C for a 250:1 taper. At point a, about 10 μm before C, the top diagram in Fig. 14 shows that the waveguide mode still retains 94 percent of the original intensity, while the lower left diagram shows the intensity distribution of the radiation at point a. At point b, about 3 μm from cutoff, 67 percent of the original power remains in the waveguide mode. At closer approaches to cutoff, points c and d, the power in the waveguide mode rapidly drains out. Correspondingly, we observe in the lower diagrams of Fig. 14 a sharp rise in the radiation intensity from point b to c to d.

At point d, the intensity distribution of the radiation is peaked at the grazing angle $\theta_r = 90°$, which agrees neither with experimental observation nor with the ray analysis. The difficulty involved here is the factor $1/(\beta^2 - \beta_r^2)$ in (15), which enhances the coupling to the substrate modes with $\theta_r \cong 90°$ as β approaches kn_0. In reality, as power is converted from the waveguide mode to radiation modes, β of the waveguide mode should be a complex number instead of the real number used in the present calculation. A more elaborate wave analysis involving complex propagation constants and including losses of the film is being studied.

VII. CONCLUSIONS

We have measured the radiation patterns of tapered thin-film optical waveguides. The radiation emerges from a certain point in the taper where the waveguide mode becomes cutoff and appears as a narrow beam of light inside the substrate. The half-intensity angular width of the radiation is 3.8° for a 120:1 taper, and is reduced to only 2.5° for a 300:1 taper; the radiation intensity peaks are at about 5° and 3.5°, respectively. For a given taper, different waveguide modes have nearly the same radiation pattern. We were able to explain all these phenomena by a simple ray-optics analysis, though the calculated radiation patterns were slightly wider than those observed experimentally. We also have studied the problem using a more rigorous wave analysis. Although we obtained a correct width for the radiation pattern, the intensity distribution was incorrect, indicating the needs for a more elaborate wave analysis with complex propagation constants.

By collecting the radiation in the substrate with an optical fiber, we have constructed a novel film-to-fiber coupler. This coupler has the advantage that the surface of the waveguide film is untouched and is left free for the fabrication of an integrated optical circuit. Because the radiation from a tapered film is very close to the film–substrate interface, construction of this type of coupler may be difficult for use with fibers having core diameters of less than 50 μm.

ACKNOWLEDGMENT

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REFERENCES

[1] P. K. Tien and R. J. Martin, *Appl. Phys. Lett.*, vol. 18, p. 398, 1971.
[2] D. Marcuse, *Bell Syst. Tech. J.*, vol. 48, p. 3187, 1969; also *Bell Syst. Tech. J.*, vol. 49, p. 273, 1970.
[3] P. K. Tien, G. Smolinsky, and R. J. Martin, *Appl. Opt.*, vol. 11, p. 638, 1972.
[4] P. K. Tien, *Appl. Opt.*, vol. 10, p. 2395, 1971.
[5] M. Born and E. Wolf, *Principles of Optics*. New York: Pergamon, 1959, p. 37.
[6] P. K. Tien, R. J. Martin, and G. Smolinsky, *Appl. Opt.*, vol. 12, p. 1909, 1973.

Tapered Optical Directional Coupler

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***Abstract*—Tapered velocity optical directional couplers showing 100-percent coupling have been fabricated in thin film form. A computer analysis shows that this type of coupler has greatly improved tolerance properties and does not, in particular, suffer from the severe tolerance restriction placed on velocity synchronism in conventional uniform couplers.**

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I. INTRODUCTION

THE AIM of current research in integrated optics is to develop a wide range of miniature optical components which will provide the means of generating, controlling, and detecting optical signals. The directional coupler is one such passive component which is a basic element in any waveguide system and which has direct application to multiplexing and modulation. Many designs of coupler are possible and in principle these may be developed from their microwave counterparts. However, the change to very much shorter wavelengths introduces serious problems.

At optical wavelengths severe tolerance restrictions are placed on both the dimensions and the material parameters of a given device. This is well illustrated by considering the difficulties involved in the fabrication of a conventional synchronous coupled mode directional coupler formed by two parallel uniform waveguides in close proximity. Assuming that uniform guides can be achieved, the coupled modes must remain in or very near synchronism over the coupling length if appreciable interchange of mode power is to occur. Further, the coupling length must be defined in some way so that the required power division is obtained. Both these considerations lead to severe tolerance restrictions on the transverse dimensions of the structure. In practice, nonuniformities in the guides would usually contribute to the uncertainty of achieving the desired power division.

The purpose of this paper is to examine the particular tolerance restrictions associated with this coupler and then to show that they may be greatly relaxed by tapering the velocity of one or both modes.

Finally, experimental results are presented for tapered velocity thin film directional couplers having 100-percent coupling efficiency.

