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CHANNEL WAVEGUIDE STUDY

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In this report we discuss some of the experimental measurements made on passive directional couplers. These measurements are designed to help check the accuracy of the processing used in formation of these devices and indicate a large degree of uncertainty in dimensions caused by both the process used in forming the Nb patterns, and in subsequent diffusion of these patterns.

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PREFACE

This Quarterly Technical Report, prepared by RCA Laboratories, Princeton, NJ 08540, describes work performed in the Physical Electronics Research Laboratory, G. D. Cody, Director. The Project Supervisor is B. F. Williams and the Project Scientist is J. M. Hammer. Other members of the Technical Staff who participated in the research and the writing of this report are W. Phillips and C. C. Neil.

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I. INTRODUCTION

In this report we discuss some of the experimental measurements made on passive directional couplers. These measurements are designed to help check the accuracy of the processing used in formation of these devices and indicate a large degree of uncertainty in dimensions caused by both the process used in forming the Nb patterns, and in subsequent diffusion of these patterns.

By using the measurements in conjunction with the theory of the preceding reports [1,2], reasonable agreement is obtained between predicted and measured behavior. The high degree of control required to obtain optimized performance is clearly shown by these results.

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1. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 1, Contract No. N00014-75-C-0078.
2. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 2, Contract No. N00014-75-C-0078.

II. EXPERIMENTAL STUDIES

As is quite clear from the theory of operation presented in the first and second quarterly reports, the operation of the "directional coupler" is very sensitive to both the gap "g" and stripe width "a". These dimensions, in addition, are experimentally interrelated because of the fabrication technique which we will briefly describe.

We start with an original photomask which has dimensions labeled with subscript o in Fig. 1. Thus, g_o is the nominal gap width in the photomask. The $LiTaO_3$ substrate is coated, using e-beam evaporation, with a layer of niobium of thickness τ (usually 0.06 to 0.08 μm). Photoresist is spun over the Nb, exposed through the photomask and the pattern developed. Subsequently, the pattern is transferred to the niobium by etching. The dimensions of the metal pattern after etching vary from those of the original photomask for two reasons. First, there is a degree of shrinkage in the photoresist which occurs during exposure and development. Second, and more important, a certain amount of undercutting occurs during the etching process. Thus, the metal pattern after formation will have dimensions g_1 and a_1 which differ from g_o and a_o. In general, $g_1 > g_o$ and $a_1 < a_o$.

The final step in the formation of the coupler is the diffusion. Based on our work under earlier contracts, very good identification and control of the depth of diffusion, b, are available. The amount of diffusion parallel to the plane of the substrate, however, has not yet been fully determined. Nonetheless, after diffusion it is clear (see Fig. 1) that the final dimensions "g", "a" will be limited and that

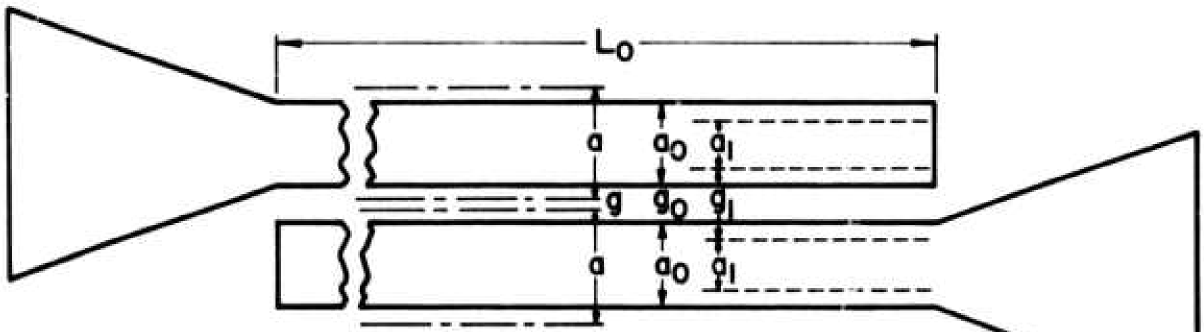
$$g < g_1 , \qquad a > a_1$$

$$g = g_o + a_o - a . \tag{1}$$

The amount of sideways diffusion (from one edge) will be

$$\frac{a - a_1}{2} \tag{2}$$

By measuring the percentage of light coupled between the stripes, an estimate of both "a" and "g" can be obtained using the closed form theory given in the first and second quarterly reports in conjunction with Eq. (1).



