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CHANNEL WAVEGUIDE STUDY

J. M. Hammer, et al

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J. M. Hammer [Principal Investigator, tel.:
W. Phillips (609)-542-2700, ext.3210]
C. C. Neil

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In this report the calculations of the properties of stripe guides previously described are extended to include calculations of the coupling coefficient, critical coupling length, and voltage behavior for diffused Gaussian stripe guides. A new technique for generating stripe guide couplers and other long narrow structures is described; it is based on the shadowing effect of *thick* slits placed between source and substrate during evaporation and seems capable of generating the types of stripe guides we are studying. The materials studied are lithium niobate and tantalates.

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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 the calculations of the properties of stripe guides described in the first quarterly report are extended to include calculations of the coupling coefficient, critical coupling length, and voltage behavior for diffused Gaussian stripe guides. The approximations used allow results to be expressed in closed form so that a variety of conditions may be easily evaluated.

A new technique for generating stripe guide couplers and other long ($\sim$cm) narrow ($\sim\mu$m) structures is described. The technique is based on the shadowing effect of *thick* slits placed between source and substrate during evaporation and seems capable of generating the types of stripe guides we are studying.

We have made a number of stripe guide couplers and are in the process of studying them and learning to place the electrodes in proper registration with the couplers to form the switches. Since this study is in progress, a detailed description of this phase of the work will be deferred.

To avoid unnecessary duplication we assume that the contract proposal [1] and the first quarterly report [2] are available to the reader of this report for reference.

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1. RCA Proposal PP. 74-124, *Channel Waveguide Study* prepared for Defense Advanced Research Projects Agency, Arlington, Va., May 6, 1974.
2. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 1, Contract N00014-75-C-0078.

II. THEORY - ANALYSIS OF COUPLING BETWEEN ADJACENT DIFFUSED STRIPE GUIDES WITH GAUSSIAN INDEX VARIATION

The coupling between adjacent stripe guides has been calculated for step index variation stripes and channels by Marcatili [3]. Formulation of the dispersion problem for "Gaussian" stripe guides was given in the first quarterly report [1]. This formulation allows the propagation constants for lower order modes to be obtained in closed form. Briefly, we showed that by using Gaussian stripe guides which have the same propagation constant as comparison step index variation guides we can directly apply Marcatili's results to our case. Before doing this to find the coupling, however, the definitions and use of the coupling coefficient and critical coupling length will be summarized [1].

We consider two parallel stripe guides, a and b (see Fig. 1 in ref. 2). If the initial intensity in guide a is I_o and in guide b is zero, after traveling a distance equal to the critical coupling length (L) the intensity in guide b will be I_o and the intensity in guide a will be zero (assuming a lossless system). Label the intensity at any point of guide a, b as I_a, I_b. At $x = 0$, $I_a = I_o$ and $I_b = 0$. For lossless systems, $I_a + I_b = I_o$ and, as shown by Yariv [4],

$$\frac{I_b}{I_o} = \frac{1 - I_a}{I_o} = \frac{\kappa^2}{\kappa^2 + (\Delta/2)^2} \sin^2 \left(\sqrt{\kappa^2 + (\Delta/2)^2}\, x\right) \tag{1}$$

where κ is the coupling constant and $\Delta/2$ is a measure of the phase mismatch. For our case we take $\Delta = 0$ when no electric fields are applied. We have shown that for our system [1]

$$\Delta = \frac{2\pi}{\lambda_o} r' n'^3 E \tag{2}$$

where, to a fair approximation, when a voltage V is applied to the push-pull electrodes of our experimental arrangement

$$E = V/a \tag{3}$$

3. E. A. J. Marcatili, Bell Syst. Tech. J. 48, 2071 (1969).
4. A. Yariv, IEEE J. Quant. Electronics QE-9, 19 (1973).

When $\Delta = 0$, 100% transfer of energy between the two systems occurs when $x = L$, such that $\sin^2 \kappa L = 1$ and $\kappa L = \pi/2$; hence,

$$L = \pi/2\kappa \tag{4}$$

If we take $x = L$ and apply voltage to the electrodes, the voltage V_m at which $\sqrt{\kappa^2 + (\Delta/2)^2}\, L = \pi$ will result in complete shut-off of the switching. Using Eqs. (2) and (3) it is readily shown that

$$V_m = \frac{\sqrt{3}}{2} \frac{\lambda_o}{L} \left(\frac{a}{r'n'^3} \right) \tag{5}$$