II. THE UNIFORM DIRECTIONAL COUPLER

The simplest form of directional coupler comprises two waveguides supporting two synchronous modes, respectively, uniformly coupled over a length z with a coupling coefficient c. If the waveguides 1 and 2 are excited by unit and zero amplitudes, respectively, at $z = 0$, then the mode amplitudes at z are given by

$$a_1 = \cos cz \exp(-j\beta z) \tag{1}$$

$$a_2 = j \sin cz \exp(-j\beta z) \tag{2}$$

where β is the propagation coefficient of the coupled modes. To attain 100-percent coupling in a length l, the following condition must be satisfied:

$$cl = \pi/2. \tag{3}$$

Fabrication of the coupler may introduce errors in l, in the transverse dimensions of the waveguides and in the spacing between the waveguides. Typically, l is of the order 50–5000 μm and (2) and (3) show that the output power $|a_2|^2$ is not critically dependent on l and may easily be maintained at or near unity with the fabrication techniques now available for defining such lengths.

Although the effects of transverse dimensional errors on the coupling coefficient are important [1], [2] they are not usually the limiting sources of error. It is maintenance of velocity synchronism which constitutes the most serious problem and which will be considered later.

If, due to a fabrication error, the propagation coefficients β_1 and β_2 differ by an amount $\Delta\beta$, then (1) and (2) must be modified to give

$$a_1 = [\cos pz - j(\delta/p) \sin pz] \exp -j(\beta_1 - \delta)z \tag{4}$$

$$a_2 = j(c/p) \sin pz \exp -j(\beta_2 + \delta)z \tag{5}$$

where

$$\Delta\beta = 2\delta = \beta_1 - \beta_2 \tag{6}$$

$$p = +(\delta^2 + c^2)^{1/2}. \tag{7}$$

If a 100-percent coupler, designed for synchronism with $cl = \pi/2$, develops an error $\Delta\beta$ during fabrication, then the resulting coupled output power found from (5) is

$$|a_2|^2 = (c/p)^2 \sin^2 pl. \tag{8}$$

A simple expression for the degradation caused by $\Delta\beta$ can be derived from (8). A nominally 100-percent coupler, of length N wavelengths would degrade to 50-percent coupling if

$$\frac{\Delta\beta}{\beta} = \frac{0.4}{N}. \tag{9}$$

Equation (9) can be derived by putting $|a_2|^2 = 1/2$ and using (3), (6), and (8), together with $l = N\lambda = 2\pi N/\beta$ to solve for $\Delta\beta/\beta$.

As N is typically in the range 100–10 000, (9) shows that there is a severe tolerance restriction on the synchronism condition. In practice this must be related to the dimensional tolerance. For example, it can be shown that for the case of coupled thin film waveguides the tolerance on guide thickness to achieve mode synchronism is smaller by at least an order of magnitude than the other tolerances mentioned earlier [2], and so is the limiting factor in coupler fabrication. Although the situation could be eased by working well away from cutoff, it is clearly undesirable to operate the waveguides under multimode conditions.

Despite these difficulties several mode coupling experiments have been performed [3]–[5]. The coupled thin film configuration is probably the easiest to fabricate as no masking process is required. However, the films are made sequentially and it is difficult to obtain the synchronism condition immediately. Step-by-step increases in the thickness of the top film can be made until synchronism can be observed.

Two modes in a single waveguide can be coupled together if a suitable periodic perturbation is present [6]. Again, a tolerance problem exists unless the perturbation period can be varied as in the case of an acoustically perturbed device. Even with a fixed perturbation, such as a deposited grating, some adjustment is possible if the angle between the grating and the incident beam is varied.

The side by side configuration with, for example, coupled rib waveguides, requires precise fabrication facilities but provides the opportunity of fabricating identical or near identical waveguides [7]–[10].

Whichever configuration is chosen, some fabrication technique must be chosen whereby the coupling length is defined so that the required power division is obtained.

III. THE TAPERED VELOCITY COUPLER

A. Description

The situation would be eased if the synchronism conditions over the whole length of the coupler could be relaxed. Suppose one or both of the propagation coefficients β_1 and β_2 vary with distance so that they cross at one position only as shown in Fig. 1(a). Complete transfer of power as shown in Fig. 1(b) is still possible if $d\beta_2/dz$ is sufficiently small for a given coupling coefficient. The "effective coupling length" is centered at the intersection of the propagation coefficients. If by some tolerance error, β_2 is in error, then, so long as the error is less than $\Delta\beta(0)$, there will still be an intersection of β_1 and β_2 and complete coupling will still occur.

This form coupling has been discussed previously [11] in the context of broad-band microwave directional couplers. Analytical results were obtained for particular propagation-coefficient profiles. However, it does not follow necessarily that a broad-band device is free from tolerance errors. The synchronous coupler with uniform coupling between identical guides is frequency sensitive only because the coupling coefficient is usually a function of frequency. Even if this coupling coefficient were to be broad banded, the device would still be susceptible to tolerance errors in the propagation coefficients.

At first sight it may appear that complete coupling will be obtained at only one angle of intersection of β_1 and β_2 so that the structure will again suffer from tolerance restrictions. It is shown in the following that 100-percent coupling can be obtained for a wide range of angles of intersection and of coupling coefficient.

B. Theory: A Computer Analysis

The general problem of two coupled modes having spatially varying propagation and coupling coefficients has been solved analytically only for special cases [11]. The results are not expressed in simple explicit terms and the task of evaluating changes of coupler performance with changes in the taper profile by perturbation methods would not be easy. It was therefore considered preferable to solve the problem numerically. Using this technique, any profile can be treated and variations of mode amplitude and phase with distance can be automatically plotted.

