AD-A031 518 HUGHES RESEARCH LABS MALIBU CALIF F/G 20/6
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THIN-FILM OPTICAL SWITCH

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September 1976

Contract N00173-76-C-0113
Midterm Report
For Period 22 January 1976 Through 21 July 1976

Sponsored by
NAVAL RESEARCH LABORATORY
4555 Overlook Avenue, S.W.
Washington, DC 20375

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (*and Subtitle*)
⑥ THIN-FILM OPTICAL SWITCH.

5. TYPE OF REPORT & PERIOD COVERED
Midterm Tech. Report
22 Jan. 1976-21 July 1976

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
⑩ Bor/Chen and Gregory/Tangonan

8. CONTRACT OR GRANT NUMBER(s)
⑮ N00173-76-C-0113

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Research Laboratory
4555 Overlook Ave., S. W.
Washington, D.C. 20375

12. REPORT DATE
⑪ September 1976

13. NUMBER OF PAGES
20

14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)
⑨ Midterm technical rept.
22 Jan - 21 Jul 76,

15. SECURITY CLASS. (*of this report*)
Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)
⑫ 21p.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)
Integrated Optics
Optical Switch
Thin-Film Waveguide

OSUB3

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

We report the fabrication and evaluation of horn-shaped taper waveguides. Waveguides of linear tapers and straight channels were formed by diffusing a pattern of Ti into $LiNbO_3$ substrate. After diffusion, the interference fringe patterns show that the waveguides have ridges of height of about 3 times the original evaporated Ti film thickness. We found the complete oxidation of Ti before diffusion is important in →

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forming high quality optical waveguides. The waveguide scattering loss is ≤ 1 dB/cm at the He-Ne laser wavelength 6328 Å. Taper coupling efficiencies for TE waves at four different taper lengths, 300, 600, 900, and 1200 μm, were measured. We determined that the single mode transmission efficiency for 1200 μm linear taper was 70% at λ = 6328 Å and 75% at λ = 5145 Å.

Lamda angstrons micrometers angstroms

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PREFACE

The following personnel contributed to the research work reported here: B. U. Chen, G. L. Tangonan, and A. Lee. The photomasks were fabricated by the photolithographic services of Hughes Aircraft Company, Fullerton, California, under the direction of W. Gray and G. Bair.

I. INTRODUCTION

In this report, we describe the fabrication and evaluation of horn-shaped taper waveguides. Waveguides of linear tapers and straight channels were formed by diffusing a pattern of Ti into $LiNbO_3$ substrates. The design and fabrication of the photomask were described in Quarterly Technical Report 1.[1] After diffusion, the interference fringe patterns show that the waveguides have ridges of height of about 3.0 times the original evaporated Ti film thickness. We found that the complete oxidation of Ti before diffusion is important in forming high quality optical waveguides. The waveguide scattering loss is $\lesssim 1$ dB/cm at the He-Ne laser wavelength of 6328 Å. Taper coupling efficiencies for TE waves at four different taper lengths-300, 600, 900, and 1200 μm-were measured. We determined that the single mode transmission efficiency for 1200 μm linear taper was 70% at $\lambda = 6328$ Å and 75% at $\lambda = 5145$ Å. The measurements of coupling efficiency versus taper length showed a possible dip of less coupling efficiency at the taper length of 900 μm. Nelson[2] has considered the efficiency of coupling from an input single-mode guide to an output single-mode guide after traversing the expansion and contraction tapers of various lengths. His numerical results show oscillations in the coupling efficiency with taper length. The origin of these oscillations is not understood at present. More studies are required for possible explanation.

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[1] G. L. Tangonan, "Thin Film Optical Switch," Quarterly Technical Report 1, Contract N00173-76-C-0113, May 1976.

[2] A. R. Nelson, Appl. Opt. <u>14</u>, 3012 (1975).

II. FABRICATION OF TAPERED WAVEGUIDES

Waveguides of linear tapers and straight channels were fabricated by diffusing e-beam evaporated Ti into $LiNbO_3$ substrates. Table 1 summarizes the processing parameters for five samples. The guides were expanded from a 4 μm single-mode channel to a 70 μm multimode channel in the taper lengths of 300, 600, 900, and 1200 μm. These taper lengths correspond roughly to 1000, 2000, 3000 and 4000 λ, where λ is the He-Ne laser wavelength in the guide. For comparison with nontapered waveguides, the tapered guides are separated by a straight channel guide of 4 μm width.