For operation with LNT guides at an angle of approximately 50° to the c-axis for y-plates or 45° for x-plates, $r' \approx 34 \times 10^{-17}$ m/V and $n' = 2.18$ [5]. At $\lambda_o = 0.6328$

$$V_m = 1.556 \times 10^3 \; a/L \tag{6}$$

The coupling constant κ and critical coupling length L will now be calculated using the approximate theory mentioned earlier. Marcatili [3] expresses the coupling constant as

$$\kappa = \frac{2k_x^2}{\beta} \; \xi/a \; \frac{\exp(-g/\xi)}{1+(k_x \xi)^2} \tag{7}$$

where $\beta = 2\pi n_{eff}/\lambda_o = 2\pi/\lambda_o \, (n_2 + \delta n)$. δn and, hence β, may be found from the approximate closed form theory described previously [2]. In terms of the normalized stripe width A and stripe thickness B the closed-form approximation gives

$$\delta n = \Delta n \left(\frac{B}{0.807} - \frac{1}{8A_1^2} - 0.284 \right) \tag{8}$$

5. J. M. Hammer and W. Phillips, Appl. Phys. Letters 24, 545 (1974).

for TE_{11} mode. For convenience, we recall that

$$A = \sqrt{n_2 \Delta n} \;\; a/\lambda_o$$

$$B = \sqrt{n_2 \Delta n} \;\; b/\lambda_o \qquad (9)$$

A_1 is defined as

$$A_1 = A + \frac{1}{\pi\sqrt{2}} = A + 0.2251 \qquad (10)$$

Also, in terms of our normalized dimensions

$$k_x = \frac{\pi\sqrt{n_2 \Delta n}}{\lambda_o A_1}$$

$$\xi = \frac{\lambda_o}{\pi\sqrt{n_2 \Delta n}\left[8 - \left(\frac{1}{A_1}\right)^2\right]^{1/2}} \qquad (11)$$

We also define a normalized gap G as

$$G = \frac{\sqrt{n_2 \Delta n}}{\lambda_o} \, g \qquad (12)$$

The coupling constant may now be written in terms of the normalized quantities of the approximate closed form theory for TE_{11} mode and becomes

$$\kappa = \frac{n_2 \Delta n \sqrt{8A_1^2 - 1}}{8\lambda_o A A_1^3 \, (n_2 + \delta n)} \; \exp\left(-\pi \sqrt{8A_1^2 - 1} \;\; \frac{G}{A_1}\right) \qquad (13)$$

Using Eqs. (4), (6), and (13) of this report and Eq. (14) of the first quarterly report, values of L for an initial Nb thickness (τ) of 0.08 μm and diffusion depth b of 1.5 μm are plotted against the gap width g for values of stripe width a of 3, 4, 5, and 6 μm. These are the solid lines labeled COUPLING LENGTHS in Fig. 1. The solid lines labeled VOLTAGE are the corresponding values