Equations (10) and (11) were applied to successive elementary lengths:

$$a_1 = \{a_1(0)[\cos pz - j(\delta/p)\sin pz] + a_2(0)(jc/p)\sin pz\}\exp[-j(\beta_1 - \delta)z] \quad (10)$$

$$a_2 = \{a_2(0)[\cos pz + j(\delta/p)\sin pz] + a_1(0)(jc/p)\sin pz\}\exp[-j(\beta_2 + \delta)z]. \quad (11)$$

It was assumed that the coupling coefficients remained constant. In practice, a change in β brings about a small change in c, but this is of second order and the results show that it has negligible effect.

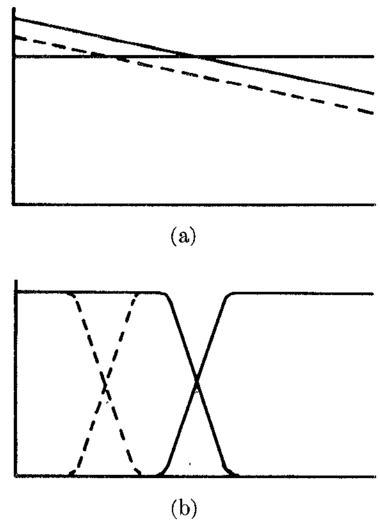


Fig. 1. Power transfers from mode 1 to mode 2 when propagation coefficients intersect. Error in β_2 merely moves point of intersection. (a) Propagation coefficients. (b) Mode power against distance.

The initial calculations were made for the case of a taper of length 1000 wavelengths, with modes 1 and 2 excited with unit and zero amplitudes, respectively, at the taper input. Calculations were made using a wide range of values for c and $\Delta\beta(0)$. It was found that the output coupled power lay between 0 and 100 percent and that the variation of mode power with distance was typically as shown in Figs. 2 and 3 (although these particular examples were calculated for longer taper lengths). These initial results are summarized in Fig. 4.

As can be seen in Figs. 2 and 3, the main interaction takes place within a length which is determined by the coupling coefficient c and the angle of intersection of the propagation coefficient profiles which is given here by $d\beta_2/dz$. For operation which is tolerant to changes in β_1 or β_2, this effective coupling length should be significantly shorter than the total length of the taper.

Although for a particular value of coupling less than 100 percent the precise values of c and $d\beta_2/dz$ (i.e., $\Delta\beta(0)$ for a given taper length) must be defined, the tolerance restrictions imposed on them are not severe. Consider the 50-percent coupling achieved in Fig. 2. Increasing the taper length by 25 percent increases the coupling to 60 percent. Similarly, increasing the value of coupling coefficient by 25 percent increases the coupling to 62 percent. This latter increase is *less* than would occur in a uniform coupler having the same coupling coefficient.

The particularly interesting result is that 100-percent coupling can be obtained for a range of values of both c and $d\beta_2/dz$. Changes of ± 50 percent in the values of c and $\Delta\beta(0)$ need cause changes of only one or two percent in the coupled output power. It is this particular mode of operation which is investigated experimentally in the following.

If for a given value of c, $\Delta\beta(0)$ is too small, then significant interchange of power occurs over the whole length

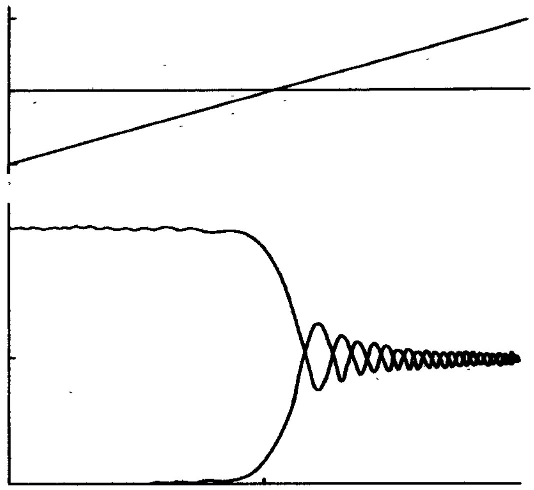


Fig. 2. Typical interaction showing 50-percent coupling. Coupling coefficient $c = 0.002\ \mu m^{-1}$, $k = 2\pi/\lambda$ where $\lambda = 0.6328\ \mu m$.

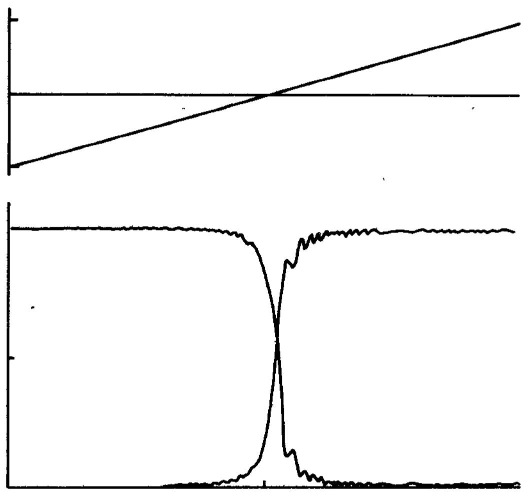


Fig. 3. Typical interaction showing 100-percent coupling. c and k are as in Fig. 2 but taper length has been increased.

