Twin Core Nonlinear Couplers with Gain and Loss

Yijiang Chen, Allan W. Snyder, and David N. Payne

Abstract—**Twin core nonlinear couplers that include gain and loss are examined. Of various structures (ranging from couplers composed of two active cores and two lossy cores to those composed of one active or lossy core and one conventional core) considered, the most interesting case is the coupler composed of one core with a certain amount of gain and the other core with an equal amount of loss where ideal low power switching is possible in a comparatively short coupler. The presence of gain in one core is found to be responsible for reduction in switching power and/or shortening in the device length, while the introduction of the loss in the other core plays a role of idealizing switching. A physical model is also presented to explain the demonstrated merits based on the operation of linear couplers with gain and loss.**

I. Introduction

The theoretical possibility of a twin core nonlinear coupler functioning as a power dependent switch was first predicted in early 1980's [1]. Later, it was demonstrated experimentally, achieving optical switching at a power level around 850 W with a device length of 2 m [2]. For practical applications, switching power P_s of the order of a kilowatt or more [3] is too high. Although by increasing the core separation, P_s can be made arbitrarily small, the device length must then be increased proportional to $1/P_s$ as couplers are constrained by the fact that the product of switching power P_s and device length L is a constant set by the nonlinear material [4]. Taking typical silica cores as an example, the coupler must be 6×10^5 m long to achieve switching at 1 mW.

Lossless is an idealized condition. In practice, large or small, material loss may be unavoidable, especially when nonlinearities are based on absorptive processes in semiconductors. This absorption, uniformly distributed over the device, was shown to set a limit to the operation of the device [5]. In the following, we will examine nonlinear couplers with both loss and gain, including couplers composed of two active cores, of two lossy cores, of one active and one lossy core, of one active core and one conventional (passive, lossless) core, and of one lossy core and one conventional core. Among them, the most interesting case is the coupler composed of one core with a certain amount of gain and the other core with an equal amount of loss where ideal low power switching is possible in a comparatively short coupler; that is, adverse effects caused by loss [5] here are turned into useful ones. The presence of gain in one core is found to be responsible for reduction in switching power and/or shortening in the device length while the introduction of the loss in the other core plays a role of idealizing switching.

II. Theoretical Framework

Coupled mode theory has proved to be a simple and reliable means for describing the operation of a nonlinear coupler for weak nonlinear perturbations and sufficiently well separated cores [1], [4], [6]. By including gain and loss, such an analysis can still be carried out by simply introducing the imaginary part of propagation constants into the coupled mode equations which for the modal amplitudes $a_{1,2}$ of individual cores read

$$-i\frac{da_1}{dz} = (\beta_1 + i\alpha_1)a_1 + \Delta\beta_1(|a_1|^2)a_1 + Ca_2 \quad (1a)$$

$$-i\frac{da_2}{dz} = (\beta_2 + i\alpha_2)a_2 + \Delta\beta_2(|a_2|^2)a_2 + Ca_1 \quad (1b)$$

where $\beta_j + i\alpha_j$ is the complex modal propagation constant of core j with $\alpha_j > 0$ referring to loss and $\alpha_j < 0$ to gain, C is the linear coupling coefficient [4], $\Delta\beta_j(|a_2|^2)$ is the nonlinearity induced index change of core j which is

$$\Delta\beta_j(|a_j|^2) = \pm 4C|a_j|^2/P_c \quad (2)$$

for the Kerr-law nonlinearity with + and − designating self-focusing and self-defocusing materials, respectively, and P_c is the critical power defined in [1]. The modal fields of each core are so normalized that the power in each core is given by $P_j = |a_j|^2$.