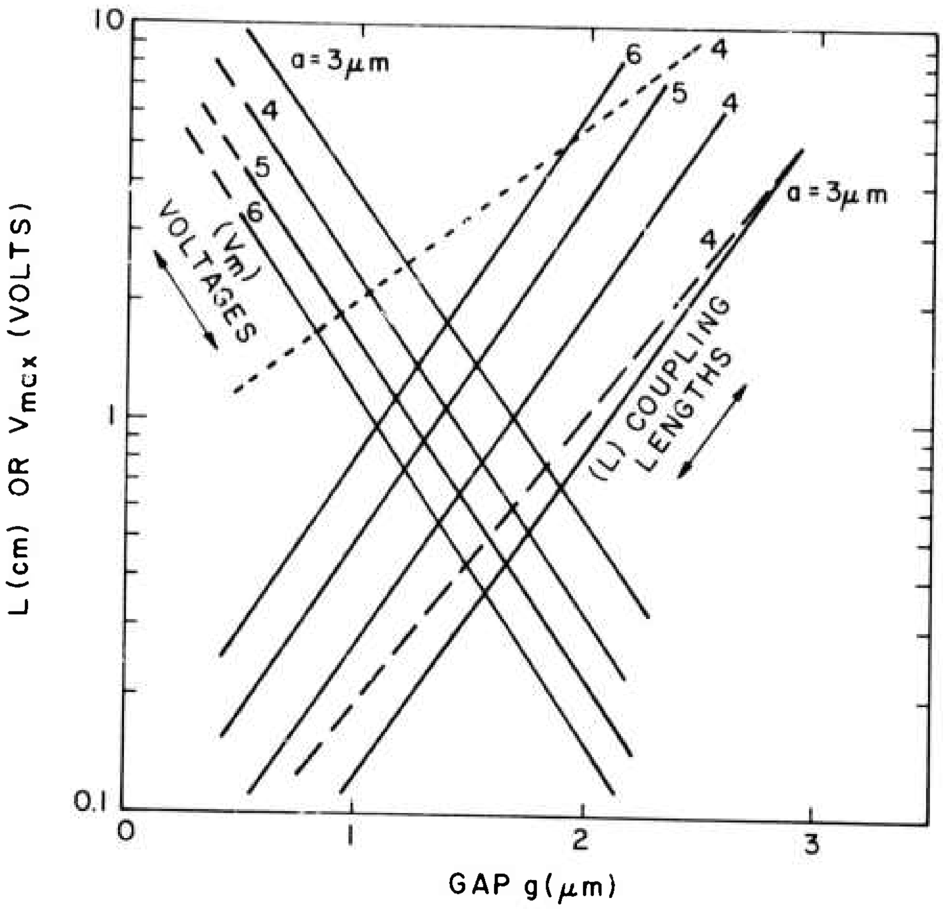


Figure 1. Critical coupling length (L) and shut-off voltage V_m vs gap g with stripe width (a) as parameter. The solid lines are for an initial Nb thickness (τ) of 0.08 μm and a diffusion depth (b) of 1.5 μm and values of (a) equal to 3, 4, 5, and 6 μm as labeled. The dotted line gives L vs g for the case b = 1.0 μm and a = 4.0 μm, and the dashed line for the case b = 2.0 μm and a = 4.0 μm. The strong dependence of L on all parameters should be noted.

of V_m found from Eq. (6). The dotted line is the critical coupling length for the case b = 1.0 μm and a = 4 μm, and the dashed line is the critical coupling length for the case b = 2.0 μm and a = 4 μm.

It may be noted how sensitive the critical coupling length is to all the parameters of the directional coupler. This implies that, unless some independent means of tuning is provided, an extremely high degree of precision in controlling the actual length of the coupler, the stripe width, thickness, and gap will be required to obtain a high percentage switching.

A possible tuning method that is under consideration is the deposition of a top layer of either plastic or other transparent material such as evaporated quartz or sapphire to modify the directional coupler parameters. The actual tuning range of such layers will have to be analyzed in greater detail but, very crudely, changes in propagation on the order of the ratio $(n_{vacuum}/n_{top\ layer})$ P/b might be expected, where P is the evanescent field penetration depth into the top layer. Very roughly, P/b will be about 0.1 and, for top layers of materials with $n \approx 1.5$, the change in effective guide index would be on the order of 0.15 (out of 2.2).

III. EXPERIMENTAL METHODS - METHOD OF FORMING STRIPE GUIDE DIRECTIONAL COUPLERS USING SHADOWING SLITS

The problem of forming optical waveguide structures which have transverse dimensions on the order of microns (μm) but which run for distances on the order of millimeters is difficult to solve. Conventional photolithographic techniques are limited in producing such structures. As a result, fairly elaborate electron micrographic equipment for the exposure of photoresist was developed at some laboratories. These devices represent investments of many hundreds of thousand dollars. It is possible, however, to use thick masking slits to directly evaporate narrow structures which have transverse dimensions on the order of micrometers and lengths on the order of centimeters. The slits need not have extremely small dimensions to achieve this result; rather, by suitably placing the evaporator source with respect to the slits, use is made of a shadowing effect that reduces the deposited pattern to the widths desired.

This approach is particularly well suited to form $LiNb_xTa_{1-x}O_3$ stripe waveguides required in this program since the Nb may be deposited in the pattern using the slits, and only a following diffusion step is then required to produce the stripe waveguide device.

The method can be understood by referring to Fig. 2.

A slit designed to have a slit width 2s and a thickness t is placed a distance h above the substrate. The slit may run any desired distance at right angles to the plane of Fig. 2. In addition, away from the plane of the paper the slit may take a form other than a straight line. We will show a form incorporating entry horns later. A source for evaporation of a desired material, e.g., niobium, is placed a distance H above the slit and displaced a distance D from the slit center plane. A limiting aperture may be used to define the source location. Evaporated atoms or molecules travel in straight lines from the source, provided the pressure during evaporation is low and the rate of evaporation is not too high. In general, this is true for most common evaporation procedures, including the method we use for evaporating niobium. The slit will shadow an evaporated stripe of width 2w on the substrate located as shown.