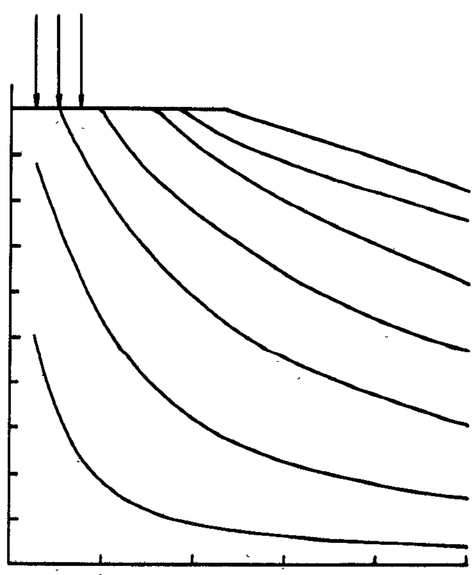


Fig. 4. Computed variation of power transfer, for a linear taper (over a length of 1000 wavelengths) with slope of taper and with coupling coefficient as a parameter. Operation at values of $\Delta\beta(0)/\beta$ below limit shown by arrow for a given c/β, involves interaction over whole length of taper, and consequent undesirable power oscillation.

of taper. This corresponds with too large a value of c/p in (5) and is usually avoided in practice.

Fig 4 illustrates the general behavior of the tapered coupler although the values of c and $\Delta\beta(0)$ used in subsequent experiments were somewhat less than those suggested by the scales of Fig. 4; the practical taper lengths used were longer than 1000 wavelengths.

It should be emphasized that the results shown in Fig. 4 do not imply that improved tolerance can be achieved only with parameter values within the range used in that diagram. The coupling would remain unchanged if for example both c and $\Delta\beta(0)$ were scaled by the same factor (so ensuring the same value of c/p) and the taper length scaled by some other appropriate factor. Extensive scaling was not explored and all subsequent calculations were made using parameters which were directly relevant to experimental couplers.

Fig. 2 shows an example of 50-percent coupling. It is seen that the ripple in power at the output is considerably larger than that at the input. This is entirely in accordance with (10) and (11).

To obtain 100-percent coupling, either c could be increased or $\Delta\beta(0)$ reduced for the same length of taper. However, both these methods would increase the ratio c/p and increase the ripple in power over the whole taper. To avoid this, the coupling is increased by increasing the taper length; the result is shown in Fig. 3.

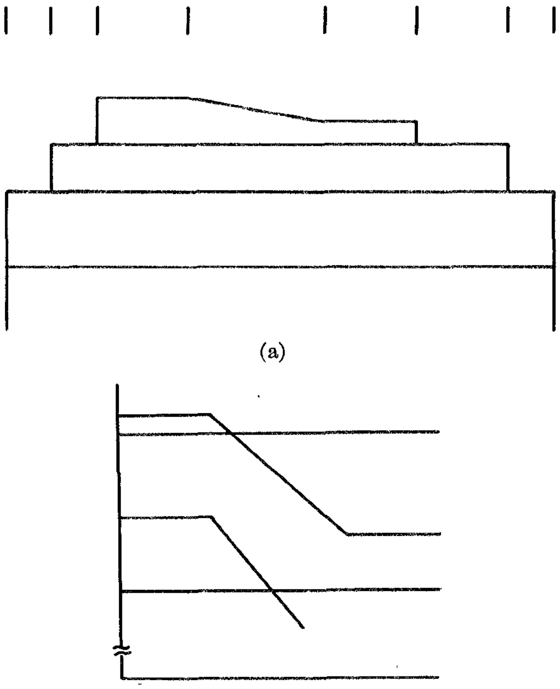
IV. EXPERIMENTAL WORK

A. Design and Fabrication

A coupled thin film waveguide geometry was chosen for the experiments. Glass films were sputtered onto standard soda lime glass microscope slides. Normally, a three film structure would be sputtered from at least two different glasses. In the present work all three films were sputtered from a single target by means of a technique developed in this laboratory by Pitt *et al.* [12]. Both the waveguide films and the spacer film were made from Corning 7059 glass, sputtered in a 80-percent argon:20-percent oxygen atmosphere at a pressure of 2×10^{-3} torr. The refractive index of the 7059 glass was controlled by the deposition rate, higher index values being obtained at higher deposition rates. This technique avoided material interface problems and the need for interchanging the targets during a sputtering run.

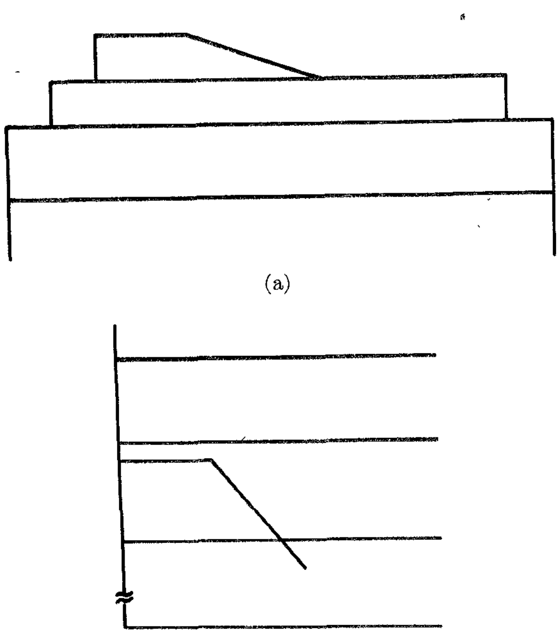
Two examples of the structures investigated are shown in Figs. 5(a) and 6(a). In each case the top waveguide was tapered by masking the film during the sputtering process. The length of the taper is approximately proportional to the height of the mask above the film.