Two different masking techniques of forming a Ti diffusion pattern were tried. For samples 1A and 1B, a Ti metal film was first evaporated onto the substrate, then followed by photolithographic exposure and development of a spun-on negative photoresist film and chemical etching of the Ti metal. Because of the inherent difficulties of handling negative photoresist, the remainder of the samples were processed with Shipley AZ 1350 B positive resist.

For this lift-off technique, Ti was evaporated onto the photoresist pattern subsequent to exposure and removal of the resist. The open area of the resist was thus filled with Ti metal, while unwanted Ti on the photoresist was removed by dissolving the Shipley resist in acetone. Two sets of patterns were formed on each sample. For easy location of a mode coupling angle, there is also a 3-mm-wide strip waveguide on the substrate.

The diffusions were carried out at 850 to 900°C in flowing oxygen atmosphere. Before diffusion, Ti was oxidized at relatively lower temperature, for instance, 600°C. We found that in order to obtain high quality waveguides, the Ti film has to be oxidized completely to TiO_2. Samples 1A and 1B were oxidized at 600°C for one hour; the resulting waveguides were hazy in appearance and exhibited high scattering losses. We measured waveguide loss of 15 dB/cm for the TE_0 wave in the central 3-mm-wide strip waveguide. By increasing the oxidation time to four hours, the waveguide losses were considerably reduced.

TABLE 1. DETAILS OF PROCESSED SAMPLES ($LiNbO_3$)

Sample	Mask	Ti-Coating, Å	Oxidation at 600°C, hr.	Diffusion		Comment
				Temperature, °C	Time, hr.	
1A and 1B	1	100	1	850	14	Milky waveguide, loss ~ 15 dB/cm
3A	1	350	4	875	18	Milky surface, ridge height ~ 1050 Å
4A	2	200	4	910	32	Good waveguide, ridge height ~ 550 Å
4B	1	350	4	No		Ridge height ~ 1100 Å
5	2	200	4	900	16	Good waveguide, Central planar waveguide loss TE_o 1.1 dB/cm, TE_1 0.9 dB/cm

Both samples 4A and 5 can support only a single TE mode over the 4 μm channel region. All the channels are parallel to the x-axis of y-cut $LiNbO_3$ plate. Hence, the change in the extraordinary index of refraction resulting from the metal in-diffusion determines the propagation constants. Since out-diffusion of LiO_2 would also increase the extraordinary index, the diffusions were carried out at as low a temperature as possible. We were able to distinguish the guiding phenomena due to Ti in-diffusion from that due to LiO_2 out-diffusion. Figure 1 shows the mode structure coming out of a 4 μm channel. It is quite clear from the absence of any other m-line output due to intermode scattering that a single mode channel waveguide has been formed. Only one mode could be excited by varying the resonant coupling angle.

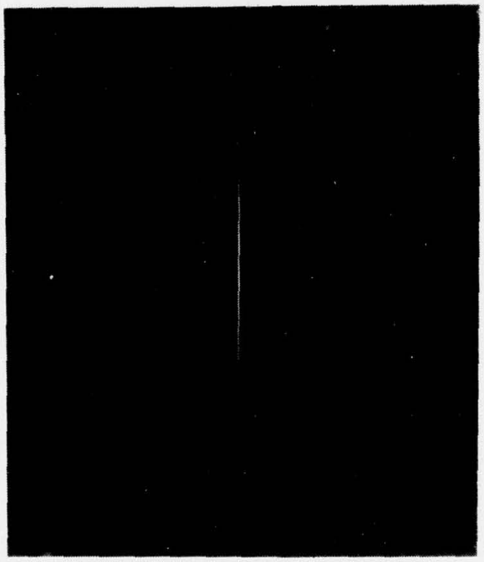

Figure 1.
Output mode pattern of 4 μm channel guide.

