as we shall show, to a significant increase in crosstalk due to differential absorption.

III. RESULTS AND DISCUSSION

Assuming a straight transition region, the coupling length for minimum crosstalk is obtained by differentiating (3). The coupling length for lowest crosstalk is given by solving the

transcendental equation

$$\frac{a_o^4}{a_e^4} = \exp(-2\Delta\beta_{iml}) \left[\frac{\Delta\beta_{im} - \Delta\beta_{re} \tan(\Delta\beta_{re}l)}{\Delta\beta_{im} + \Delta\beta_{re} \tan(\Delta\beta_{re}l)} \right]. \quad (4)$$

The parameters $\Delta\beta_{re}$ and $\Delta\beta_{im}$ are the real and imaginary parts of $\Delta\beta$, where $\Delta\beta$ is defined as the difference between the even and odd mode propagation constants, i.e., $\Delta\beta = \beta_e - \beta_o$. In the absence of material absorption, the parameter $\Delta\beta_{re}$ determines the coupling length in a directional coupler. In directional couplers with absorption, $\Delta\beta_{re}$ and $\Delta\beta_{im}$ together determine the coupling length. The parameter $\Delta\beta_{im}$ measures the difference in loss experienced by even and odd modes, indicating the effect of nonuniform material absorption. Solving (4) for the coupling length and then using (3), we obtain the lower limit of the crosstalk due to material absorption and asymmetric excitation.

As can be seen from (3) and (4), the crosstalk performance depends strongly on the asymmetry parameter a_o/a_e along with the differential modal absorption $\Delta\beta_{im}$. Fig. 2 shows a_o/a_e as a function of refractive index in the guiding region. We assumed the cladding index to be 3.400 and the wavelength of operation to be $1.15 \mu\text{m}$. The waveguide width was chosen to be $2 \mu\text{m}$ to keep the waveguide single moded in the Δn range of 0.00–0.01. Graphs corresponding to a waveguide separation d of 1–5 μm are shown in the figure. We evaluated the coupling coefficients a_o and a_e by first numerically finding eigenmodes and complex propagation constants of the coupled waveguides by using multilayer waveguide analysis [13] and then by computing the overlap integrals for the projections. As this figure indicates, the asymmetric parameter is close to unity (unity corresponding to completely symmetric case) when the waveguides are strongly guiding, or when the waveguide separation is large. The corresponding crosstalk for this device is small, but, due to strong guiding, the coupling lengths are fairly large. When the system is weakly guiding, or when the waveguide separation is small, the asymmetry parameter is smaller than unity, and the corresponding crosstalk is high, but, the coupling length is short. The even and odd modes may be considered as combinations of the individual modes of the two separate waveguides, but, due to the presence of an extra waveguide, a small perturbation of the mode profiles occurs that leads to the difference between the coupled modes and the sum or difference of the individual waveguide modes. Consequently, the input guided mode can never be equally split into the odd and even modes of the coupled system and as can be seen from the Fig. 2, the parameter a_o/a_e is never equal to unity.

Using (3) and (4), we calculate the minimum possible crosstalk and the corresponding coupling lengths as a function of $\Delta\beta_{im}$. The coupling length for minimum crosstalk is shown in Fig. 3(a) and the minimum achievable crosstalk is shown in Fig. 3(b) for different values of a_o/a_e . In most of the practical devices, the loss in the guiding region is smaller than the loss in the surrounding region to keep the total modal loss as small as possible. We considered only cases in which the loss in the guiding region is smaller than the loss in the surrounding cladding. The sign of $\Delta\beta_{im}$ depends on the loss experienced by even and odd modes, which is a function of

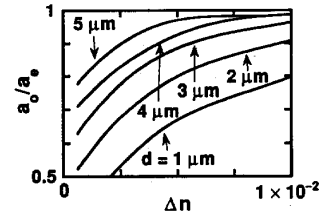


Fig. 2. Measure of asymmetry in excitation of odd and even modes as a function of difference in waveguide and cladding refractive index (Δn). Refractive index of the cladding is 3.400 and operating wavelength is $1.15 \mu\text{m}$. Width of the waveguide w is $2.0 \mu\text{m}$. Waveguide separation in the coupling region d is used as a parameter with values of 1–5 μm .