The designs were based on the computer calculations discussed earlier. Mode propagation coefficients and hence film thickness and refractive index for each film were determined from prism coupler measurements [13]. Coupling coefficients were then calculated for the synchronous condition [14]. The taper profile was estimated by viewing the interference fringes formed by reflection



(b)

Fig. 5. Thin film tapered velocity coupler with approximately 100-percent coupling. (a) Geometry of three film coupler; top guide is tapered to beyond the TE_1 cutoff. (b) Variation of normalized propagation coefficients with distance. Effective taper length $L = 5 \pm 1$ mm.



(b)

Fig. 6. Thin film tapered velocity coupler with approximately 100-percent coupling. (a) Geometry of three film coupler; top guide is tapered to zero thickness. (b) Variation of normalized propagation coefficients with distance. Effective taper length $L = 2.25 \pm 0.75$ mm.

when the taper was illuminated by collimated laser light.

Calculated and measured parameters are given in Figs. 5(b) and 6(b) and in Table I.

All measurements were made with He:Ne laser light having a wavelength of 0.6328 μm.

TABLE I

PARAMETERS FOR FIRST AND SECOND DIRECTIONAL COUPLERS

Coupler	Film	Refractive Index	Taper Length L [a] (mm)	Film Thickness (micron)	Calculated Coupling coefficient (micron^{-1})
First	top	1.5694	4 ± 1	2.7, 1.2	TE_1-TE_1
	spacer	1.5437		1.9	0.004
	bottom	1.5694		1.7	(TE_0-TE_0)
	substrate	1.5124		-	(<0.0001)
Second	top	1.5708	2.25 ± 0.75	0.95	
	spacer	1.5455		1.56	0.008
	bottom	1.5708		2.85	
	substrate	1.5124		-	

[a] Measured from top edge of taper to mode cutoff point.

B. Measurement Technique

Having fabricated a structure with experimentally determined dimensions, refractive indices, and propagation coefficients, the remaining task is to measure its coupling efficiency and to ascertain whether or not its behavior is in accord with the proposed model.

Mode coupling should occur when: 1) propagation coefficient profiles cross, and 2) coupling coefficients are large enough. By fabricating structures supporting several modes of which only some meet these requirements one is able to establish the coupling mechanism.

It is important to recognize the path taken by a propagating mode [3]. This can be done often by observing the difference in scattering from a guide with a large Δn interface (glass–air) to that from a guide with a small Δn interface (glass–glass). The scattering is diminished in the latter case. Thus one is able to observe a mode disappear under a cladded section of guide and emerge into an uncladded section as a bright streak.

The prism coupler [15] was used extensively during this phase of the work both for coupling-in a selected mode and for coupling-out several modes simultaneously. During measurements it was noted that certain modes (with large enough transverse decay lengths) could be excited in the bottom film by a prism placed on the top film. Conversely, light could be completely removed from these modes in the bottom film by a prism placed on the top film. This effect was exploited when measuring the power coupling ratio. Power directionally coupled to the top film was coupled out by the prism and displayed as a characteristic "m line." Power remaining in the bottom film was also coupled out by the same prism but with a different characteristic angle, so forming a separate "m line" (the measurement is taken at a position where the modes are not in synchronism).

C. First Directional Coupler

It would appear from Fig. 5(b) that two coupling interactions are possible between: 1) the TE_0 modes of the top and bottom films and, 2) the TE_1 modes of the top and bottom films. However, the coupling coefficients for these two cases are very different as shown in Table I. Computer calculations show that the TE_1(top)–TE_1(bottom) interaction should result in 100-percent coupling, whereas the TE_0(top)–TE_0(bottom) interaction should result in negligible coupling. These predictions were confirmed by a series of experiments some of which are described.

1) The TE_0(bottom) mode was excited by means of a prism placed at position G. The resulting laser streak appeared bright in sections A and G, but very weak in sections B to F, as shown in Fig. 7. This is consistent with the TE_0 mode remaining in the bottom guide and scattering less in the cladded sections of the guide.

The power coupled out by a prism placed at position C was negligible. This prism, or an absorbing ink dot at C had no measurable effect on the streak in section A.

The results of these and other tests show that, as expected, the TE_0(top)–TE_0(bottom) coupling was negligible.

2) The TE_1(bottom) mode was excited by means of a prism placed at position $F1$. This was possible because of the long decay length of the TE_1 mode in the spacer film and was preferable to excitation at G because scattering at the FG interface was avoided. A small ink dot at position $F2$ absorbed any modes associated with the spacer film; the attenuation of the TE_1 mode was not prohibitive.

