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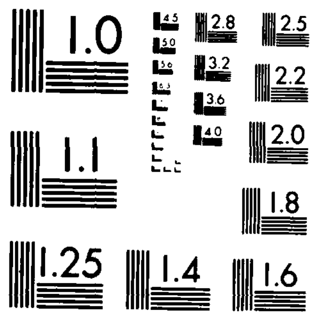

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During the third year (FY'82), a great deal of progress was made in the experimental investigation of chirped grating lenses on glass and $LiNbO_3$ waveguides. Efficiency as high as 70% has been demonstrated in $LiNbO_3$ using deposited TiO_2 on Ti-indiffused waveguides and doubly ion exchanged $LiNbO_3$ in benzoic acid. Properties of chirped grating lenses affected by the waveguide parameters, higher orders of diffraction and substrate mode conversion have been evaluated.

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INTERIM SCIENTIFIC REPORT

FRESNEL (CHIRPED GRATING) LENSES AND BEAM CONTROL IN OPTICAL WAVEGUIDES

AFOSR

AFOSR GRANT No. 80-0037

October 1st, 1981 through September 30th, 1982

Submitted by

William S.C. Chang (Principal Investigator)

Siamak Forouhar, Jean Marc Delavaux and

Christopher Warren

Department of Electrical Engineering and Computer Sciences

(C-014)

University of California, San Diego

La Jolla, CA 92093

Tel: 619-452-2737

1. Overview

For signal processing in planar waveguides, it is necessary to integrate, focus, collimate, image or Fourier-analyze guided-wave beams by efficient and low cost lenses that have both diffraction-limited performance and low noise. Figure 1 shows a typical linearly chirped grating lens that has been investigated in this research contract.

In the interim scientific reports covering the period FY'80 and FY'81 we have reported the successful design and the theoretically calculated performance of linearly chirped grating and parabolic curved chirped grating lenses by the generalized two-dimensional coupled mode analysis [1], supplemented by perturbation analysis and by an iterative perturbation anaylsis [2]. Our theoretical design data shows that very high efficiency (e.g. 95%) with very small angular field of view or moderately high efficiency (e.g. 70% ± 10%) with moderate angular field of view (e.g. 0.1 radians), diffraction limited spot size and low side-lobe intensity can be obtained on both low and high index waveguides, provided that the appropriate coupling coefficient between the incident and the diffracted beams can be obtained and that diffraction into substrate modes or higher diffraction order guided-wave beams can be neglected.

A great deal of progress was made in FY'82 in the experimental investigation of chirped grating lenses on glass and $LiNbO_3$ waveguides. Efficiency as high as 85% has been demonstrated. Properties of chirped grating lenses affected by the waveguide parameters, higher orders of diffraction and substrate mode conversion have been evaluated.

Experimental investigation of the fabrication and evaluation of grating lenses on glass waveguides in FY'81 had led to the choice of fabricating CeO_2 grating lenses by the lift-off method. The best performance that has been demonstrated is a total through-put insertion loss of 0.7dB and an angular field of view of several degrees. However, in order to optimize the performance and to evaluate the reproducibility of the performance for lenses that will have various angular field of view $\Delta\theta$, focal length f and aperture size H, we have initiated the investigation of three topics in FY'82:

(a) The tolerance and the control of the refractive index and the thickness of CeO_2 grating grooves. Both of these factors will determine the limitation, the control and the reproducibility of the coupling coefficient K_c of the diffracted and incident guided-wave beams. In a given waveguide structure, an apropriate combination of the groove length d and the K_c is necessary to maximize the diffraction efficiency.

(b) The effect of the coupling coefficient K_c, the groove length d and the grating periodicity variation on the suppression of higher orders of diffracted beams. The understanding of this effect is fundamental to the optimization of angular field of view $\Delta\theta$ by using small groove length d.

(c) The effect of the tolerances of microfabrication processes such as the lithography resolution on the performances of grating lenses.

The results of these studies are presented in Section 2. Some of the investigation is carried out in constant periodicity CeO_2 gratings on glass waveguides to simplify the interpretation of experimental results. The objective of all the studies conducted on the glass waveguide is to take advantage of the simplicity of a step index waveguide and the convenience of the CeO_2 film to investigate the fundamental limitations of the chirped grating lenses that are caused by diffraction properties and by fabrication tolerances.

Experimental work on the fabrication and evaluation of chirped grating lenses on $LiNbO_3$ waveguides has been expanded a great deal in FY'82. We have found from this study not only that high efficiency can be realized but also that the $LiNbO_3$ lens performance (i.e. high efficiency combined with reasonably large angular field of view) is limited primarily by the properties of single mode Ti-indiffused $LiNbO_3$ waveguides due to three reasons:

(a) The mode index n_e of the Ti-indiffused $LiNbO_3$ waveguide is close to the substrate index, n_s, so the coupling to the substrate modes may limit the maximum angular field of view or the efficiency of small F-number grating lenses.

(b) The Ti-indiffused single mode $LiNbO_3$ waveguides have large mode depth as well as small $(n_e - n_s)$. The large mode depth implies weak interaction (i.e. small coupling coefficient), thus requiring long groove length d for efficient diffraction. Long groove length implies small angular field of view.

(c) The grating grooves should be fabricated in such a way that the grooves will create a large perturbation of n_e with submicron resolution. This is difficult to accomplish in $LiNbO_3$ with known lithographic and microfabrication processes.

Nevertheless, a maximum diffraction efficiency of 67% and $\Delta\theta = 2^0$, have been obtained experimentally in a single mode Ti-indiffused waveguide. Alternatively, if one accepts the use of double mode waveguides, then the best measured efficiency is 61% with $\Delta\theta = 2^0$. In this case the high efficiency is produced by the smaller mode depth of the TE_0 mode in a double mode waveguide. Higher efficiency should be able to be obtained by optimizing better the $K_c d$ value. However, the d values of these lenses are relatively long, approximately 300 μm, implying a small $\Delta\theta$. On the other hand, two alternate approaches to Ti-indiffused $LiNbO_3$ waveguides have also been investigated experimentally to increase K_c and to shorten d. They are (1) the use of ion exchange to fabricate $LiNbO_3$ waveguides and chirped gratings, and (2) the use of deposited Nb_2O_5 on $LiNbO_3$ as a transition waveguide interconnecting two separate sections of Ti-indiffused $LiNbO_3$ waveguide. A maximum diffraction efficiency of 80% and a measured $\Delta\theta$ of 2.4 degrees have been demonstrated in a linearly chirped grating lens in an ion exchanged waveguide. Details of all the work on $LiNbO_3$ waveguide lenses are given in Section 3.