The complex differential equation (1) involves four real equations. Converted to real parameters [7], here called S with $S_1 = |a_1|^2 - |a_2|^2$, $S_2 = a_1a_2^* + a_1^*a_2$, and $S_3 = ia_1^*a_2 - ia_1a_2^*$, Eq. (1) becomes

$$\frac{dS_1}{dz} = -(\alpha_1 + \alpha_2)S_1 - (\alpha_1 - \alpha_2)P + 2CS_3 \quad (3a)$$

$$\frac{dS_2}{dz} = -(\alpha_1 + \alpha_2)S_2 - (\beta_1 - \beta_2 + \Delta\beta_1 - \Delta\beta_2)S_3 \quad (3b)$$

$$\frac{dS_3}{dz} = -(\alpha_1 + \alpha_2)S_3 - 2CS_1 + (\beta_1 - \beta_2 + \Delta\beta_1 - \Delta\beta_2)S_2 \quad (3c)$$

$$\frac{dP}{dz} = -(\alpha_1 + \alpha_2)P - (\alpha_1 - \alpha_2)S_1 \quad (3d)$$

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where $P = P_1 + P_2 = (S_1^2 + S_2^2 + S_3^2)^{1/2}$ is the total power. For a linear coupler or at "low" power, the nonlinearity induced index changes $\Delta\beta_i$ is negligible. Equation (1) or (3) is then solvable analytically. In terms of the modal amplitudes $a_{1,2}$, the solution has the form

$$a_1(z) = \Big\{a_1(0)\cos\left(\frac{C}{F}z\right) + iF\left[a_2(0) + \frac{\beta_1 - \beta_2 + i(\alpha_1 - \alpha_2)}{2C}a_1(0)\right] \cdot \sin\left(\frac{C}{F}z\right)\Big\}\exp\left[\left(i\frac{\beta_1 + \beta_2}{2} - \frac{\alpha_1 + \alpha_2}{2}\right)z\right] \tag{4a}$$

$$a_2(z) = \Big\{a_2(0)\cos\left(\frac{C}{F}z\right) + iF\left[a_1(0) - \frac{\beta_1 - \beta_2 + i(\alpha_1 - \alpha_2)}{2C}a_2(0)\right] \cdot \sin\left(\frac{C}{F}z\right)\Big\}\exp\left[\left(i\frac{\beta_1 + \beta_2}{2} - \frac{\alpha_1 + \alpha_2}{2}\right)z\right] \tag{4b}$$

with

$$F = \left\{1 + \left[\frac{\beta_1 - \beta_2 + i(\alpha_1 - \alpha_2)}{2C}\right]^2\right\}^{-1/2}. \tag{4c}$$

In the presence of nonlinearity, closed form analytical solutions of (1) or (3) for $\alpha_j \neq 0$ seem not possible. We solve it numerically. The results are shown in Fig. 1 for gain or loss coefficients $\alpha_1/C = \alpha_2/C = \pm(\alpha/C) = 0$, ± 0.1, ± 0.3, ± 0.6, ± 0.9 and the coupler length $L_c = \pi/2C$, over which complete power is transferred from the feed core to the branch core at "low" power. For the lossy couplers ($\alpha_j/C > 0$) of Fig. 1(a), switching power is observed to increase with increasing ratio α_j/C while the switching characteristics deteriorate. The switching power is defined here as that necessary for 50% power transfer which from Fig. 1 is observed to occur when $P = P_c$ for $\alpha_j = 0$. The interesting cases are in Fig. 1(b) where the switching power decreases with increasing ratio $-(\alpha_j/C)$, indicating that material gain can reduce the switching power without increasing device length. Unfortunately, the switching features degrade when $|\alpha_j/C|$ is large especially as $\alpha_j/C \to -1$. Thus, we conclude that gain or loss uniformly distributed over two cores may erode the operation of a twin core nonlinear coupler functioning as a switch.