The resulting streak appeared weak in sections E and D up to beta crossover point. Here the streak grew in intensity to full brightness and continued into section C where it was terminated by an absorbing ink dot at position C. No light was observed in sections A or B. These observations are shown in Figs. 8 and 9, the latter photograph having been taken through a microscope focused onto the taper section of the top film.

These results are consistent with the TE_1 mode propagating in the bottom guide until being coupled completely into the top film by the tapered velocity coupler.

3) To obtain a quantitative measure of the coupling performance, the TE_1(bottom) mode was excited and an output prism placed at position C displayed the resulting mode lines. Lines were observed for the TE_1(top), TE_0(top), TE_1(bottom), and spacer leaky modes. All but the first gave very weak lines and a detector, scanned through the mode lines, recorded the trace shown in Fig. 10(a), indicating that very nearly 100-percent coupling had occurred in the taper. It should be explained that the prism was capable of coupling out all TE_1(bottom) mode [but very little TE_0 (bottom) mode].

4) The coupler is of course a reciprocal device and an incident TE_1 (top) mode was observed to couple almost completely to the TE_1 (bottom) mode.

5) The insertion loss of the coupler was determined by exciting the TE_1 (bottom) mode at $F1$ and measuring the TE_1 mode powers at positions C and E separated by a length 1 cm. The powers differed by 1.2 dB and this can be approximately accounted for by the loss in the film.

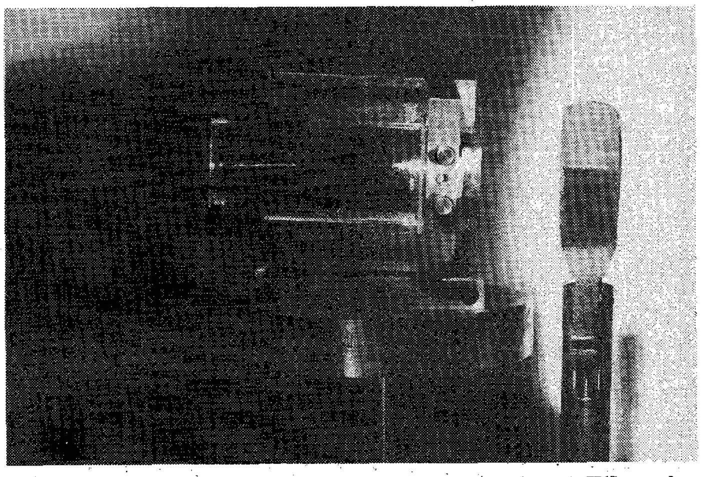


Fig. 7. TE_0 mode in first coupler shows zero coupling. A TE_0 mode excited in bottom film at far right passes under cladding films and emerges as a bright streak at far left.

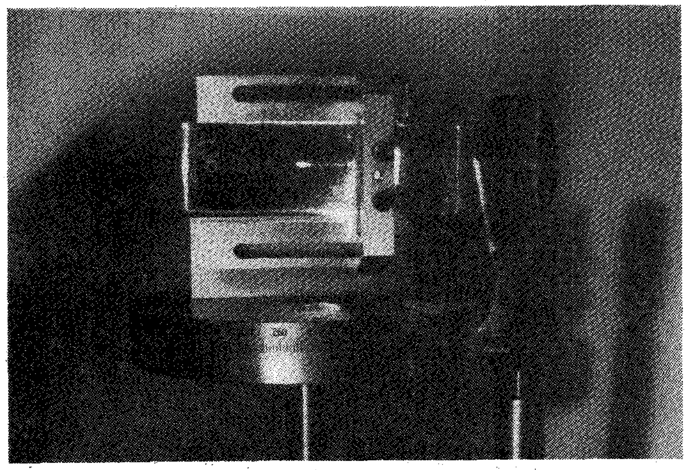


Fig. 8. TE_1 mode in first coupler shows approximately 100-percent coupling. A TE_1 mode excited in bottom film at far right passes under cladding films but is coupled up into the top film where it shows as a bright streak. This is terminated by ink dot.

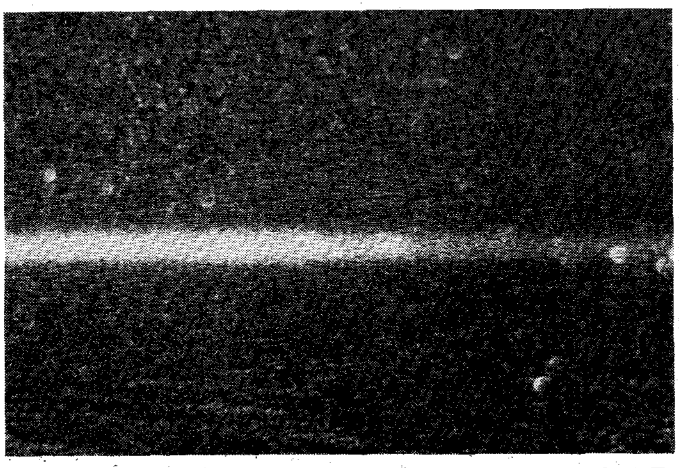


Fig. 9. Showing mode coupling from bottom to top film. The TE_1 (bottom) mode passing from right to left couples into the TE_1 (top) mode and hence scatters more.