The major objectives of the study of the chirped grating lenses on $LiNbO_3$ waveguides are (a) to determine the best performance that can be obtained in Ti-indiffused waveguides, (b) to find alternative material structures that can circumvent the difficulties of the large mode depth and small $(n_e - n_s)/n_s$ ratio and (c) to assess the limitations imposed by these structures. The continuation of this study will be carried in a new joint TRW-UCSD program sponsored by the Air Force Avionics Laboratory in Wright Patterson AFB, Ohio, during the next contract period.

2. Investigation of CeO_2 Chirped Grating Lenses on Glass Waveguides

2.1 The Tolerances of the n_e in Glass Waveguides

In order to obtain high quality glass waveguides reproducibly that have low in-plane scattering and specific mode depth, we have standardized our glass waveguide fabrication to the following process:

(1) Oxidation of Si wafers in wet oxygen at 1000^0 for approximately 30 hours to obtain high quality SiO_2 substrates;

(2) In order to avoid surface contamination either the oxidized samples are used immediately after removal from the oxidation process or the samples are re-heated in the oxidation furnace at 800°C for 60 minutes before sputter deposition;

(3) Sputter deposition of BaO glass is carried out with 400 watts of r.f. power, under a total pressure of 15×10^{-3} Torr with a gas mixture of Ar to O_2 at a ratio of 1:2. The average deposition rate is 20 A/min, and the d.c. bias voltage of the target is 1200 Volts;

(4) The typical waveguide has a 7059 glass layer 7000 A thick with a film index of $n_f = 1.56 \pm .01$ and a substrate index of $n_s = 1.465 \pm .005$. The typical attenuation rate of our waveguides is 1 to 2 dB/cm and the n_e is 1.527. Alternatively, the typical waveguide that has a BaO glass layer has $n_f = 1.53 \pm .01$, attentuation rate = 2 to 3 dB/cm and $n_e = 1.50$. The tolerance of the waveguide parameters represents the best we can do using an ordinary r.f. sputtering setup with base vacuum of 5×10^{-7}, turbo molecular pump, mass-flow control of gas mixture and no temperature monitoring of the substrate.

2.2 The Tolerances of the Index and the Thickness in the CeO_2 Deposition Process

In FY'81, we deposited CeO_2 films by thermal evaporation which gave an index variation of ±0.08 from one run to another and a poor control of film thickness, ranging from 50 to 700 A. After some investigation, we have found that the E-beam evaporation gives much better index and thickness tolerances. Furthermore, we found that the content of H_2O in the CeO_2 charge is a dominant cause for index fluctuation [3]. Thus, we have developed a new standard CeO_2 deposition process consisting of the following procedure:

(a) Press CeO_2 at 1500 psi to form a disc of CeO_2 charges.

(b) Anneal the pressed charges in nitrogen (flow rate 1000 cc/min) at 1100^0 for 2 hours.

(c) Store the annealed charge under vacuum to prevent water vapor contamination.

(d) Place the charge in a vitreous carbon boat for E-beam evaporation (typical background vacuum 1×10^{-7}, 9KV, unfocused beam, beam current = 5.3 mA).

Figure 2 shows the indices of the CeO_2 measured by an ellipsometer for different deposition runs. Clearly the index of our E-beam deposited CeO_2 is $n = 1.89 \pm .02$. The tolerance of the thickness of the E-beam evaporation process is ± 20 A.

2.3 The Variations of n_e and Δn_e for TE and TM Modes

Theoretical results have been obtained previously to give the value of n_e as a function of the waveguide glass layer thickness and the change in effective index from the original waveguide (i.e. Δn_e) when certain thickness of CeO_2 film is deposited on top, as shown in Figure 3. Δn_e is related to the coupling coefficient K_c, and $K_c d$ is the predominant factor that determines the efficiency of the lens. For every glass waveguide chip (consisting of a 2 inch wafer) fabricated by sputter deposition, we first measure the n_e of that waveguide. We have found that within the same chip, the variation of n_e from one region to another region is only $\pm$ 0.005. Several waveguides are obtained from the same chip by subdividing the 2 inch wafer. For that measured average n_e, we calculated the CeO_2 thickness required to give a desired Δn_e and then fabricate the CeO_2 film on these waveguides by electron beam evaporation. The index and the thickness of the deposited CeO_2 films are monitored by the ellipsometer and by the Dektak. For 4 samples of BaO glass waveguides cut form the same chip, the measured Δn_e for the TE modes (Δn_{TE}) and for the TM modes (Δn_{TM}) are given in Table 1. A comparison of the experimental Δn_e with theoretical predictions is given in Figure 4. Clearly, the variation of Δn_e is approximately 30% to 50%; it is too large for practical production of chirped grating lenses, but adequate for exploratory research investigations. Based upon this experience, we conclude that in order to make a significant improvement much more engineering development work will be needed to control the tolerance of both the n_e of the waveguide and the index and thickness of CeO_2 film for the production of such lenses in the future.

2.4 The Coupling Coefficient Variation

The solid line in Figure 5 shows the calculated coupling coefficient K_c as a function of Δn_e based on perturbation analysis. The discrete data points are obtained from the measured K_c and Δn_e of our samples that have both CeO_2 overlay films and CeO_2 constant periodicity gratings with different periodicity Λ fabricated simultaneously in two different regions on the same glass waveguide. Clearly that, in glass waveguides, $K_c = \Delta n_e/(\lambda_0/2)$ is valid for K_c values up to 0.02 (1/μm). The spread of the experimental points are within the accuracy of the measurement procedures of K_c and Δn_e .