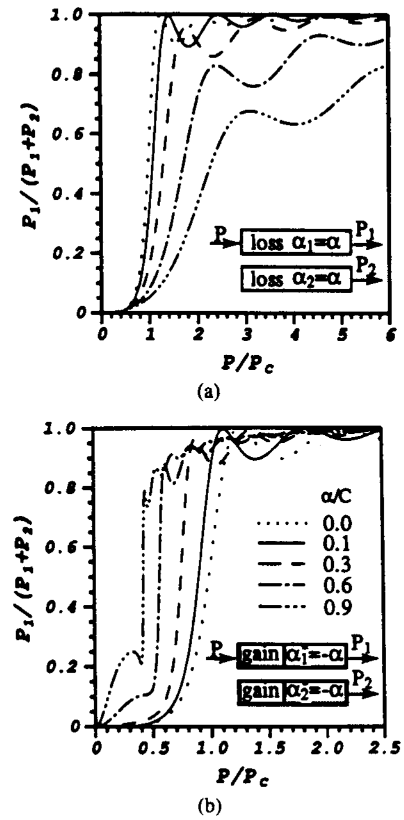

Fig. 1. Switching characteristics of nonlinear couplers composed of two self-focusing cores with loss or gain uniformly distributed in the two cores. (a) Lossy couplers. (b) Active Couplers. The line identification is given in (b) and $\alpha/C = 0$ identifies the conventional nonlinear coupler.

III. Low Power Switching by Short Active Couplers

Loss or gain uniformly distributed over the device deteriorates its operational characteristics. Can this detrimental effect be converted to a useful one? What are the switching characteristics of nonlinear couplers composed of two cores with different loss and/or gain coefficients? Is it possible to achieve complete power transfer from the feed core to the branch core when the cores are mismatched in the presence of gain and loss? These questions are to be addressed in this section.

A. Coupling Length

The operation of a nonlinear coupler functioning as a switch is based on the fact that at "low" power all the power initially launched into one core is swapped to the other core within a coupling length (which is equal to L_c for two identical cores) and that at high power all the power remains in the feed core due to the intensity induced mismatch. In the presence of a linear mismatch $M_r = |\beta_2 - \beta_1|/2C$, complete power transfer between the two guides at "low" power is not possible. This, however, is not the case for the mismatch

$$M_i = (\alpha_2 - \alpha_1)/2C$$

stemming from the difference in the imaginary part of the modal propagation constants of the individual cores. Specifying initial excitations to be $a_1(0) \neq 0$ and $a_2(0) = 0$ with $M_r = 0$, (4) reduces to

$$a_1(z) = a_1(0)\left[\cos\left(\frac{C}{F}z\right) + M_iF\sin\left(\frac{C}{F}z\right)\right] \cdot \exp\left(i\frac{\beta_1 + \beta_2}{2}z - \frac{\alpha_1 + \alpha_2}{2}z\right) \tag{5a}$$

$$a_2(z) = ia_1(0)F \sin\left(\frac{C}{F}z\right) \cdot \exp\left(i\frac{\beta_1+\beta_2}{2}z - \frac{\alpha_1+\alpha_2}{2}z\right) \quad (5b)$$

with F simplified to $F = (1 - M_i^2)^{-1/2}$. At the coupling length

$$L = L_c\left(1 + \frac{2}{\pi}\sin^{-1} M_i\right)\Big/\sqrt{1 - M_i^2} \quad (6)$$

one has $a_1(L) = 0$ provided $|M_i| < 1$. Thus even with the mismatch $M_i \neq 0$ complete power transfer between the two cores is possible. This provides the basis for an active coupler with different loss and gain coefficients between two cores to function as a switch as shown in the following.