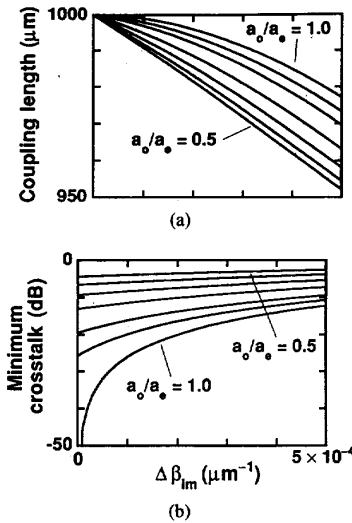


Fig. 3. (a) Coupling length corresponding to minimum crosstalk and (b) minimum crosstalk in a two-guide symmetric directional coupler switch. Differential absorption on even and odd modes cause crosstalk and also change the coupling length corresponding to lowest crosstalk. Asymmetry parameter a_o/a_e is used with values of 1.0, 0.95, 0.9, 0.8, 0.7, 0.6, and 0.5. Value of $\Delta\beta_{re}$ is chosen to be $\pi/(1000 \mu)$.

field distribution of these modes and nonuniformity in material absorption. In our analysis, as shown in Fig. 3, we only show results corresponding to positive $\Delta\beta_{im}$ which corresponds to the odd mode experiencing more loss than the even mode. When $\Delta\beta_{im}$ is negative, results can be obtained in a similar way by solving (3) and (4).

The minimum achievable crosstalk is a function of the ratio of the power coupled into even and odd modes at the input (a_o/a_e), the differential absorption in even and odd modes ($\Delta\beta_{im}$), and the difference between the real propagation constants ($\Delta\beta_{re}$). An increase in asymmetry, corresponding to lower values of a_o/a_e , increases crosstalk. An increasing differential absorption increases the crosstalk. As can be seen from the Fig. 3(b), the deterioration in crosstalk due to the differential absorption ranges from tens of dB to a few dB depending on the asymmetry of the excitation. If the directional coupler is designed to give low crosstalk, then the effect of asymmetry of excitation is minimal, and differential absorption solely determines the crosstalk. In effect, the absorption plays a crucial role in low crosstalk devices and sets a floor to

minimum achievable crosstalk. As can be seen from Fig. 3(a), the coupling length in the cases with and without loss differ by about 50 μm in a coupler of length 1000 μm . The minimum crosstalk is neither at a coupling length of $l_c = \pi/|\Delta\beta|$ nor at $l_c = \pi/\beta_{re}$. Crosstalk due to absorption will be even higher if measured at the coupling length corresponding to the case without absorption; so, one has to optimize the coupling length to achieve the lowest crosstalk. From these two graphs, the designer can determine the minimum crosstalk achievable in a lossy directional coupler and find the exact coupling length to obtain that minimum crosstalk. The results of Fig. 3 present the fundamental limits on the crosstalk performance of a symmetric directional coupler with absorption.

In a device with absorption, the coupling length for maximum power transfer need not be same as the coupling length for minimum crosstalk. From (2), we solve for the coupling length corresponding to maximum power transfer to the output port. The coupling length is obtained by solving the transcendental equation

$$\frac{a_o^2}{a_e^2} = \frac{\Delta\beta_{re} a_o^2 \sin(\Delta\beta_{re} l) + \text{Im}(\beta_o) a_o^2 \exp(-\Delta\beta_{im} l)}{\text{Im}(\beta_e + \beta_o) a_e^2 \cos(\Delta\beta_{re} l) - \text{Im}(\beta_e) a_e^2 \exp(\Delta\beta_{im} l)}, \quad (5)$$

where $\text{Im}(x)$ indicates the imaginary part of x . From (4) and (5), we observe that the coupling length for maximum power in the output waveguide need not be the same as the coupling length for minimum crosstalk. When absorption is low, the difference in the coupling lengths is very small.