2.5 The Maximum Diffraction Efficiency and the Higher Orders of Diffraction

Constant periodicity gratings at 4 different values of Λ (Λ = 1, 2, 4 and 8 μm) and two different groove lengths (d = 80 μm and d = 250 μm) have been fabricated on glass waveguides with various CeO_2 thicknesses to check the accuracy of the coupled mode analysis. The discrete data points in Figure 6 show the measured diffraction efficiency η as a function of Δn_e for an example that has d = 80 μm (the square dots) and d = 250 μm (the circular dots) and Λ = 4 μm. The solid curves represent the theoretical predictions based upon the coupled mode theory. Figures 7 and 8 show the similar results obtained for Λ = 2 μm and 8 μm. Notice that for the d = 80 μm and Λ = 8 μm case the experimentally measured η is significantly below the theoretical predictions. Significant amounts of power diffracted into higher orders of diffraction has been observed in this case. For other cases Λ = 2 and 4 μm, d = 80 μm and 250 μm and Λ = 8 μm, d = 250 μm, the measured results are in agreement with the predictions of the coupled mode theory. Maximum diffraction efficiency of 91%, 98% and 88% have been obtained for Λ = 8, 4 and 2 μm at $K_c d \approx 1.58$. Thus, we have shown experimentally that:

(a) Random scattering loss can be kept to less than 10% in grating deflectors.

(b) The coupled mode analysis gives accurate prediction of diffraction efficiency for both the TE and TM modes, provided that higher orders of diffraction can be neglected.

(c) The coupling coefficient should be designed according to $K_c d = \pi/2$ for maximum efficiency. $K_c = \Delta n_e/(\lambda_0/2)$ where Δn_e is the change in the effective index of the guided ve mode caused by the CeO_2 layers. The maximum limit ('- value within which the relationship $K_c = 2\Delta n_e/\lambda_0$ is \ i has not yet been determined. It is expected to vary accorc :· ɔ the waveguide structure (e.g. glass waveguide, $LiNbO_3$, etc.).

In order to predict the conditions (i.e. Bragg diffraction condition) under which the diffraction into higher orders can be ingored, we note that Moharam, Gaylord and Magnusson [4] had predicted theoretically an upper bound of the diffraction efficiency into the higher order modes to be $1/\rho^2$, where

$$\rho = \frac{\lambda_0^2}{\Lambda^2 n_e \; \Delta n_e} \tag{1}$$

In terms of the more familiar Q factor ($Q = \frac{2\pi d \lambda_0}{n_e \Lambda^2}$) :

$$\rho = \frac{Q}{2 \times K_c \times d \times \cos \theta_B} \tag{2}$$

The significance of equation (2) is that the diffraction into the higher orders can be significant even for large Q if $K_c d$ is large. Conversely, diffraction into higher orders may still be negligible for low Q gratings provided $K_c d$ is small. However, for efficient grating lenses $K_c d \approx \pi/2$ In that case $Q = \pi\rho \cos \theta_B$, there is no significant difference in using either ρ or Q as the criteria for Bragg diffraction.

Experiments have been performed in UCSD on the waveguides that have $\Lambda = 8, 4, 2$ µm, d = 250, 80 µm and various Δn_e to measure the diffracted guided wave power into the higher orders. So far, for the limited cases that have been examined we have found that $1/\rho^2$ serves well as an upper bound to power diffracted into higher orders at $Q > 40$. In those cases the measured power in the higher orders is well below that predicted by $1/\rho^2$. For $Q \approx 10$ and 15, the measured power in the higher orders of diffraction is of the same order as that predicted by $1/\rho^2$. For $Q \approx 3.5$, the measured power in the higher orders of diffraction is sometimes larger than that predicted by $1/\rho^2$, i.e. the use of $1/\rho^2$ as an upper bound becomes questionable. The investigation of the higher orders of diffraction is continued in the next contract period, the details of these results will be reported later.

2.6 The Lens Performance Limitation Imposed by Λ_{min} and Λ_{max}

From the experimental studies of the higher orders of diffraction using constant periodicity gratings, we may conclude that there is a maximum Λ for a given groove length d such that significant amounts of optical power may be diffracted into higher orders when $\Lambda > \Lambda_{max}$. In order to evaluate this Λ_{max}, we can define a local Q factor such that $Q = 2\pi\lambda_0 d/n_e\Lambda^2$ as a function of the transverse position within the lens aperture. Assuming $Q \approx 10$ (i.e. $\rho \approx 30$) is the limit within which the power diffracted into the higher orders at $K_c d \approx \pi/2$ is within the acceptable limit, then

$$\Lambda_{max} = (2\pi\lambda_0 d/n_e Q_{max})^{1/2} \quad (3)$$

At $\lambda_0 = 0.6328$, $\Lambda_{max} = 0.51(d)^{1/2}$ in µm. On the other hand, as discussed in the FY'82 interim scientific report, the Λ_{min} will be limited by the resolution of electron beam lithographic process to 1 µm, and the minimum F number limited by Λ_{min} alone is $\Lambda_{min}\, n_e/\lambda_0$. Thus, the minimum F-number of the lens will be limited by both the Λ_{min} and the Λ_{max}.

If the lens design calls for an F number larger than the above limit, then it is generally preferable to use Λ as small as possible so that (a) relatively large Q values can be maintained for shorter d (i.e. larger Δn_e) and larger $\Delta\theta$ and (b) that the larger Bragg angle will reduce the amount of radiation noise that may be scattered into the focused spot from other orders of diffraction.

2.7 Conversion into Substrate Modes

As opposed to Ti-indiffused $LiNbO_3$ waveguides, conversion of the power to the substrate mode by the chirped grating lens has not yet been observed in the glass waveguide. We attribute this phenomena to the large $(n_e - n_s)/n_s$ ratio in glass waveguides.