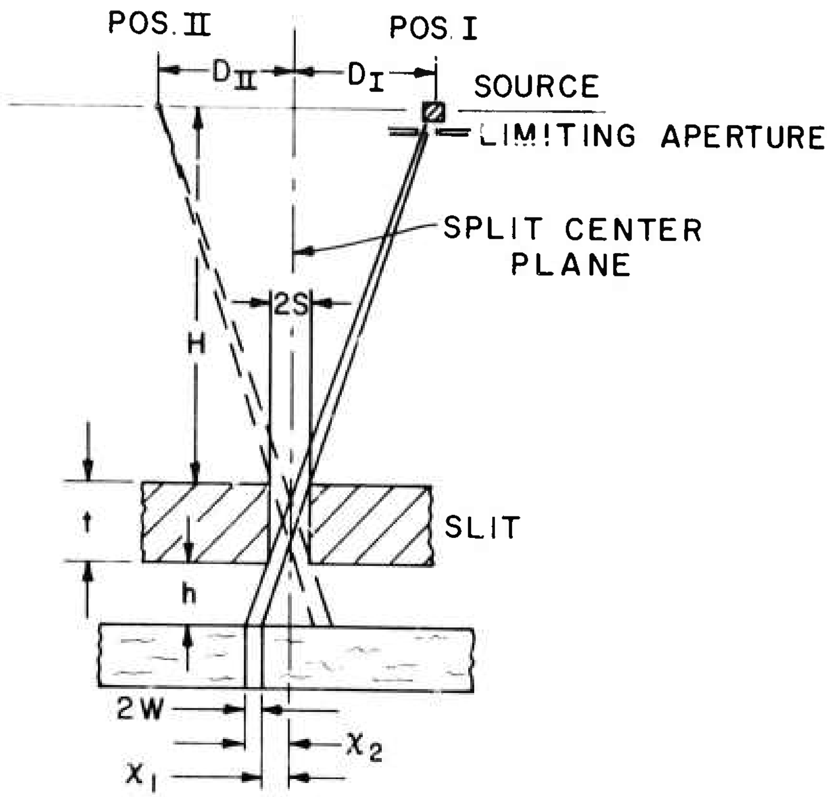


Figure 2. Schematic of thick shadowing slits arrangement for direct formation of waveguide patterns during evaporation.

It is readily calculated that, if the assumption D >> s,t and H >> s,t is made

$$2w = 2s - \frac{D}{D}\, t \tag{14}$$

The approximation is sufficiently accurate since H will be ∿20 cm, D ∿2 cm, while t and s will be ∿0.01 cm. To this same approximation

$$x_1 = (t + h)D/H \tag{15}$$

If a stripe is formed with the source at position I and then the source is displaced to position II located to the left of the center plane, and if $D_{II} = D_I$, then a second stripe can be deposited running parallel to the first stripe and separated from it by a near edge distance g = 2x. If $D_I \neq D_{II}$, the second stripe will have a thickness other than 2w. The width of the second stripe may be found by using $D = D_{II}$ in Eq. (14). The second stripe will be displaced from the first by a near edge distance obtained from Eq. (15) as

$$g = x_1 + x_1' = (t + h) \quad D_I + D_{II} \quad /H \tag{16}$$

Thus, by using a simple thick slit two parallel stripes, which have widths less than the slit width and spaced a chosen distance apart, can be obtained.

As an example, in order to construct a $LiNb_xTa_{1-x}O_3$ stripe guide modulator, two stripes, each of width 4 μm and separated by a gap (distance between nearest edges) of 2 μm before diffusion, might be used. These have to run parallel for 0.4 cm. The gap after diffusion would be reduced to a value of about 1 μm.

A slit with a thickness t = 5 mils $\approx$ 125 μm and a slit width 2s = 10 μm ($\sim$0.4 mil) is used. The slit length perpendicular to the plane of Fig. 1 is chosen to be 0.4 cm. Using Eqs. (1) and (2) it is readily shown that D/H = 0.048 and thus, if D = 1.2 cm and H = 25 cm, the desired 4-μm stripes spaced 2 μm apart will be obtained for the case that corresponds to h = 0, the substrate being in direct contact with the slits.