$$
\begin{aligned}
g_1 &= g_o + a_o - a_1 \\
g &= g_1 - (a - a_1) \\
&= g_o + a_o - a_1 \\
&\qquad - a + a_1 \\
g &= g_o + a_o - a
\end{aligned}
$$

Figure 1. Schematic of stripe guide directional coupler showing stripe width and gap; on photomask a_o, g_o; on Nb pattern before diffusion a_1, g_1; and on coupler after diffusion a, g.

The dimension "a" can be estimated independently of g by using a prism to couple light out directly from the stripe and observing the diffraction angle (in space) which for lowest order mode operation will be given by

$$\sin\theta = a/\lambda_o \tag{3}$$

Upon referring to Fig. 2 we see that the stripe guides are formed so that only the region, which bounds the stripes and horns, is free of waveguide film. This is indicated by the shaded area of Fig. 2. Thus, at the ends of the directional coupler, a planar LNT guide exists. The coupling prisms are arranged so that with the output prism at position 1, the output from the directional coupler can be measured by placing the input at I_{01} while the transmission through the planar guide can be measured if the input is placed at I_{02}.

Assuming the prism coupling does not vary when the input light is moved between the two positions and neglecting waveguide losses, the fractional coupling will be given by the ratio of the output coupled from the upper horn (I_1) when the input is coupled into the lower horn (as at I_{01}) to the output coupled from the planar guide (I_2) when the input is coupled into the planar guide (as at I_{02}).

We will discuss the validity of these assumptions in connection with the actual measurements given below.

Finally, if the output prism is moved to position 2 near the input horn, and if light is coupled at I_{01}, then a diffraction spread (θ) indicating the magnitude of "a" will be observed in the light coupled out.

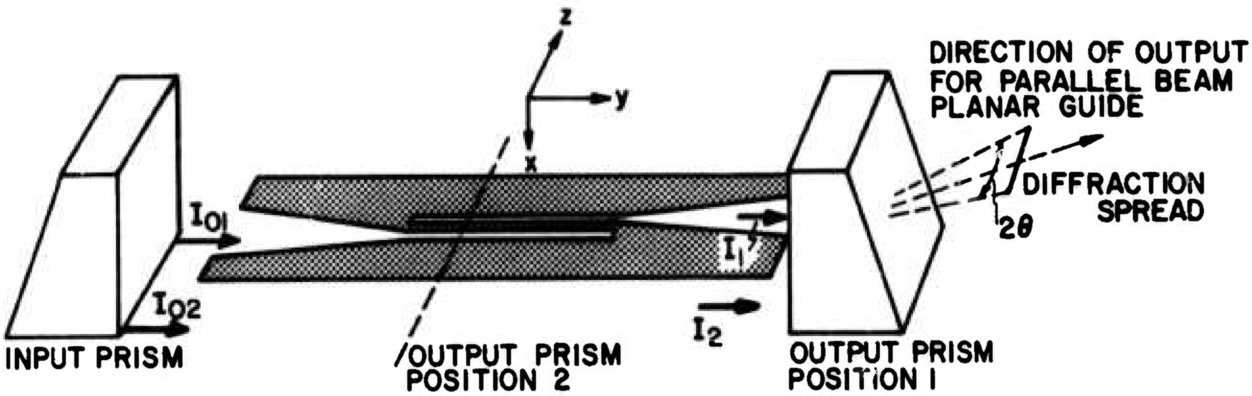


Figure 2. Experimental arrangement used in measuring some directional coupler properties. When output prism is in position 2, the diffraction spread is that associated with a mode in the stripe guide. In position 1 the transmission properties of the planar guide ($I_{02} \rightarrow I_2$) can be compared with those of the stripe coupler ($I_{01} \rightarrow I_1$).