3. Investigation of Chirped Grating Lenses in $LiNbO_3$ Waveguides

Since the report of the first chirped grating lens on a $LiNbO_3$ waveguide in the FY'81 Inte im Scientific report, substantial progress has been made to optimize its performance in FY'82. (1) Chirped grating lenses with throughput efficiency as high as 75% have been fabricated and measured in both the Ti-indiffused waveguides and the ion exchanged waveguides made from emersing $LiNbO_3$ in benzoic acid. (2) Extensive studies have been conducted on the TiO_2 lenses deposited on Ti-indiffused waveguides to determine (a) the limitation on the coupling coefficient, (b) the extent in which conversion into substrate modes affects the efficiency, and (c) the tolerances within which $K_c d$ can be controlled to optimize the efficiency. (3) Transition waveguides made by sputter deposition of Nb_2O_5 on $LiNbO_3$ has been demonstrated to have a very low interconnection insertion loss, less than 1.2 dB. (4) Chirped grating lenses fabricated by a second ion exchange in benzoic acid on ion exchanged $LiNbO_3$ waveguides have demonstrated very large coupling coefficient K_c and high diffraction efficiency; a throughput efficiency of 75% has been observed. The details of these studies are described in the following subsections.

3.1 TiO_2 Lenses Deposited on Ti-indiffused $LiNbO_3$ Waveguides

For chirped grating lenses made by depositing TiO_2 grooves on Ti-indiffused waveguides, we need to know (a) the repoducibility and the limitation of Δn_e in this method, (b) the coupling coefficient K_c as a function of Δn_e , and (c) the efficiency as it is affected by conversion of guided wave power into substrate modes and the losses into higher orders of diffraction. This knowledge will then show how the chirped grating lenses can be designed and whether they can meet the specifications of various applications directly on the Ti-indiffused waveguide.

We have found that the TiO_2 films obtained by our method of oxidizing Ti films evaporated by an electron beam gives very reproducible index (n = 2.63 ± 0.01) and thicknesses (thickness control within ± 10 A), as long as the base vacuum within the belljar is kept below 5×10^{-7}Torr. The n_e of the Ti-indiffused waveguide for a given process condition (i.e. diffusion temperature and time, oxygen flow rate and water bubble temperature) seems to be reproducible within the accuracy of our measurement techniques. However, the Δn_e (i.e. the change in effective index of the waveguide with and without the TiO_2 film) that can be realized with a given TiO_2 film depends on the amount of H_2O content during the diffusion process of the $LiNbO_3$ waveguide. With oxygen flowing through the water bubbles at room temperature (no temperature control), the highest Δn_e that we have obtained so far is only 0.0013. Much larger Δn_e (Δn_e = 0.0033) has been obtained by flowing oxygen through water at 95^0 temperature. The Δn_e that can be obtained for waveguides produced with a given condition of the Ti-indiffusion process and without water temperature control are also not reproducible, fluctuations of Δn_e as large as 0.004 have been observed experimentally. We suspect the changes in Δn_e are caused by variations in mode depth. More research will be conducted to unravel the nature of the variation in Δn_e .

The small Δn_e will limit severely the angular field of view of high efficiency lenses. For example, for Δn_e = 0.0007 and an F = 14, Λ_{max} = 14.2, Λ_{min} = 3.2, and d = 300 μm lens, the Δn_e has already limited out measured efficiency to 45% and measured $\Delta\theta$ to less than 2^0. Nevertheless, when $K_c d$ is close to $\pi/2$ we have obtained high efficiencies. For a constant periodicity grating with $\Lambda = 3$ µm, Δn_e 0.0024 and d = 200 µm we obtained experimentally an 85% throughput efficiency. For an F = 14, $\Lambda_{max} = 14.2$ $\Lambda_{min} = 3.2$ µm and d = 350 µm we obtained an unexpected large Δn_e of 0.0033 which means that $K_c d$ becomes much larger than 1.5. Yet we have still obtained a 67% throughput efficiency for this lens. On the other hand we also have experimental evidence that the value of K_c is not always proportional to Δn_e by a factor of $\lambda_0/2$ as predicted by perturbation analysis, the K_c value seems to saturate at $\Delta n_e > 0.004$. A saturation of K_c at 0.015 (1/µm) will still imply a relatively small $\Delta\theta$ for high efficiency lenses because the optimum d is 100 µm for $K_c d = \pi/2$. More results concerning this saturation phenomena will be reported in the future. We are currently measuring the K_c as a function of Δn_e by means of constant periodicity gratings.

Preliminary probing has also been made to find out the Δn_e that can be realized for thicker Ti diffused layers or larger n_e such that the region under the TiO_2 layer will propagate two T.E. modes. The reason for doing this is that the TE_0 mode of a two-mode waveguide will have a smaller mode depth, therefore, a larger Δn_e for a given TiO_2 layer. For an F = 12 lens with $\Lambda_{min} = 1.73$ µm and $\Lambda_{max} = 3.44$ µm on Ti-indiffused $LiNbO_3$ waveguide made with water bubbles at room temperature we have obtained $\Delta n_e = .0038$ and a 61% throughput efficiency at d = 150 and a 60% efficiency at d = 80 µm. Δn_e as large as .007 has also ben obtained on a two-mode Ti-indiffused $LiNbO_3$ waveguide with water bubble temperature at 95^0.

So far, we have not observed any significant amount of power diffracted into higher orders. Most of our gratings and lenses have Q values ranging from 7 to 86. However, substantial conversion of the guided wave power into substrate modes has been observed in some of the samples, especially in the curved chirped gratings. We have not yet found a more precise criteria that can be used to judge whether a given lens design in the Ti-indiffused waveguide will have a severe problem in substrate mode conversion.