B. Low Power Switching by Couplers Composed of Two Self-Focusing Cores

Setting the coupler length to be L of (6) and taking the upper sign in the nonlinearity induced index changes of (2), we examine the fraction of the output power in the feed core versus the input power for the case of $\alpha_1 = -\alpha_2$, i.e., the feed core has a certain amount of gain while the branch core has an equal amount of loss. Solving (3) with $\beta_1 = \beta_2$ we find that gain and loss within $0 < M_i < 1$ can improve a nonlinear coupler's performance dramatically. Fig. 2 illustrates the switching feature of the couplers for several different M_i. The closer the mismatch M_i approaches 1, the greater the improvement. Note that the improvement here is reflected in two aspects. One is the reduction in switching power and the other is idealization of switching. (Ideal switching is characterized by a step function.) Although the length of the device increases with increasing M_i, this increase is much smaller compared with that required for the conventional (passive, lossless) coupler assuming an equal amount of the power reduced. Recall that conventional nonlinear couplers are constrained by the fact that the product of switching power and device length is a constant set by the nonlinear material. By introducing a certain amount of gain in one core and an equal amount of loss in the other core, this constant is reduced and the reduction is significant as $M_i \to 1$. This is shown in Fig. 3 where P_s is the switching power defined as that necessary for 50% power transfer. The relation between the constant P_sL and the mismatch M_i illustrated in the figure can well be approximated by

$$P_sL = \nu P_cL_c(1 - M_i) \quad (7)$$

where $\nu = 1$ for $M_i < 0.9$ and $\nu = 1.25$ for $M_i \geq 0.9$. Given the device length in terms of the mismatch in (6), the switching power P_s can then be expressed as a function of the mismatch M_i alone upon substitution of (6) into (7). Fig. 4 is the illustration of P_s and L versus M_i. Here we observe that significant reduction in switching power occurs as $M_i \to 1$. For this interesting case, (6) is simplified to

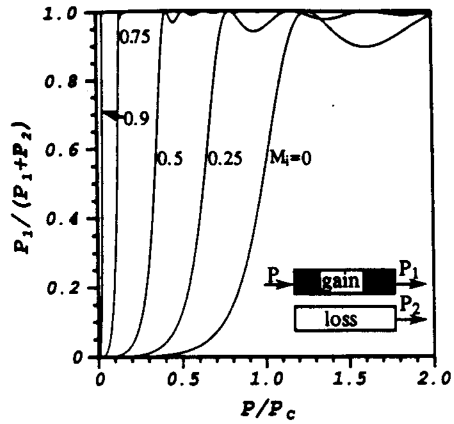

Fig. 2. Switching characteristics of couplers composed of two self-focusing cores with one core having a certain amount of gain and the other core having an equal amount of loss for different mismatches $M_i = (\alpha_2 - \alpha_1)/2C$. $M_i = 0$ is referred to the conventional nonlinear coupler.

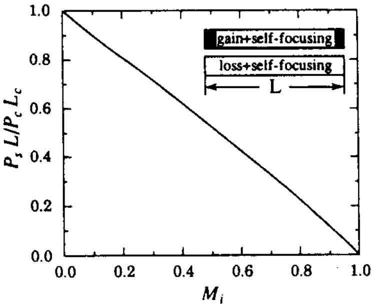

Fig. 3. The product of switching power P_s and coupler length L versus mismatch $M_i = (\alpha_2 - \alpha_1)/2C$ for the couplers of Fig. 2.

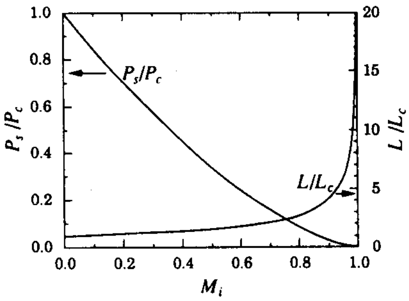

Fig. 4. The switching power (on the left scale) and the coupler length (on the right scale) versus M_i for the couplers of Fig. 2.

$$L \cong \sqrt{2}L_c/\sqrt{1 - M_i} \quad (8)$$

while the switching power is found from (7) to be

$$P_s \cong 0.884(1 - M_i)^{3/2}P_c. \quad (9)$$

As aforementioned, the conventional nonlinear coupler has the property of the switching power times the device length equal to a constant set by the material nonlinearity. However, from (8) and (9) we find that for an active coupler

$$\frac{P}{P_s} = 2.5\left(\frac{L_c}{L}\right)^3. \quad (10)$$

In other words, the switching power is reduced by $1/L^3$ instead of $1/L$ as in a conventional coupler.