Drawings of the experimental device with shaped slits to produce a stripe guide directional coupler, including entry horns, are shown in Fig. 3. The slits (1) are positioned in the holder (2) so that the required gap is obtained. The slits shown have a straight section of length L equal 0.4 cm. Curved sections of radius R = 4.5 cm are provided so that the completed pattern will have entry horns. With the masking aperture (4) at the extreme right in the masking aperture slot (5), and the source at position I, a pattern consisting of a stripe and a single horn on the right will be formed as labeled [A] in Fig. 4. With the masking aperture (4) at the left of the slot (5) and the source moved to position II, a second stripe and horn will be formed shown as [B] in Fig. 4.

Thus, by use of this arrangement a directional waveguide coupler can be directly fabricated during the evaporation without recourse to complex lithographic techniques.

Other patterns with small dimensions in one direction and large dimensions in the direction perpendicular to the small direction can also clearly be fabricated using suitable slit pairs.

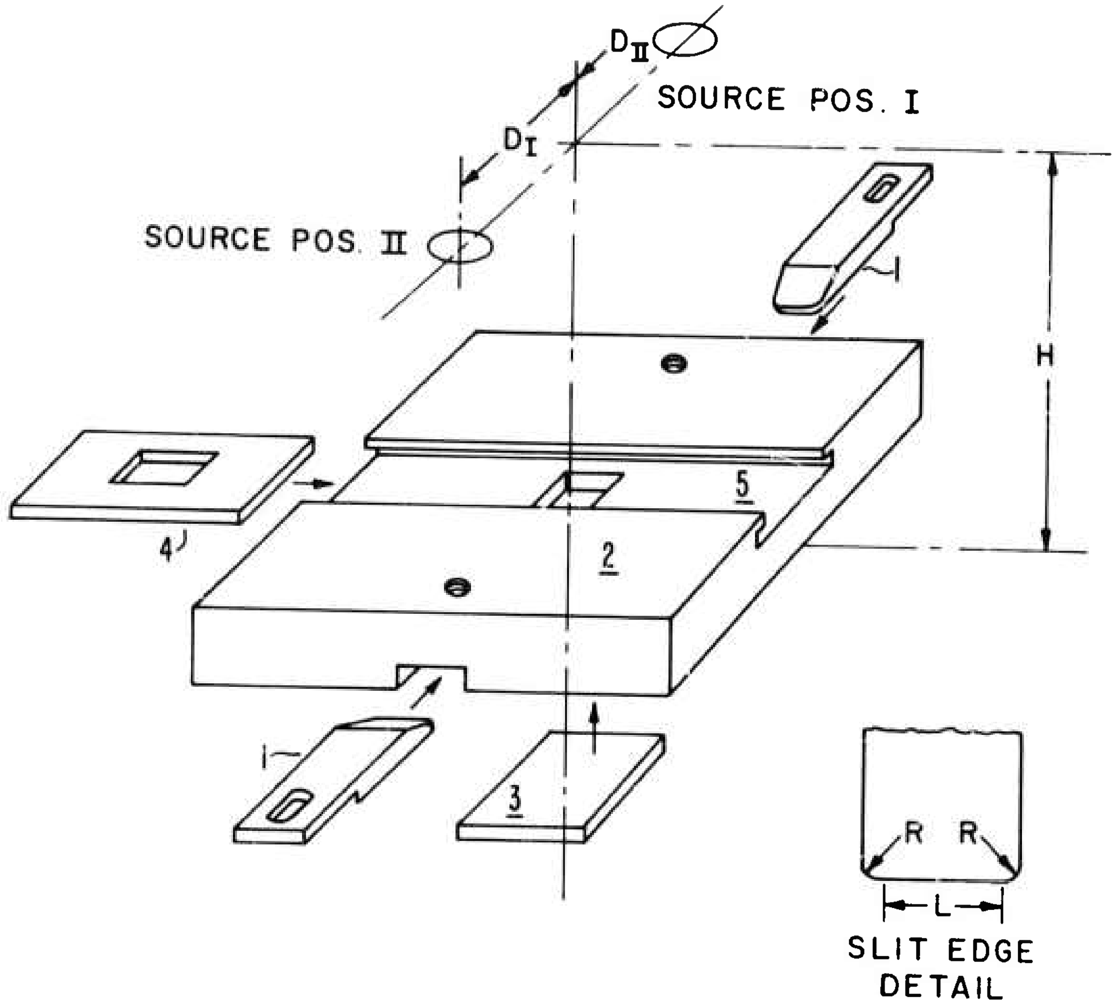


Figure 3. Sketch of experimental jig for forming stripe guide coupler patterns during evaporation.