3.2 Doubly Ion Exchanged Chirped Grating Lenses

The ion exchange process in $LiNbO_3$ [5] has been reported to give a large index change. Thus, we have developed single mode waveguides by emersing x-cut $LiNbO_3$ in benzoic acid in the temperature range of 200 - 230^0 for a few minutes. Using an 8-mode waveguide processed at 218^{0}C for 446 minutes and the WKB approximation, we have determined experimentally that the ion exchanged waveguide can be approximated by a step index waveguide with a material index of 2.32 in the guiding layer. Figure 9 shows the fit of the step index profile to the index values calculated from the WKB method for an 8-mode waveguide. When samples are immersed in benzoic acid at 218^{0}C for 10 minutes, we obtain single mode ion exchanged waveguides with $n_e = 2.26 \pm 0.01$ for the TE_0 mode. For a single mode step index waveguide with 2.32 material index, this corresponds to an average waveguide thickness of 0.40 μm and a diffusion coefficient of 0.24 μm^2/hr. Such a waveguide differs from a Ti-indiffused waveguide in its layer $(n_e - n_s)/n_s$ ratio and in its shallow mode depth.

When ion exchange is applied to a Ti-indiffused waveguide, the appearance of the second mode after the exchange limits the Δn_e that we can get. Using Ti-indiffused waveguides on x-cut $LiNbO_3$ with $n_e = 2.2031$ before the exchange, we obtained $\Delta n_e = 0.0021$ for 8 minutes at 208°C and $\Delta n_e = .0004$ for 4 minutes at 205°C. Exchange at 12 minutes at 203°C, 5 minutes at 220°C and 10 minutes at 213°C have all yielded double mode waveguides after the exchange.

Because of the limitations in Δn_e that can be obtained in single mode Ti-indiffused waveguides with ion exchange, we have investigated the use of double ion exchange for making grating lenses. For a second exchange at 204°C for 3 minutes, we have obtained Δn_e varying from 0.0030 to 0.0096. The average Δn_e that has been obtained for a second ion exchange at 204°C is $\Delta n_e = 0.0017\ t_{exc}$ where t_{exc} is the second exchange time in minutes. However, there is a considerable uncertainty about the variations of the Δn_e that can be obtained from the same nominal conditions of the exchange. For example, for 4 samples that have undergone the second exchange at 204°C for 3 minutes, the Δn_e varies from 0.0032 to 0.0096.

Chirped grating lenses have been fabricated by first making an Al grating lens mask (approximately 1000 A thick) on top of a single-mode ion exchanged $LiNbO_3$ waveguide by the lift-off method, followed by a second ion exchange in benzoic acid at 204°C for 3 minutes. The Al mask is then removed by chemical etching after the second exchange. For an F = 12 linear chirped grating lens with $\Lambda_{min} = 1.73$ µm, $\Lambda_{max} = 3.45$ µm and d = 80 µm, we have measured a throughput efficiency of 75% and a $\Delta\theta$ of approximately 2 degrees.

If the sample that has both a Ti-indiffused waveguide and a benzoic acid exchanged layer to obtain Δn_e is heated a second time in the air, the Δn_e created by the exchanged layer is found to increase. For heating at 218^{0}C, we found that the Δn_e is increased from 0.004 to 0.014 after 15 minutes and to 0.018 after 30 minutes. A second sample that had Δn_e = 0.0021 before heating at 218^{0}C has a measured Δn_e = .0075 and .0099 after 15 minutes and 30 minutes of heating respectively. This effect seems to saturate after 30 minutes.

In short, our preliminary results indicate that ion exchange in benzoic acid can produce large Δn_e. The large Δn_e should lead to efficient lenses with small d. The potential major drawbacks of the ion exchanged waveguide are (a) large inplane scattering loss and (b) significant amount of power scattered into substrate modes, but these effects still remain to be measured. The potential major drawbacks of using ion exchange to obtain grating fingers are (a) non-reproducibility of Δn_e and (b) the stability of Δn_e (or K_c) as a function of temperature. More data will be collected and reported in the future concerning the ion exchanged chirped grating lenses.

3.3 Chirped Grating Lenses on Nb_2O_5 Waveguides on the $LiNbO_3$ Substrate

A second alternative to the Ti-indiffused waveguide is a waveguide made of Nb_2O_5 films (n = 2.24 to 2.29) deposited on top of a $LiNbO_3$ substrate. Such a waveguide will have a smaller mode depth and a larger $(n_e - n_s)/n_s$ ratio than the Ti-indiffused waveguides. Since the Ti-indiffused waveguide is superior to Nb_2O_5 in electro-optical acousto-optical interactions, it is important that we can perform other signal processing functions in Ti-indiffused waveguides while the lens function is carried out in the Nb_2O_5 waveguide on the same chip. Thus, we have proposed, developed and evaluated a Nb_2O_5 transition waveguide interconnecting two sections of Ti-indiffused waveguide as shown in Figure 10.

In our laboratory, the Nb_2O_5 film is deposited by reactive sputtering of Nb metal target in an argon-oxygen atmosphere. The refractive index of the sputtered films are very sensitive to the sputtering parameters such as r.f. power, argon-oxygen partial pressures; it can vary from 2.21 to 2.28. For our interconnection films, we have used 150 watts of r.f. power under a 3 to 1 argon to oxygen mixture at 15 μm of total pressure, a total flow rate of10 sccm/min. and a target to sample distance of 4 inches. Under this condition the deposition rate is 7 Å/min. and the index of the Nb_2O_5 material is 2.245 ± .005. The attenuation of our Nb_2O_5 waveguide is 7 dB/cm. However, Nb_2O_5 film waveguide with much lower attenuation has been reported by R. Davis [6]. Figure 11 shows the calculated coupling coefficient as a function of the etching depth. Clearly, a large coupling coefficient can be expected. Based upon our experience with the chirped grating lenses in various waveguides reported in the preceeding sections, we can expect an efficient chirped grating lens on Nb_2O_5 waveguide, provided we can obtain a low loss for the interconnections.