III. EXPERIMENTAL MEASUREMENTS

A. Effective Channel Guide Width

When the guided light is coupled out of a channel waveguide, the diffraction angle, θ, for the lowest order mode is given by

$$\mathrm{Sin}\,\theta = \frac{\lambda}{d}$$

where λ is the light wavelength in vacuum and d is the effective channel guide width. From the photograph in Figure 1, we estimate the effective width is about 4. 7 μm, which is comparable to the Ti mask width before diffusion. There is no sign of enhanced lateral diffusion.

B. Ridge Formation Studies

During evaporation, the Ti film thickness is monitored by a quartz crystal acoustic oscillator. After diffusion, we noticed that waveguides formed ridges of height about 3 times the original Ti thickness. Figure 2 shows the interference pattern of the structure in sample 4A after diffusion. The 4-μm-wide ridges are barely seen between 70 μm channel. Each fringe spacing in the interferogram corresponds to a height difference of 2950 Å, which is half the wavelength of sodium D line. We further notices that the ridge height was increased by nearly the same factor right after oxidation. Figure 3 is the interferogram of sample 4B. After four hours oxidation at 600°C, the ridge height was increased from 350 Å to 1100 Å.

C. Waveguide Loss Measurements

Waveguide loss of a wide strip (>2 mm) was measured by using the two-prism technique. Unfocused He-Ne laser light was coupled into the waveguide by the first coupling prism. After traversing a certain distance, the guided light was coupled out by the second coupling prism. By plotting the output power as a function of prism separation in a semilogarithmic scale, we calculated the loss

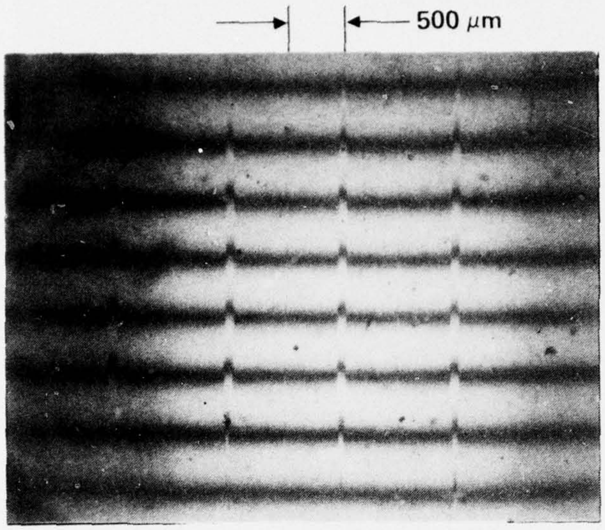

Figure 2. Interferogram of sample 4A after diffusion.

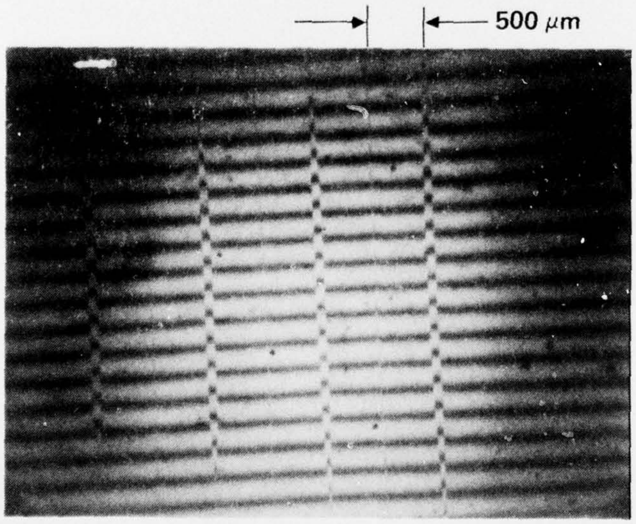

Figure 3. Interferogram of sample 4B after oxidation.

coefficient from the slope of the straight line. Figure 4 shows the measurements for sample 5. The planar waveguide can support two TE modes. The measured waveguide losses are 1.1 dB/cm for TE_0 mode and 0.9 dB/cm for TE_1 mode.