In Fig. 3, the graphs corresponding to $a_o/a_e = 1$ show the coupling length and minimum crosstalk when both the even and odd modes are excited equally at the input of the coupler region. The effect of absorption on crosstalk and deviation in coupling length is minimum when $a_o/a_e = 1$. In this case, the transcendental equation to solve for coupling length corresponding to minimum crosstalk reduces to

$$\Delta\beta_{re} \tan(\Delta\beta_{re} l) = -\Delta\beta_{im} \tanh(\Delta\beta_{im} l). \quad (6)$$

The coupling length can be shown to be smaller than $\pi/\Delta\beta_{re}$. When the even and odd modes are excited symmetrically, the coupling length for maximum power transfer efficiency is given by solving

$$\frac{\Delta\beta_{re} \sin(\Delta\beta_{re} l) + \text{Im}(\beta_o) \exp(\Delta\beta_{im} l)}{\text{Im}(\beta_e + \beta_o) \cos(\Delta\beta_{re} l) - \text{Im}(\beta_e) \exp(\Delta\beta_{im} l)} = 1. \quad (7)$$

Assuming that $\text{Im} \beta_e$ and $\text{Im} \beta_o$ are small, and using a Taylor expansion of the arctangent, we find that the coupling length for maximum power transfer also has a value slightly smaller than $\pi/\Delta\beta_{re}$. But these coupling lengths for minimum crosstalk and maximum power transfer efficiency need not be equal as they are solutions of two different equations.

From (6), we find that if the differential absorption $\Delta\beta_{im}$ is small, the crosstalk due to absorption will be very small. For a structure with uniform loss and with a symmetric excitation, the crosstalk reduces to zero. But in reality, absorption is nonuniform, and the input excitation is never symmetric. The coupling length to obtain this idealistic zero crosstalk is not a function of the amount of absorption. The coupling length

is π/β_{re} , just as in the lossless case. In this case, though the crosstalk can be zero and the corresponding coupling length is independent of absorption, the coupling length for maximum power transfer depends on the absorption and is different from that for zero crosstalk.

When losses are uniform throughout the device both longitudinally and laterally, the crosstalk as a function of asymmetry is shown as the intersection of the curves with crosstalk-axis in Fig. 3(b). The coupling length will remain unchanged for different asymmetries when the loss in the device is uniform. If the losses are uniform only laterally, but vary in the longitudinal direction, then the modes will evolve as the structure is changing in the propagation direction and a full propagation analysis is required which we did not pursue in this work. If the even and odd modes are not excited equally and if the losses are uniform or there is no loss, then the minimum possible crosstalk becomes

$$C = \left| \frac{a_e^2 - a_o^2}{a_e^2 + a_o^2} \right|^2 \quad (8)$$

as already shown in [5]. In the case where the losses are uniform throughout the device, the coupling length for maximum power transfer is given by

$$l_c = \frac{2}{\Delta\beta_{re}} \tan^{-1} \left[\frac{-\Delta\beta_{re}}{\text{Im}(\beta_e + \beta_o)} \right]. \quad (9)$$

In the lossless case, the coupling length for the minimum crosstalk as well as for maximum power transfer efficiency reduces to $l_c = \pi/\Delta\beta$. Coupled mode analysis predicts zero minimum crosstalk for a lossless system with symmetric excitation, as in the case just discussed. Coupled mode analysis is applicable when the coupling between the waveguides is weak in which case the input pulse excites the even and odd modes equally. In this approximation, the normal mode and the coupled mode approaches should give identical results. However, in almost all practical situations, the odd mode spreads further outside the guiding region, and the overlap between input to the odd mode is smaller than the overlap between input to the even mode, thus contributing to the fundamental crosstalk limit. Ideally, when the waveguides are far apart and strongly guiding, the crosstalk is negligibly small.