An extensive amount of work has been done in controlling the profile of sputtered films for fabrication of integrated optic devices such as Luneberg lens [7]. Edges with long tapers and very gentle slopes can be obtained by undercutting the bottom surface of the shadowing masks. We have experimentally studied and evaluated different taper slopes using glass shadow masks during sputtering. Glass masks instead of metal masks are used in order to avoid perturbation of the electric field. Figure 12 shows the mask configurations used in our deposition process and the thickness variation of the sputtered taper measured by the Dektak. The insertion loss of the tapered interconnection is measured by placing our input prism coupler on side A of the Ti-indiffused waveguide and an output prism coupler on side B as illustrated in Figure 10. The total insertion loss is the logarithm of the ratio of the power detected on side B to the power that would have come from the output coupler when the Ti-indiffused waveguide is continuous and where there is no Nb_2O_5 transition waveguide. The best insertion loss we have obtained is 1.2 dB with 2 sections of Ti-indiffused waveguide separated by 1mm.

In short, we have demonstrated that efficient Nb_2O_5 transition waveguides interconnecting 2 Ti-indiffused waveguides can be realized. A comparative study among the use of the Ti-indiffused waveguides, the ion exchanged waveguide and the TiO_2 transition waveguide for optimizing the performance of the chirped grating lenses will be undertaken in the joint UCSD-TRW project.

3.4 Papers Published and Submitted

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Z-Q. Lin, S. T. Zhou, W. S. C. Chang. S. Forouhar and J. Delavaux, "A Generalized Two-Dimensional Coupled-Mode Analysis of Curved and Chirped Periodic Structures in Open Dielectric Waveguides", MTT Transactions, MTT-29, 881 (1981).

W. S. C. Chang, Z-Q. Lin, S. T. Zhou, J. Delavaux and S. Forouhar, "The Feresnel and Chirped Grating Lenses in Optical Waveguides", Proceedings of SPIE Technical Symposium, Vol. 269, p.105, North Hollywood, 1981 (February).

S. Forouhar and W. S. C. Chang, "Analysis of Chirped Grating Lenses", 1980 IEEE MTT-S International Microwave Symposium, May 28th-30th, 1980, Washington, D.C.

W. S. C. Chang, Z-Q. Lin, S. T. Zhou, J. Delavaux and S. Forouhar, "The Fresnel and Chirped Grating Lenses in Optical Waveguides", SPIE Technical Symposium, Los Angeles, 1981 (February).

Z-Q. Lin, S. T. Zhou, W. S. C. Chang, S. Forouhar and J. Delavaux, "A Generalized Two-Dimensional Coupled-Mode Analysis of Curved and Chirped Periodic Structures in Open Dielectric Waveguides", MTT International Symposium, Los Angeles, 1981 (June).

W. S. C. Chang, S. T. Zhou, Z-Q. Lin, S. Forouhar and J. M. Delavaux, "Performance of Diffraction Lenses in Planar Optical Waveguides", The Third International Conference on Integrated Optics and Fiber Optics, Communications, San Francisco, 1981 (April).

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J. Delavaux, S. Forouhar, W. S. C. Chang and R. X. Lu, "Experimental Fabrication and Evaluation of Diffraction Lenses in Planar Optical Waveguides", paper submitted to IEEE/OSA CLEO '82, April 14th-16th, 1982, Phoenix, Arizona.

W. S. C. Chang, S. Forouhar, J. Delavaux, R. X. Lu, "Fabrication and Performance of Diffraction Lenses", SPIE Technical Symposium, Los Angeles, California, January 28th-29th, 1982.

J-M. Delavaux, S. Forouhar, W. S. C. Chang and R. X. Lu, "Experimental Fabrication and Evaluation of Diffraction Lenses in Planar Optical Waveguides", paper submitted to IEEE/OSA CLEO '82, April 14th-16th, 1982, Phoenix, Arizona.

W. S. C. Chang, S. Forouhar, J-M. Delavaux, R. X. Lu, "Fabrication and Performance of Diffraction Lenses", SPIE Technical Symposium, Los Angeles, California, January 28th-29th, 1982.

W. S. C. Chang, S. Forouhar, J-M. Delavaux, C. Warren and R. X. Lu, "Chirped Grating Lenses in Ti-indiffused $LiNbO_3$ Optical Waveguides". Paper presented at the European Conference on Optical Systems and Applications, 7th-10th, September, 1982, Edinburgh, Scotland. To be published in the Proceedings.

3.5 Persons Supported in this Grant During FY'82

1. William S. C. Chang, Professor
2. Siamak Forouhar, Graduate Assistant
3. Jean-Marc Delavaux, Graduate Assistant
4. Wilson Yu, Graduate Assistant
5. Christoper Warren, Graduate Assistant
6. Interactions and coupling with other groups.

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Ron Xin Lu is a visiting scholar from Chengtu Institute of Radio Engineering, People's Republic of China. He is not supported by this grant. However, he has carried out the work of the reactive sputtering of Nb_2O_5 film and the sputtering of glass waveguides.

During FY'82 we have prepared a proposal to the Air Force Avionics Laboratory, WPAFB, jointly with TRW Technology and Research Center, El Segundo, California, for developing a chirped grating lens on $LiNbO_3$ for r.f. spectrum analysis. As a result, such a contract has been awarded to the TRW-UCSD team. This represents a successful transfer of the 6.1 basic research results into a 6.2 applied research program to be jointly conducted by the industry and the University.

3.6 References

1. Z-Q. Lin, S. T. Zhou, W. S. C. Chang, S. Forouhar nad J-M. Delavaux, "A Generalized Two-Dimensional Coupled-Mode Analysis of Curved and Chirped Periodic Structures in Open Dielectric Waveguides", MTT Transactions, MTT-29, 881 (1981).

2. S. Forouhar and W. S. C. Chang, "Analysis of Chirped Grating Lenses", 1980 IEEE MTT-S International Microwave Symposium, May 28th-30th, 1980, Washington, D.C.

3. G. Hass, J. B. Ramsey and R. Thun, "Optical Properties and Structure of Cerium Dioxide Films", JOSA, vol. 48, No.5, p. 324, May (1958).