Equation (9) or Fig. 4 indicates that arbitrary low switching power occurs by setting $M_i \rightarrow 1$. This requires a length $L/L_c \rightarrow \infty$ as shown in (8) or Fig. 4. Accordingly, the minimum device length for a given switching power P_s is achieved with touching cores, capitalizing on the fact that the length L_c for the linear coupler is then physically smallest. However, for the touching cores, the coupling coefficient C is the maximum possible, and hence requires the maximum material gain. For the example of Fig. 5, this needs a gain or loss of approximately 16 600 dB/m. The necessary length versus the switching power is shown in Fig. 5(a). This length is orders of magnitude less than that for the conventional coupler of Fig. 5(b). For example, 0.2 m is needed for a switching power of 0.1 W instead of 5000 m for the conventional coupler.

Based on the present technology, the available gain may not be sufficient for the optimum switch of Fig. 5(a). For an achievable gain of 20 dB/m [8], the minimum length necessary for a specified power is found from (6) leading to Fig. 6. Comparing Fig. 6 with Fig. 5(b) it is observed that for a given device length, the switching power is significantly reduced though not as dramatically as for that in Fig. 5(a). For instance, 6 m is required for a switching power of 2 W instead of 300 m for the conventional nonlinear coupler.

The active nonlinear coupler with a certain amount of gain in one core and an equal amount of loss in the other core (ANCGL), demonstrated here, offers the advantage of both shortening the device length and idealizing switching over the conventional nonlinear coupler. For shortening of the device length at a given switching power alone, this, however, may also be realized by the compound device consisting of a conventional nonlinear coupler plus a preamplifier. Consider the example of the switching power of 2 W and the preamplifier of single core fiber 2 m long, which produces 40 dB of gain. The length of the conventional nonlinear coupler to switch at 2×10^4 W is 3 cm. Thus the total length of the compound device to achieve switching of 2 W is 2.03 m which is shorter than that of ANCGL. In fact, if the idealization of switching is not concerned, low power switching in a short active coupler can be achieved alternatively by the active nonlinear coupler composed of an active core and a conventional core (ANCGC). Still assume switching power of 2 W. The required device length of ANCGC is 2.2 m. But the switching characteristic becomes unacceptable with increasing M_i as shown in Fig. 7.

Although the active nonlinear coupler with a certain amount of gain in one core and an equal amount of loss in the other core achieves low power switching in a device length relatively longer than the compound device and ANCGC, the ideal switching it offers can never be realized by the other two schemes. The ANCGL would appear unique in this respect. Here, the slightly longer length of ANCGL is due to the loss introduced in one core which

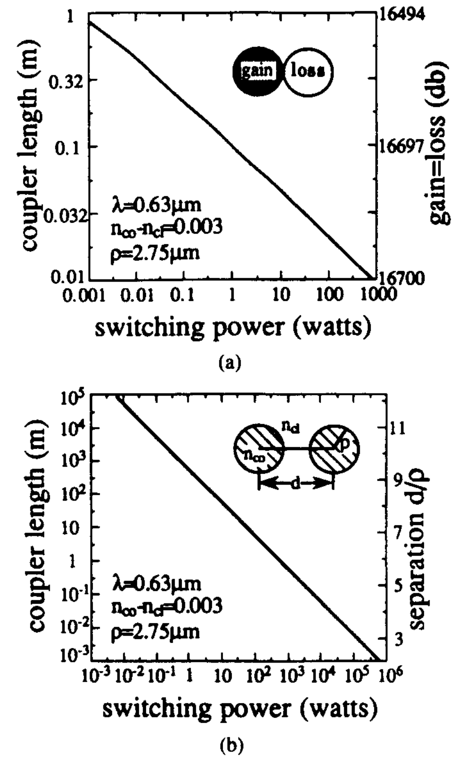

Fig. 5. Comparison of the minimum device length for a conventional switch in (b) with one with a material gain of approximately 16 600 dB/m in core 1 and an equal amount of loss in core 2 in (a) where ρ is the core radius, λ is the wavelength, and n_{co} and n_{cl} are the refractive indexes of the core and cladding, respectively.