IV. APPLICATION TO A FIELD-INDUCED DIRECTIONAL COUPLER SWITCH

As an example, we calculated the effects of absorption on crosstalk performance in a field-induced waveguide directional coupler switch. The coupler is designed to provide switching of the input power to the adjacent waveguide when cross voltage is applied and to remain in the bar state when no voltage is applied to the waveguide region. We investigated the crosstalk in the cross state. The field-induced waveguides are reported to have high absorption in the cladding region due to proton implantation [14]. A wavelength of 1.15 μm was used. The mode propagation constants were evaluated numerically from slab waveguide analysis [13] for the TE polarization. We assumed a straight coupler without bends. The coupling coefficients of the input to the even and odd modes

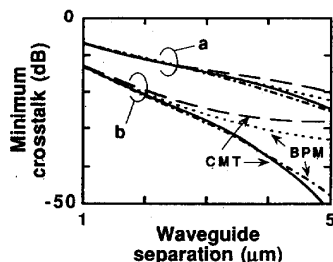


Fig. 4. The crosstalk performance of a lossy field-induced waveguide directional coupler switch. The absorption of the guiding and cladding regions are assumed to be 1 per cm and 5 per cm. The indices of refraction of the guide and cladding regions are (a) 3.405, 3.400 and (b) 3.410, 3.400 respectively. The wavelength of operation is 1.15 μm . The waveguide width is 2 μm . The line curves and the dashed curves show the minimum crosstalk with and without absorption obtained using coupled mode theory (CMT) described in this paper. The dotted curves in (a) and (b) show the crosstalk in a system with absorption as calculated by the direct numerical simulations using the beam propagation method (BPM). Dash-dot curves in (a) and (b) indicate the crosstalk in a system without absorption as calculated by the numerical simulations.

of the coupling region are evaluated from overlap integrals. The index of the cladding region is 3.400 and the index of the guiding region is assumed to be 3.405 and 3.410 in two different cases. The absorption coefficients of the guiding and cladding regions are 1 cm^{-1} and 5 cm^{-1} respectively. We chose a waveguide width of 2 μm so that all waveguides support only the lowest order mode. The waveguide edge-to-edge separation is 1–5 μm . Shown in Fig. 4 is the minimum crosstalk achievable for each configuration and the minimum crosstalk possible when no losses are assumed. Curves in (a) indicate the results obtained with a waveguide index of $n_g = 3.405$ and curves in (b) indicate the results obtained with waveguide index of $n_g = 3.410$. Continuous lines show the crosstalk performance without absorption, and the dashed lines show crosstalk performance with absorption. The crosstalk decreases exponentially as the waveguide separation increases. The crosstalk deterioration due to absorption becomes more severe as the crosstalk decreases as was calculated in the previous section. The crosstalk increase due to absorption is as high as 20 dB in a coupler system with a waveguide separation of 5 μm and a waveguide index of 3.410.

We simulated this directional coupler switch using a finite difference beam propagation method which gives a unified treatment of guided and radiation modes. We measured the minimum possible crosstalk for the same example used in Fig. 4, and the results are shown in Fig. 4 for comparison. Waveguide indices of (a) 3.405 and (b) 3.41 are considered. The dotted curves indicate the results obtained with absorption, and the dash-dot curves indicate the results obtained without absorption. The numerical results agree with theoretical calculations, indicating that the effect of absorption remains severe when radiation is included in the calculations. The performance deterioration is more severe for low crosstalk switches. The presence of radiation can increase the crosstalk significantly [15]. The effects of radiation depend upon the radiation present at the input and the physical dimensions of the device. The BPM calculations included the effects due to the presence of radiation, while these effects are not

included in the eigenmode analysis. As the amount of radiation present is small, it can be seen that the eigenmode analysis is appropriate for evaluating the crosstalk deterioration due to the presence of absorption in the material.