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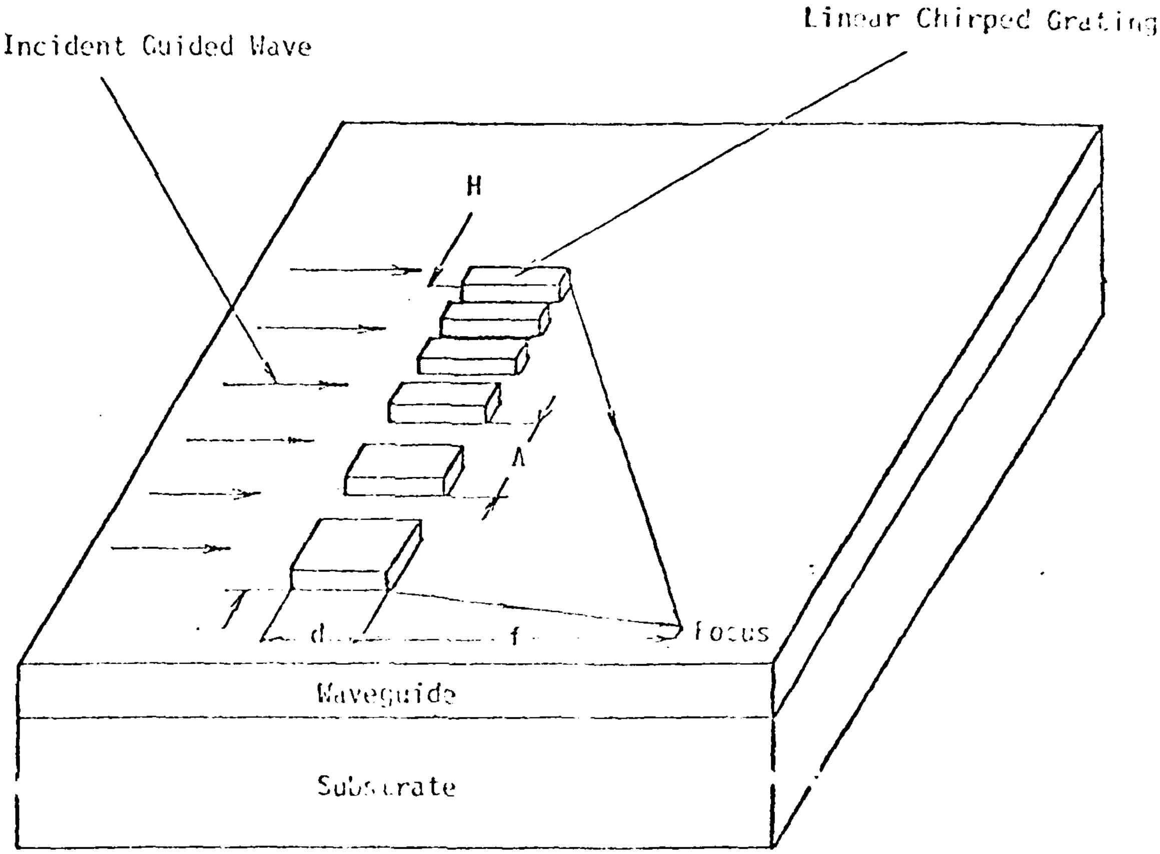
TABLE 1

Sample I.D.	Δn TE x 10^3	Δn TM x 10^3	τCeO_2 (Å) D	τCeO_2 (Å) E	n_{CeO_2} Si	n_{CeO_2} Glass	Comments
SEBWG1	8.4 (± 1)	6.5 (± .5)	260 ± 15	300	1.88		All four samples are from the same wafer. All Δn_e measured with same prism $n = 1.75$ $\tau_{BaO} = .45$ $\tau_{SiO_2} = 2\mu m$
N18	5.97 (± 1.41)	5.48 (± .54)		250	1.91		
SB7	8.1 (± .3)	4.75 (± .25)	290 ± 40	350	1.89	1.97 BaO	
SB8	10.89 (± .34)	8.41 (± 12)	230 ± 10	335	1.87	1.94	

Note: D and E stand for thickness measurements with the Dektak insturment and the ellipsometer.

BRAGG DIFFRACTION

CHIRPED GRATING LENS



TYPICAL DIMENSIONS OF A GRATING LENS

d = (15 - 400 μm)

Λ = (1 - 20 μm)

H (1 to several mm)

f = (5 - 30 mm)