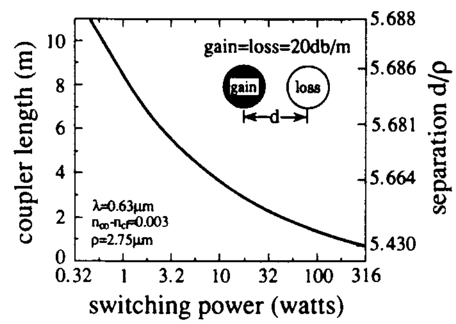

Fig. 6. Minimum device length for a practical coupler with a material gain of 20 dB/m in one core and a loss of 20 dB/m in the other core where ρ, λ, n_{co}, and n_{cl} are defined in the caption of Fig. 5.

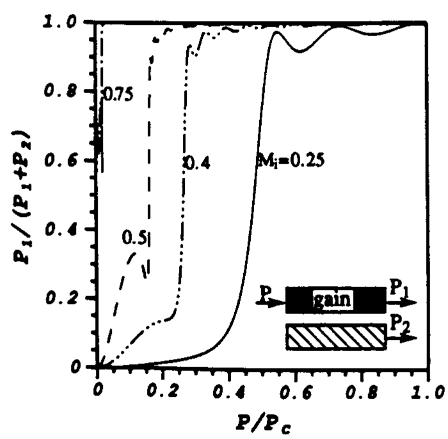

Fig. 7. Same as Fig. 2 but core 2 is passive and lossless.

plays a role of idealizing switching but at expense of counteracting some of the benefits of the gain.

For practical applications, the total loss or gain of a device may also be concerned. The total output power of the ANCGL here is always greater or equal to the total input power. At "low" power, the total output power is equal to the total input power. But at "high" power, the total input power is amplified by the amount of gain in the active core multiplied by L.

C. Couplers Composed of One Self-Focusing Core and One Self-Defocusing Core

A lossless, passive coupler composed of one self-focusing and one self-defocusing core achieves switching at power 0.4 P_c, 2.5 times lower than the corresponding one composed of two self-focusing cores. Similarly, introducing a certain amount of gain in the core with the positive Kerr coefficient and an equal amount of loss in the core with the negative Kerr coefficient, the switching power can be reduced dramatically when $M_i \to 1$, as Fig. 8 shows. The corresponding product of switching power P_s and device length L versus the mismatch M_i is shown in Fig. 9. Comparison of Fig. 9 with Fig. 3 demonstrates that the constant P_sL for the coupler with opposite sign Kerr coefficients decreases more quickly with increasing M_i than that with the identical sign Kerr coefficient. This indicates that for a given length L the switching power for the coupler of Fig. 9 is reduced more rapidly with increasing M_i than that for the coupler of Fig. 3. For example, at length $L = 1.54\ L_c$, $M_i = 0.5$ gives switching power $P_s = 0.086\ P_c$ for the coupler composed of one self-focusing and one self-defocusing core, whereas it produces only $P_s = 0.34\ P_c$ for the coupler composed of two self-focusing cores. With M_i increased to 0.75 at length $L = 2.33\ L_c$, the switching power for the former reduces to 0.02 P_c while that for the latter is 0.12 P_c.