V. CONCLUSION

In conclusion, we have shown that a two-guide symmetric directional coupler has an inevitable crosstalk due to nonuniform losses in the waveguide and cladding regions. This paper presents the fundamental limits on crosstalk performance due to intrinsic material absorption. We used normal mode analysis and evaluated the effect of absorption on crosstalk. We showed that the crosstalk due to absorption cannot be compensated by adjusting the coupling length. The coupling length for minimum crosstalk is not same as the coupling length for maximum power transfer efficiency. The difference in the coupling lengths is not significant for low absorption materials, but the increase in crosstalk due to absorption can be very large. We also calculated the minimum achievable crosstalk. The larger the nonuniformity, the larger the crosstalk. The effect of absorption on crosstalk is more severe when the devices are designed to provide low crosstalk values. The deterioration in crosstalk can be as high as 20 dB. The analysis is in good agreement with numerical simulations. This crosstalk can be compensated in asymmetric couplers, which we have not considered here, by precision tuning the geometric parameters. Even in asymmetric couplers, the elimination of crosstalk due to absorption is only possible in either the bar state or the cross state but not in both.

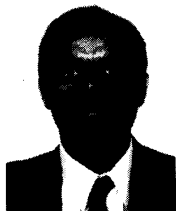
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V. R. Chinni received the Ph.D. degree in 1994 from the University of Maryland, Baltimore, in the areas of computational photonics and integrated optics. His doctoral work included simulation, modeling, and design of integrated optical waveguide devices.

Prior to his doctoral work, he was involved in design and development of high-speed long-distance fiber optic communication systems at Indian Telephone Industries, Bangalore. Currently, he is working with AT&T Bell Laboratories, Holmdel, NJ.



T. C. Huang received the B.S. degree in physics from Jilin University, Jilin, China, in 1982, the M.S. and Ph.D. degrees in electrical engineering from the University of California, Santa Barbara, in 1987 and 1991, respectively. During this Ph.D. research he worked on the design, fabrication, modeling and characterization of integrated optoelectronic devices in III–V compound semiconductors.

From 1991–1994 he was at the Army Research Laboratory, Adelphi, MD, where his work was concerned with optoelectronic components and their applications to lightwave communications and optical signal processing systems. Currently he is at the Hewlett-Packard Laboratories, Palo Alto, CA, engaged in work optoelectronic devices and systems for parallel optical data link.



P. -K. A. Wai was born in Hong Kong on January 22, 1960. He received the B.S. degree from the University of Hong Kong in 1981, and the M.S. and Ph.D. degrees from the University of Maryland, College Park, in 1985 and 1988, respectively.

In 1988, he joined Science Applications International Corporation (SAIC) as a Research Scientist where he worked on the Tethered Satellite project. Since 1990 he has been a Research Associate with the Laboratory of Computational Photonics in the Electrical Engineering Department at the University of Maryland, Baltimore County. His research interests include theory of solitons, modeling of fiber lasers, simulation of integrated optical devices, long distance fiber optic communication, and neural networks.



C. R. Menyuk (SM'88) was born on March 26, 1954. He received the B.S. and M.S. degrees from MIT in 1976 and the Ph.D. degree from UCLA in 1981.

He has worked as a Research Associate at the University of Maryland, College Park, and at Science Applications International Corporation in McLean, VA. In 1986 he became an Associate Professor in the Department of Electrical Engineering at the University of Maryland, Baltimore County, and he was the founding member of this department. In 1993, he was promoted to Professor. For the last few years, his primary research area has been theoretical and computational studies of nonlinear and guided wave optics. Computer codes that he wrote to model the nonlinear propagation of light in optical fibers have been used by industrial, government, and university research groups throughout the United States.

Dr. Menyuk is a member of APS, OSA, and SIAM.

G. J. Simonis, photograph and biography not available at the time of publication.