III. EXPERIMENTAL MEASUREMENTS ON TWO SAMPLES

On Sample 35175S (Y plate) the patterns are formed with propagation direction perpendicular to the "c"-axis. The original mask has dimensions of $a_o = 5\ \mu m$, $g_o = 3\ \mu m$, and $L_o = 0.3$ cm. After pattern development the dimensions were found to be $a_1 = 4\ \mu m$ and $g_1 = 4\ \mu m$. From Eq. (1) the final gap must be $g = 8 - a\ (\mu m)$.

The initial Nb thickness is $\tau = 0.08\ \mu m$, the diffusion time (t) is 3 hr, and the diffusion temperature (T) is 1180°C. These values give a guide thickness b of 1.3 μm. With these dimensions we would expect the stripe to be cut off for TE modes at 6328 Å but to propagate TM modes.

Photographs of the output (6328 Å) from this sample under various conditions taken from a screen placed an optical distance 26 cm from the output prism edge are shown in Fig. 3. The two upper photographs show the outputs with the output prism at position 1 (see Fig. 2). The top photograph [Fig. 3(a)] shows the output through the planar guide (input at I_{02} output I_2). The middle photograph [Fig. 3(b)] shows the output from the upper horn (I_1) when the input is to the lower horn (I_{01}). The bottom photograph [Fig. 3(c)] shows the output directly from the (lower) stripe when the input is at I_{01} and the prism is in position 2 (see Fig. 2). Figure 3(a) shows the usual teardrop output and M-line structure of a planar guide [3]. Figure 3(b) is similar, showing, however, some structures which may be an artifact due to the coupling prism. It would be expected that the output through the horn would show a diffractive spread limited by the effective horn aperture. We will not discuss the horn behavior further in this report but will treat it in the final contract report. Finally, the relatively large diffraction from the stripe is apparent in Fig. 3(c).

Using the scale included in the photograph the height (H) of the diffraction pattern is estimated as being 4.3 ± 0.1 cm. We will tabulate predicted values of θ, a, and g below.

With the prism returned to position 1, the light intensity I_1 is measured to be 0.258 mW and I_2 measured to be 0.645 mW. Since the distance from the input prism is the same for both measurements, and because, to first order,

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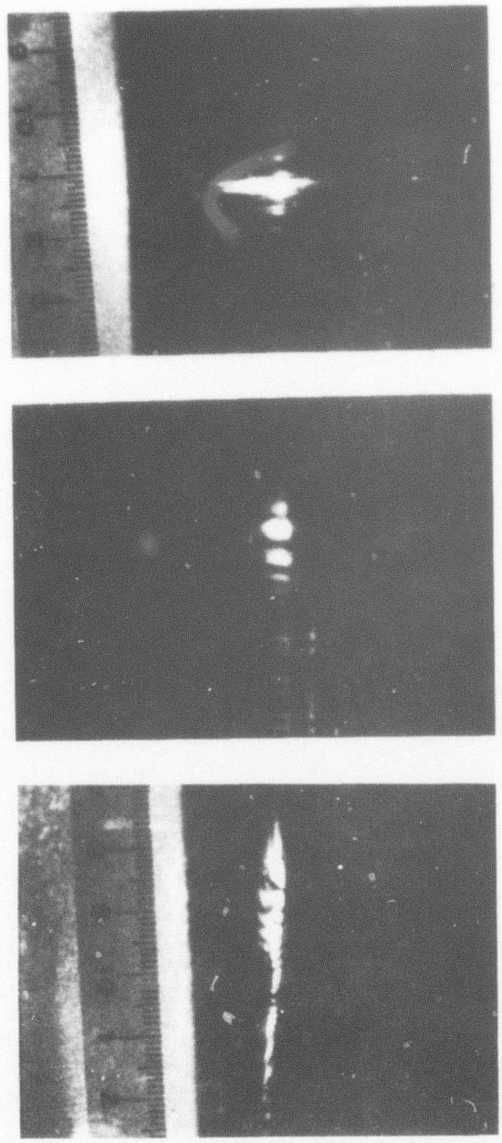
3. P. K. Tien, Appl. Optics <u>10</u>, 2395 (1971).