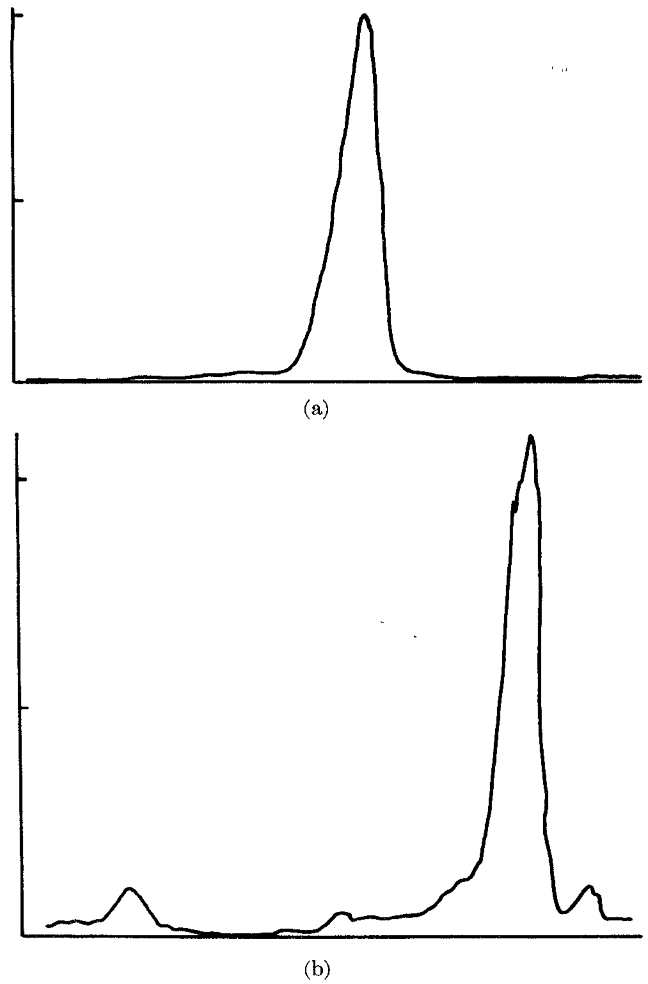


Fig. 10. Scan of mode lines obtained from prism placed on top film. (a) First coupler: with TE_1 bottom) excited, output from prism is wholly due to coupled TE_1 (top) mode. (b) Second coupler: with TE_2 (bottom) excited, output from prism is mainly coupled TE_0 (top) mode with some residual uncoupled TE_2 (bottom). Spurious TE_1 (top) and cladding modes due to scattering are observed.

The attenuation of the TE_1 (bottom) mode propagating under the spacer film, was measured using a prism sliding on a liquid and found to be approximately 1 dB/cm. This, with some additional loss due to propagation of the TE_1 (top) mode in the top film, would account for the measured insertion loss.

D. Second Directional Coupler

In this design the top film was tapered to zero thickness as shown in Fig. 6. The only possible interaction would appear to be between the TE_0 (top) and TE_2 (bottom) modes. The computed variation of mode power shows that 95-percent coupling should be achieved with a ripple of ± 5 percent.

A series of tests similar to those described earlier confirmed the theoretical prediction. Negligible interaction occurred between the TE_0 (top) mode and either the TE_0 (bottom) or the TE_1 (bottom) modes. However, when the TE_2 (bottom) mode was excited, strong coupling to the TE_0 (top) mode was observed. When the mode line output of a prism placed on the top film was scanned with a detector the trace shown in Fig. 10(b) was obtained. Again it should be emphasized that the output prism was able to extract all power from the TE_1 and TE_2 modes; coupling to the TE_0 (bottom) mode was weak. The trace shows that although some power remains in the TE_2 (bottom) mode, approximately 95 percent of the TE_2 (bottom) mode has been coupled to the TE_0 (top) mode. There is also some power in the TE_1 (bottom) mode and a leaky mode of the spacer. These were probably excited at the edge of the spacer film.

The insertion loss of the coupling section was measured over a distance of 3.8 mm and found to be 1.14 dB. This was expected as the measured lower film loss was 3.0 dB/cm.

V. DISCUSSION AND CONCLUSION

The linear velocity taper with constant coupling coefficient discussed in this paper was chosen initially for its simplicity although it represents quite closely the taper obtained in the experimental couplers. The computer analysis showed that 100-percent coupling was possible and put on a firm foundation the prediction that improved tolerance to changes in propagation coefficient, would be achieved, according to the mechanism shown in Fig. 1.

The key prediction of the analysis was that 100-percent coupling could be obtained for a wide range of values for coupling coefficient and taper slope. It followed that a 100-percent coupler would be the easiest to fabricate and indeed all the experimental effort so far has been directed to this end.

It is also very desirable to demonstrate experimentally 100 percent, rather than 50-percent coupling, the latter result being most easily explained by spurious causes such as scattering rather than a coupled mode process.

Complete coupling has its place in waveguide systems. For example, two dissimilar guides such as a fiber and a film can be coupled together in this way and in fact this particular example is currently under investigation in this laboratory.

In addition, complete coupling to one of several modes may be required in a mode filtering application.

The experimental results confirm the theoretical predictions. Near 100-percent coupling has been observed in three couplers, two of which are described in this paper.