We have also tried to measure the waveguide loss of 4 μm straight channels using focused input light and by varifying the prism separation. This experimental technique is quite difficult to implement and a large experimental error was found. However, we have been able to conclude that the loss of 4 μm channel quides is also on the order of 1 dB/cm. Usually, two-dimensional channel guides have higher scattering loss than one-dimensional planar waveguides do because of the scattering due to edge roughness. For our case, we believe the edge roughness of Ti coating is smoothed out during diffusion.

D. Taper Coupling Efficiency Measurement

The taper waveguide structures which were tested, consist of a 4 μm single mode channel guide section, a linear expansion taper section, a 70 μm multimode channel guide section, a linear contraction taper section, and a 4 μm single mode channel guide section. The mask design used to define this taper structure is shown in Figure 5. We measured the single mode coupling efficiency between two 4 μm wide single mode channel guide sections. The impedance transforming horn is well understood in microwave circuit theory. If the taper is sufficiently gentle, radiation will be transmitted adiabatically, continuously readjusting to the slow variation of the transmission line impedance with virtually no reflection or coupling to higher order modes. In reality, one scarifices perfect coupling in order to use a taper of reasonable length. In our experiment, four different taper lengths, 300, 600, 900, and 1200 μm, were studied.

The two-prism technique was employed to measure the coupling efficiencies of the tapers. Both the input and output coupling prisms were placed on the 4 μm channel section. By comparing the output power of the taper structure with that of the neighboring 4 μm channel,

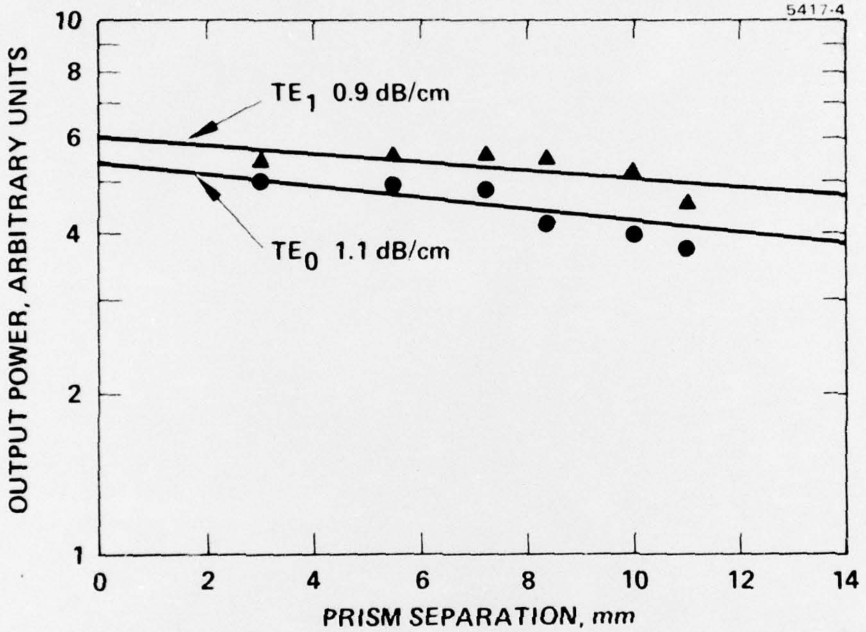

Figure 4. Loss measurement on Ti - diffused $LiNbO_3$ waveguide.