(a)

(b)

(c)

Figure 3. Photographs of output for (a) operation as planar guide, (b) operation as a coupler (horn output), and (c) direct prism coupling from stripe.

we would expect the waveguide loss of the stripe guide not to vary widely from that of the planar guide. We estimate that the coupling between the two stripe guides is $I_1/I_2 \approx 0.4$ or 40%.

The effect of possible input coupling change is uncertain. Great care, however, was taken in selecting the input prism and clamping it in place. Based on our experience in looking at the output when the input is placed at various points of an input prism on a planar guide, variation on the order of 25% or less might be expected. The output prism couples out all the guided light so output coupling differences between the I_1 and I_2 positions can be neglected.

It is instructive to calculate the values expected if the height of the diffraction spot is varied over its range of uncertainty. Thus, values of critical coupling length calculated using the closed-form theory for TM modes, in conjunction with Eqs. (1) and (3) of this report and the resulting expected percentage coupling, are tabulated in Table 1.

Table 1. Calculated Expected Values

H/cm	Tanθ $(\frac{H}{2}/26)$	θ	$a=\lambda_o/\sin\theta$ (μm)	g=8−a (μm)	Predicted Critical Coupling Length L(cm)	Predicted % Coupling $\sin^2\left(\frac{\pi}{2}\frac{L_o}{L}\right)$ (L_o=0.3 cm)
4.4	0.0846	4.84°	7.49	0.51	1.35	11.7%
4.3	0.0827	4.73°	7.65	0.35	0.87	26.5%
(4.25)	0.0817	4.67°	7.74	0.26	0.67	40.2%
4.1	0.0788	4.51°	7.83	0.165	0.41	83%
						Measured % (I_1/I_2)~40%

It is clear from Table 1 that very small errors in finding the width of "a" result in large changes in L, g, and in the percentage coupled. Nonetheless, it is also clear that the final value of a, after diffusion, is close to 7.7 μm.

We thus find, using Eq. (2), that the side diffusion is on the order of 1.9 μm in this sample. This is a larger diffusion distance than we had originally expected and must obviously be carefully taken into account in optimizing coupler and modulator design.

To further check the side diffusion we examined a second sample (sample 35196S). In this sample, which is formed in an X-plate, propagation is at an angle of ~45° to the "c"-axis, $\tau = 4$ hr, and $T = 1185°C$, giving $b = 1.5$ μm. The same mask dimensions as used to make the previous sample were used but the niobium pattern was more heavily undercut.

The niobium pattern dimensions, before diffusion, were estimated to be $a_1 = 3.5$ μm and $g_1 = 4.5$ μm. These stripe guides will not be cut off for the TE_{11} mode, and for this mode at 6328 Å we measured $I_1/I_2 = 21.3\%$. If we assume that $a = 7.2$ μm, then $g = 0.8$ μm, and we calculate $L = 0.88$ cm. This gives a calculated percentage coupling of 26% which is close to the measured value. Thus, here the sideways spreading is 1.85 μm, which is very close to that estimated in the previous sample despite the somewhat longer processing time of the second sample. The values, however, do fall within the rather large error expected for this type of measurement. We thus infer that sideways diffusion is one to one-and-one-half times the diffusion depth b.

IV. MODULATOR STRUCTURES

Our attempts to position electrodes on the passive directional couplers have been based on a lift-off technique and have been unsuccessful. The problem has been that the contrast of the directional coupler in the mask-positioning microscope is too low to allow good alignment.

We are now attempting to apply electrodes using an etching technique. Here, the sample (passive directional coupler) is coated with chrome gold before photoresist is applied. The contrast is better in this approach. We have made well-centered electrodes on one sample, but, unfortunately, because of an error during the removal of the chromium many opens appeared in the 2-μm center electrode. We are, however, optimistic that this approach will work.

Two other approaches are being considered. First, platinum electrodes applied before diffusion may survive the diffusion step. These electrodes can be applied after the Nb stripes so that there will be no contrast problem.

Finally, we are considering using a series of indexing marks which can be colored into the substrate by such metals as chromium. This approach is complicated and requires extremely accurate mask indexing so that it will be considered as a last resort.

REFERENCES

1. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 1, Contract No. N00014-75-C-0078.

2. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 2, Contract No. N00014-75-C-0078.

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