It should be noted that the improvement in tolerance is obtained at the expense of having a longer device. The interchange of power takes place over a length comparable with that required for uniform coupling with the same coupling coefficient. However, the taper may be an order of magnitude greater in length. Thus, for example, the second coupler had a taper of length approximately 2.0 mm, whereas a uniform coupler having the same coupling coefficient would require a coupling length of only 0.2 mm.

A feature of the tapered coupler which may well be advantageous is that there is no need to define a precise coupling length by reducing the coupling coefficient to zero outside a prescribed region. In the tapered coupler the interaction ceases when the two modes are sufficiently far from synchronism, even though the guides may still be in close proximity.

The 50-percent (or 3-dB) coupler has more obvious application. No experimental results are available using the tapered coupler design but the computer analysis shows that the improved tolerance to changes in propagation coefficient brings with it no tightening of the tolerance on either coupling coefficient or taper slope.

The present discussion has been limited to passive couplers. The improvement in tolerance would seem to make electrical control, via the electrooptic effect for example, more difficult. However, this can be solved by a suitable circuit rearrangement. For example, switching can be effected by the use of two passive 3-dB couplers and a simple phase shifter [5]. It appears that the present improved design has a direct application here.

Coupling of modes by a periodic perturbation provided either passively or by electrooptic or acoustooptic means is well known. This class of coupling can be "tapered" by simply tapering the pitch of the perturbation, and so avoiding the severe tolerance restriction on the K vector relationship.

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REFERENCES

[1] E. A. J. Marcatili, "Dielectric rectangular waveguide and directional coupler for integrated optics," *Bell Syst. Tech. J.*, vol. 48, p. 2093, Sept. 1969.
[2] M. G. F. Wilson and G. A. Teh, "Improved tolerance in optical directional couplers," *Electron. Lett.*, vol. 9, pp. 453–455, Sept. 1973.
[3] A. Ihaya, H. Furuta, and H. Noda, "Thin-film optical directional coupler," *Proc. IEEE* (Lett.), vol. 60, pp. 470–471, Apr. 1972.
[4] A. Gedeon, "The effective thickness of optical waveguides in tunable directional couplers," *J. Opt. Soc. Amer.*, vol. 64, pp. 615–618, May 1974.
[5] F. Zernike, "Integrated optics switch," in *OSA Tech. Dig. Integrated Optics* (New Orleans, La.), Jan. 1974, paper WA5-1.
[6] F. W. Dabby and A. Kestenbaum, "Forward scattering in periodic waveguides," in *OSA Tech. Dig. Integrated Optics* (New Orleans, La.), Jan. 1974, paper TuB3-1.
[7] S. Somekh *et al.*, "Channel optical waveguide directional couplers," *Appl. Phys. Lett.*, vol. 22, pp. 46–47, Jan. 1973.
[8] E. A. Chandross, C. A. Pryde, W. J. Tomlinson, and H. P. Weber, "Photolocking—A new technique for fabricating optical waveguide circuits," in *OSA Tech. Dig. Integrated Optics* (New Orleans, La.), Jan. 1974, paper ThA5-1.
[9] J. E. Goell, "Electron-resist fabrication of bends and couplers for integrated optical circuits," *Appl. Opt.*, vol. 12, pp. 729–736, Apr. 1973.
[10] H. Furuta, H. Noda, and A. Ihaya, "Optical directional coupler consisting of optical stripline," in *OSA Tech. Dig. Integrated Optics* (New Orleans, La.), Jan. 1974, paper WB4-1.
[11] W. H. Louisell, "Analysis of the single tapered mode coupler," *Bell Syst. Tech. J.*, vol. 34, pp. 853–870, 1955.
[12] C. W. Pitt, "Sputtered glass optical waveguides," *Electron. Lett.*, vol. 9, pp. 401–403.
[13] R. Ulrich and R. Torge, "Measurement of thin film parameters with a prism coupler," *Appl. Opt.*, vol. 12, pp. 2901–2908, Dec. 1973.
[14] D. Marcuse, *Light Transmission Optics*. New York: Van Nostrand, 1972, p. 412.
[15] P. K. Tien and R. Ulrich, "Theory of prism-film coupler and thin-film light guides," *J. Opt. Soc. Amer.*, vol. 60, pp. 1325–1337, Oct. 1970.

Coupling from Multimode to Single-Mode Linear Waveguides Using Horn-Shaped Structures

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(Invited Paper)

***Abstract*—Coupling from a multimode to a single-mode linear waveguide using horn-shaped structures is investigated. The approximate coupling efficiency is found by numerical solution of coupled-mode equations that apply to the reciprocal problem, i.e., to the problem of propagation in an expanding horn. A coupling efficiency in excess of 90 percent is calculated when coupling is from the principal mode of a sample 50-μm-wide multimode waveguide to a 3-μm-wide single-mode guide ($\lambda = 0.63$ μm). This efficiency results from a uniformly tapered horn whose length is on the order of 2 mm. The length can be decreased by using a shaped coupling region. One such region is found to result in a coupling length of approximately 1.6 mm.**

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INTRODUCTION

THE DESIGN of integrated optical devices finds conflicting requirements. One area where this is true is in the design of modulators. On the one hand, the figure of