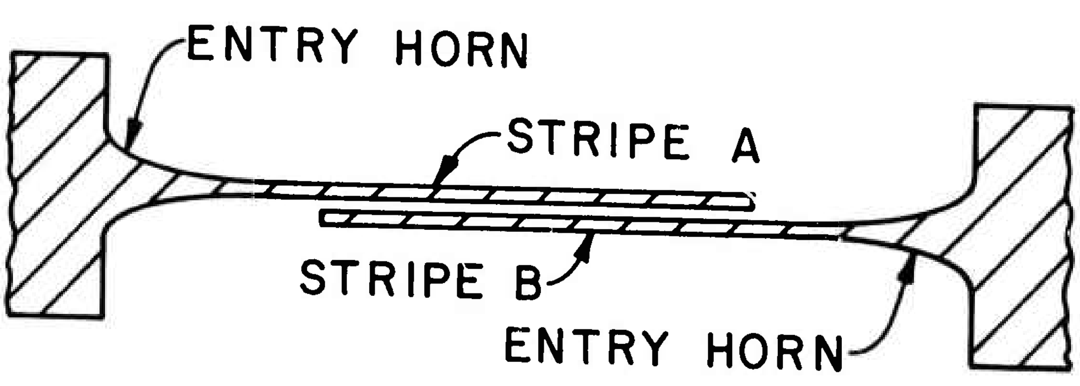
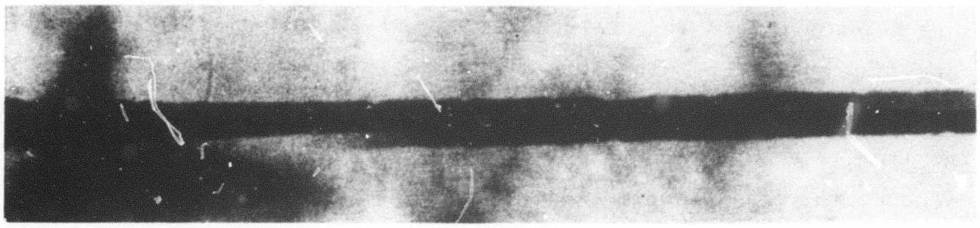


Figure 4. Sketch of expected pattern formed after masking, slide positioning, and evaporation.

Our first attempt to use this method revealed a problem in the slit quality and precision of placement of the slits but did demonstrate that the principle is sound. A photograph of the Nb stripes after the double evaporation is shown in Fig. 5. Here nominal dimensions were chosen to give a = 6 μm and g = 2 μm. In Fig. 5(a) the right-hand horn and associated double guide section are shown. Clearly, the masking aperture slide was out of position so that the horn was double-exposed. The gap is well-defined, and the imperfections are readily traced to the rather rough slit edges. Optically polished slits are in preparation. The left side horn is shown in Fig. 5(b). Here the masking aperture slide was in position, but the gap is obliterated, indicating that the line of the two source positions is out of plumb with respect to the slit. These are readily correctible deficiencies, and it seems that this method will allow the production of structures about 1 cm in length with smallest transverse dimensions on the order of 1 μm. The cost of the technique is rather low.

We have proceeded with conventional photolithographic techniques and have constructed two additional stripe guide couplers. One of these has an L of 3 mm and g = 3 μm before diffusion. This coupler is diffused to a depth b of 1.5 μm and is being actively studied. Electrode patterns have also been prepared and we expect to place electrodes on this coupler in the near future. The second coupler is similar to that described in the first quarterly report.

(a)



(b)

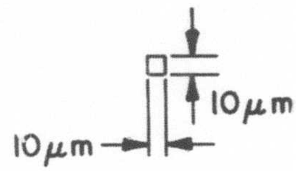


Figure 5. Photograph of patterns actually formed in first attempt at applying shadowing slits.

IV. EXPERIMENTAL MEASUREMENTS

Because we are actively engaged in characterizing both the couplers described briefly above and individual stripe guides in order to optimize the parameters and compare the operation to theoretical predictions, reports on these studies will be deferred and given in later reports.

REFERENCES

1. RCA Proposal PP. 74-124, *Channel Waveguide Study* prepared for Defense Advanced Research Projects Agency, Arlington, Va., May 6, 1974.
2. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 1, Contract N00014-75-C0078.
3. E. A. J. Marcatili, Bell Syst. Tech. J. 48, 2071 (1969).
4. A. Yariv, IEEE J. Quant. Electronics QE-9, 19 (1973).
5. J. M. Hammer and W. Phillips, Appl. Phys. Letters 24, 545 (1974).