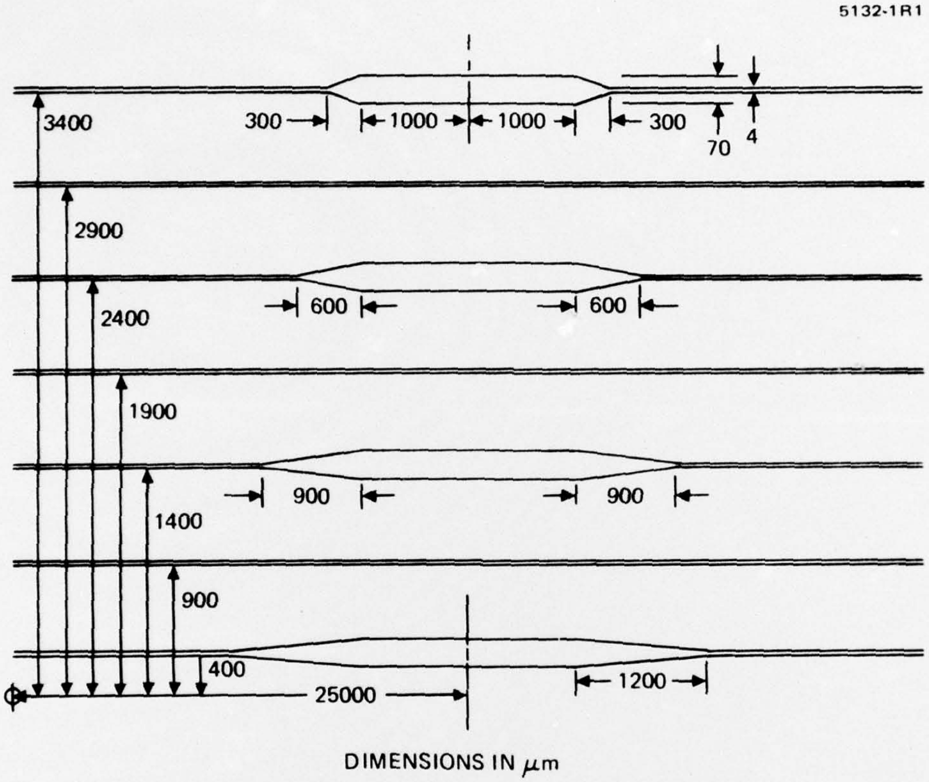

Figure 5. Mask design for linear taper structures.

we determine the throughput of the structure of one expansion taper and one contraction taper. Assuming the expansion taper and contraction taper have the same coupling efficiency, we take the square root of the throughput and define it as the taper coupling efficiency.

Table 2 lists the detected output power for the tapered structures formed on samples 1A and 1B. The He-Ne laser light was focused on the input prism corner by a lens of focal length f = 1.8 cm. The focused spot size was estimated to be around 10 μm. The light coming out of the 4 μm channel sections by output coupling prism was focused by a cylindrical lens onto a calibrated UDT 11C detector.

Set No. 1 shows irregular behavior of the output powers for the various tapers and channels. We concluded that the imperfections caused during processing dominated the performance of these structures. In set No. 4, all 4 μm channels have about the same throughput, which is ~6.4 times higher than the result of the best taper. Comparing the result of 300 μm taper and of the neighboring 4 μm channel, we estimate 16% throughput for the structure of one expansion taper and one contraction taper. Higher throughputs were thus expected for better processed samples.

Table 3 lists the detected output power and taper coupling efficiency for structures on sample 4A. Table 4 shows the results for sample 5. The focal lens was changed to f = 20 cm and two prisms were separated by 6 mm. In the calculations of taper coupler efficiency, we neglected the scattering loss difference between 4 μm channel and taper. This was verified to be a correct assumption when we moved the prisms to a distance of 12 mm and obtained similar results.

Figure 6 shows the averaged value of coupling efficiency for different taper length and the variation of measurements when the prism positions were changed. We estimate that at least 15 μW He-Ne laser light is guided in the 4 μm channel, which corresponds approximately to power density of 200 W/cm^2. No optical damage at this power level was observed.

TABLE 2. TAPER COUPLING EFFICIENCY MEASUREMENT FOR SAMPLES 1A AND 1B

	Detected Output Power	
	1A (Set No. 1)	1B (Set No. 4)
1200 μm taper	2.0×10^{-8} W	3.2×10^{-8} W
4 μm channel	0.2	23.4
900 μm taper	2.0	1.4
4 μm channel	0.88	21.0
600 μm taper	4.0	0.3
4 μm channel	2.6	23.0
300 μm taper	6.4	3.6

TABLE 3. TAPER COUPLING EFFICIENCY MEASUREMENT FOR SAMPLE 4A

	Detected Output Power	Taper Coupling Efficiency
1200 μm taper	3.16×10^{-6} W	69%
4 μm channel	6.64	—
900 μm taper	1.27	44% 48%
4 μm channel	5.70	—
600 μm taper	1.79	56% 52%
4 μm channel	6.77	—
300 μm taper	2.33	59%