IV. Discussions

In the last section, it is shown that switching power of a nonlinear coupler can be reduced significantly by introducing a certain amount of gain in one core and an equal amount of loss in the other core or by introducing gain in one core and leaving the other core passive and lossless. This can in fact be anticipated from the linear coupler with loss and gain or with gain in one core only (see Appendix). Such a coupler is acute sensitive to minute differences in the real part of the refractive index between the cores in the presence of gain and loss especially when $M_i \to 1$. Illustrated in Fig. 10 is the fraction of the output power in the feed core versus the mismatch $M_r = |\beta_2 - \beta_1|/2C$ that arises from the differences in the real part of the refractive index of the cores for an active linear coupler with the length L. As M_i increases toward 1, the mismatch M_r required for the 50% power switch decreases, bearing a strong resemblance to the switching characteristic of the active nonlinear coupler of Fig. 2 provided

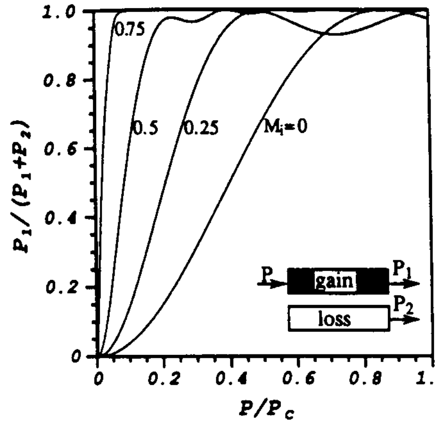

Fig. 8. Switching characteristics of couplers composed of one self-focusing core with a certain amount of gain and one self-defocusing core with an equal amount of loss for different M_i.

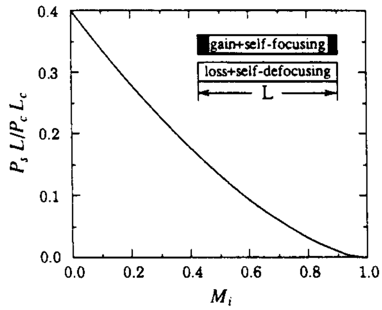

Fig. 9. The product of switching power P_s and coupler length L versus M_i for the couplers of Fig. 8.

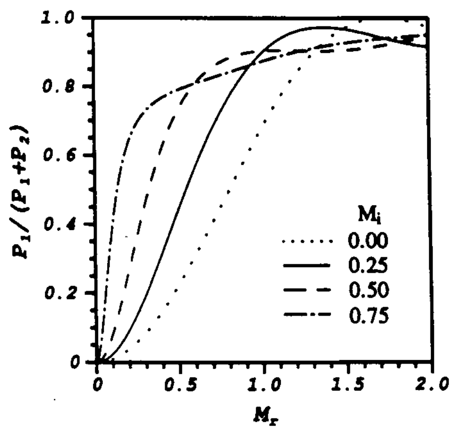

Fig. 10. The percentage of the power at the output of the feed core of an active linear coupler with the coupling length L of (6) versus the mismatch $M_r = |\beta_2 - \beta_1|/2C$ for different M_i. $M_i = 0$ identifies the conventional linear coupler.

that M_r in the transverse coordinate here is replaced by the input power there. In the nonlinear coupler, the index difference results from the power induced index change. Accordingly, the linear model anticipates the merit of the active nonlinear coupler as in a conventional coupler [4]. However, in the nonlinear case, the sensitivity of power transfer to the power induced refractive index difference between the cores is further exaggerated because the ini-

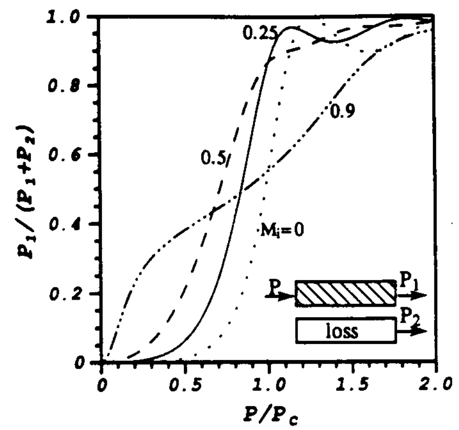

Fig. 11. Same as Fig. 2 but core 1 is passive and lossless.

tial mismatch is amplified with the propagation distance along the active core. This is manifested clearly by comparing Figs. 2 and 7 with Fig. 10.