TABLE 4. TAPER COUPLING EFFICIENCY MEASUREMENT FOR SAMPLE 5

	Detected Output Power	Taper Coupling Efficiency
1200 μm taper	4.39×10^{-6} W	67%
4 μm channel	9.74	—
900 μm taper	1.03	33% 30%
4 μm channel	9.29	—
600 μm taper	1.77	44% 42%
4 μm channel	9.94	—
300 μm taper	1.32	36%

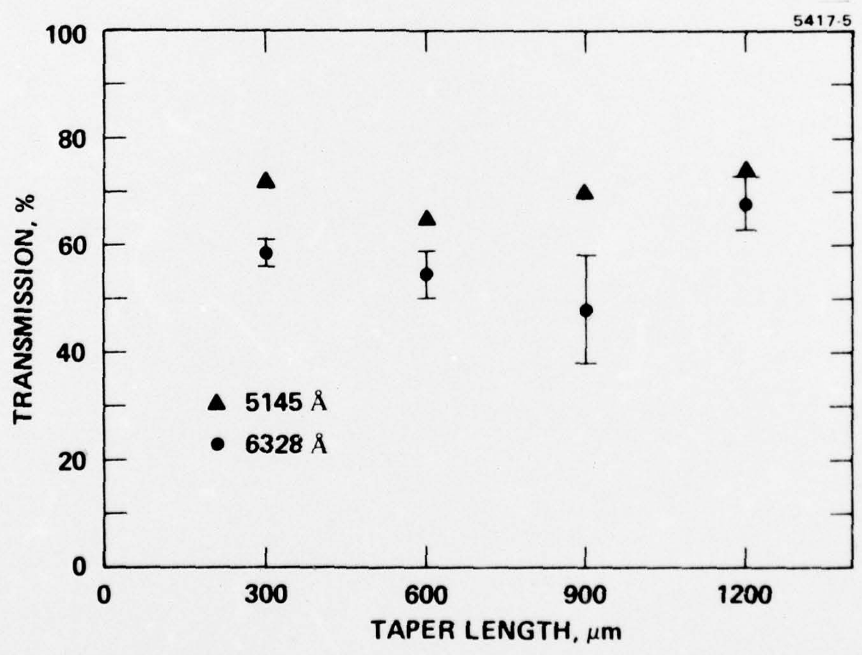

Figure 6. Single mode coupling efficiency for various taper length.

We have also measured the taper coupling efficiency at Ar^+ laser wavelength 5145 Å. At this shorter wavelength, the four different taper lengths would correspond to 1200, 2400, 3600, and 4800 times the wavelength in the guide. The laser power incident on the input coupling prism was reduced to 100 μW to avoid any possible optical damage, since the damage threshold decreases with decreasing λ. As shown in Figure 6, the taper coupling efficiencies at 5145 Å are generally higher than the value at 6328 Å for each taper length, which is consistent with the expectation that the more gentle the taper length the greater the single mode to single mode throughput.

IV. PLANS FOR THE NEXT QUARTER

Because the 70% throughput obtained in the experiments reported here is not as high as the 90% required throughput, several design modifications will be made and included in the final switch design. Instead of expanding the 4 μm channel guide to 70 μm width, a lower value of 35 μm will be used. We will also investigate the use of parabolic-shaped horns to improve the throughput.[3]

A $LiTaO_3$ boule has been ordered so that the tapered structures may be studied in a material with much higher damage threshold. The new mask design, including the electrode mask, will be completed early in the next quarter and the fabrication of the optical switch mask will be carried out immediately upon receipt of this final mask.

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[3] W.K. Burns, Private Communication.

V. SUMMARY

We have fabricated and tested linear taper horn structure formed by controlled in-diffusion of Ti into $LiNbO_3$. The single mode to single mode coupling efficiency for a TE wave was measured for four different taper lengths, corresponding to 1000, 2000, 3000, and 4000 λ using a He-Ne laser. The measured taper coupling efficiency is as high as 70% for the 4000 λ tapered structure. Waveguide losses at 6328 Å have been found to be approximately 1 dB/cm for planar guides and an estimate of the single mode channel waveguide losses yield approximately the same value of 1 dB/cm.