As mentioned earlier, loss introduced into one core in ANCGL of Fig. 2 gives rise to ideal switching, although it counteracts some of the benefits of the gain. Naturally, one then might wonder whether loss alone introduced into one core of a conventional nonlinear coupler would lead to an improvement in switching. Our study shows that the introduction of loss into one core of a conventional nonlinear coupler without the accompanying gain in the other core unfortunately does not improve switching, rather it results in unacceptable operational characteristics as Fig. 11 shows. Therefore, only the combination of one core having a certain amount of gain with the other core having an equal amount of loss works miraculously to yield ideal low power in a short length.

V. Conclusion

Nonlinear couplers that include gain and loss are investigated. By introducing a certain amount of gain in one core and an equal amount of loss in the other core, ideal low power switching is found possible in a comparatively short coupler. Ultralow power switching in a short coupler requires larger gain.

Appendix

Linear Twin Core Couplers with Gain and Loss

Here we give details of a linear coupler with loss and gain.

A. Normal Modes

Diagonalizing the coupled mode equations (1) with $\beta_1 = \beta_2 = \beta$ and $\Delta\beta_1 = \Delta\beta_2 = 0$ directly leads to the normal modes $E_{a,b}$ of the structure [9]

$$E_{a,b} = N_{a,b}(\psi_1 + \gamma_{a,b}\psi_2) \cdot \exp\left[\left(i\beta - \frac{\alpha_1+\alpha_2}{2} \pm iC\sqrt{1-M_i^2}\right)z\right] \quad \text{(A1)}$$

for $|M_i| \neq 1$, where M_i is defined as $M_i = (\alpha_2 - \alpha_1)/2C$, $\gamma_{a,b} = iM_i \pm \sqrt{1-M_i^2}$, $\psi_{1,2}$ are the modal fields of individual cores and $N_{a,b}$ are the normalization constants or modal amplitudes determined by initial excitation. At the critical point, i.e., $|M_i| = 1$, the two modes become degenerate and are then indistinguishable from each other

$$E_a = E_b = \left[\left(iN_a\frac{\alpha_1-\alpha_2}{2}z + N_b\right)\psi_1 - \frac{M_i}{|M_i|}\left(N_a\frac{\alpha_1-\alpha_2}{2}z + N_a - iN_b\right)\psi_2\right] \cdot \exp\left[\left(i\beta - \frac{\alpha_1+\alpha_2}{2}\right)z\right]. \quad \text{(A2)}$$

B. Power in Each Core with Core 1 Initially Excited

Taking the absolute square of (5) yields power in each core

$$P_1(z) = P_1(0)\exp[-(\alpha_1+\alpha_2)z]\begin{cases} 1 + F^2(2M_i^2-1)\sin^2\frac{C}{F}z + M_iF\sin\frac{2C}{F}z & |M_i| < 1 \\ \left(1+\frac{\alpha_2-\alpha_1}{2}z\right)^2 & |M_i| = 1 \\ 1 + |F|^2(2M_i^2-1)\sinh^2\frac{C}{|F|}z - M_i|F|\sinh\frac{2C}{|F|}z & |M_i| > 1 \end{cases} \quad \text{(B1)}$$

$$P_2(z) = P_1(0)\exp[-(\alpha_1+\alpha_2)z]\begin{cases} F^2\sin^2\frac{C}{F}z & |M_i| < 1 \\ C^2z^2 & |M_i| = 1 \\ |F|^2\sinh^2\frac{C}{|F|}z & |M_i| > 1 \end{cases} \quad \text{(B2)}$$

where F is defined in (4c).

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