Figure 1

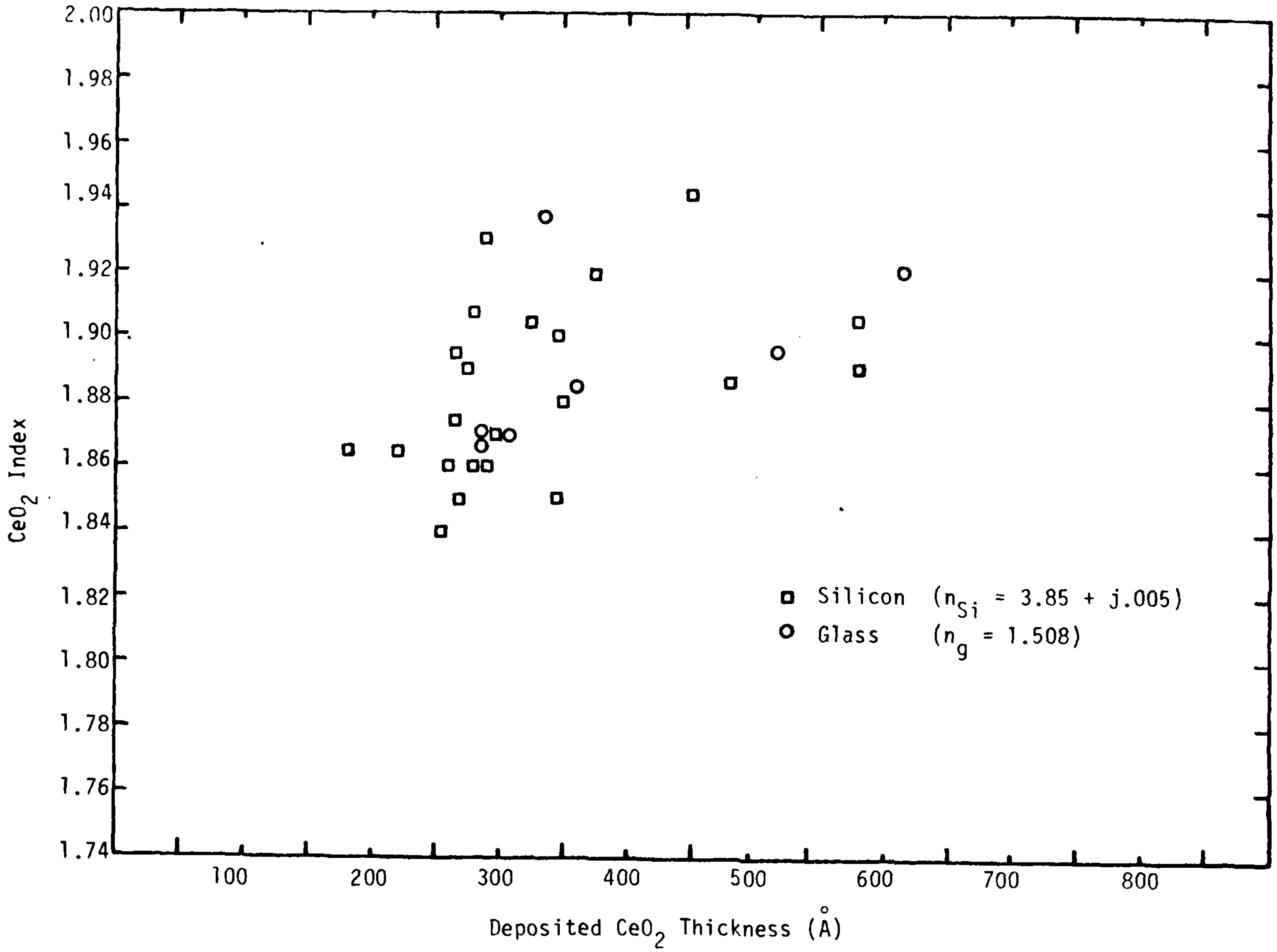


Figure 2 Indices of the CeO_2 Deposited by E-beam Evaporation

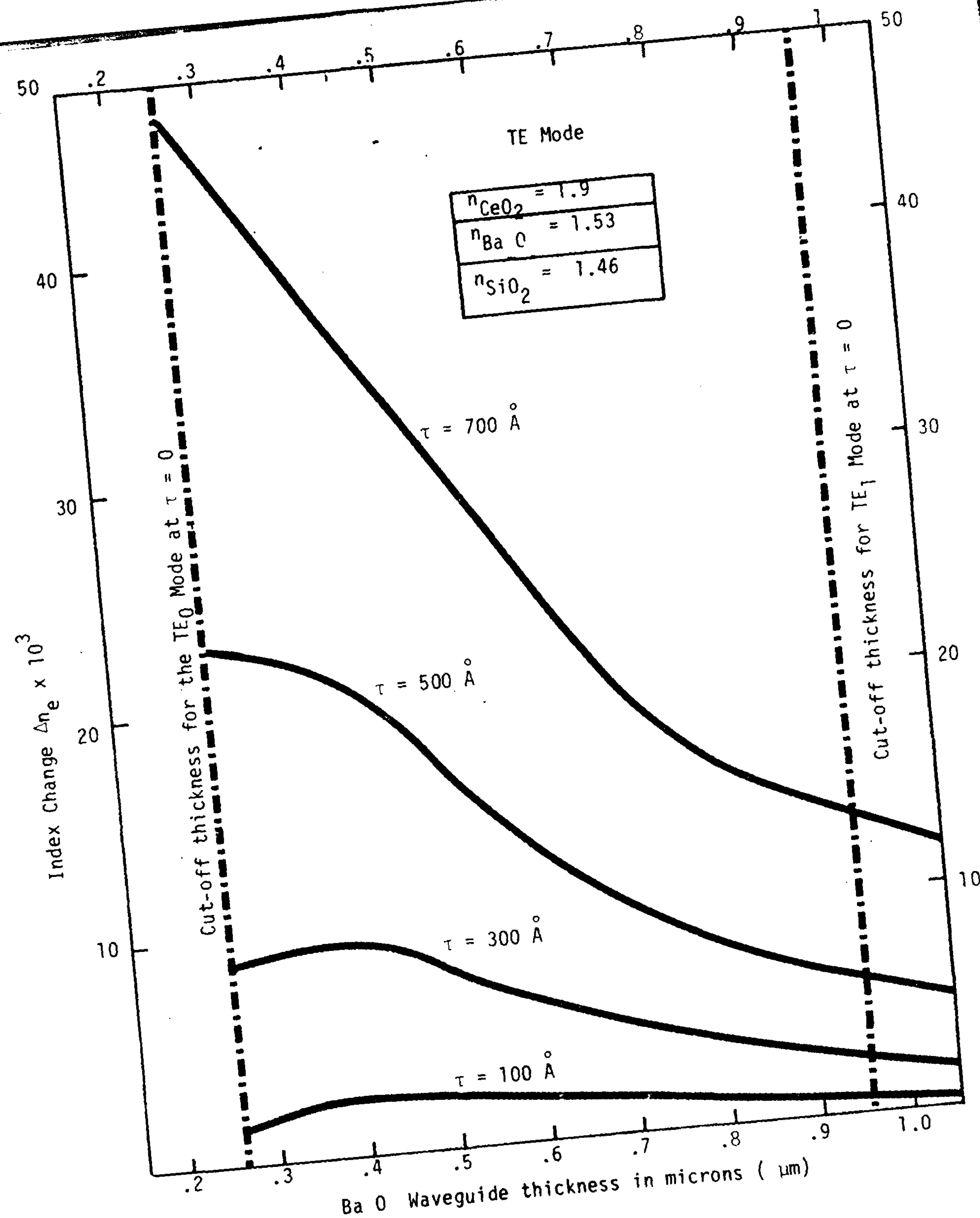
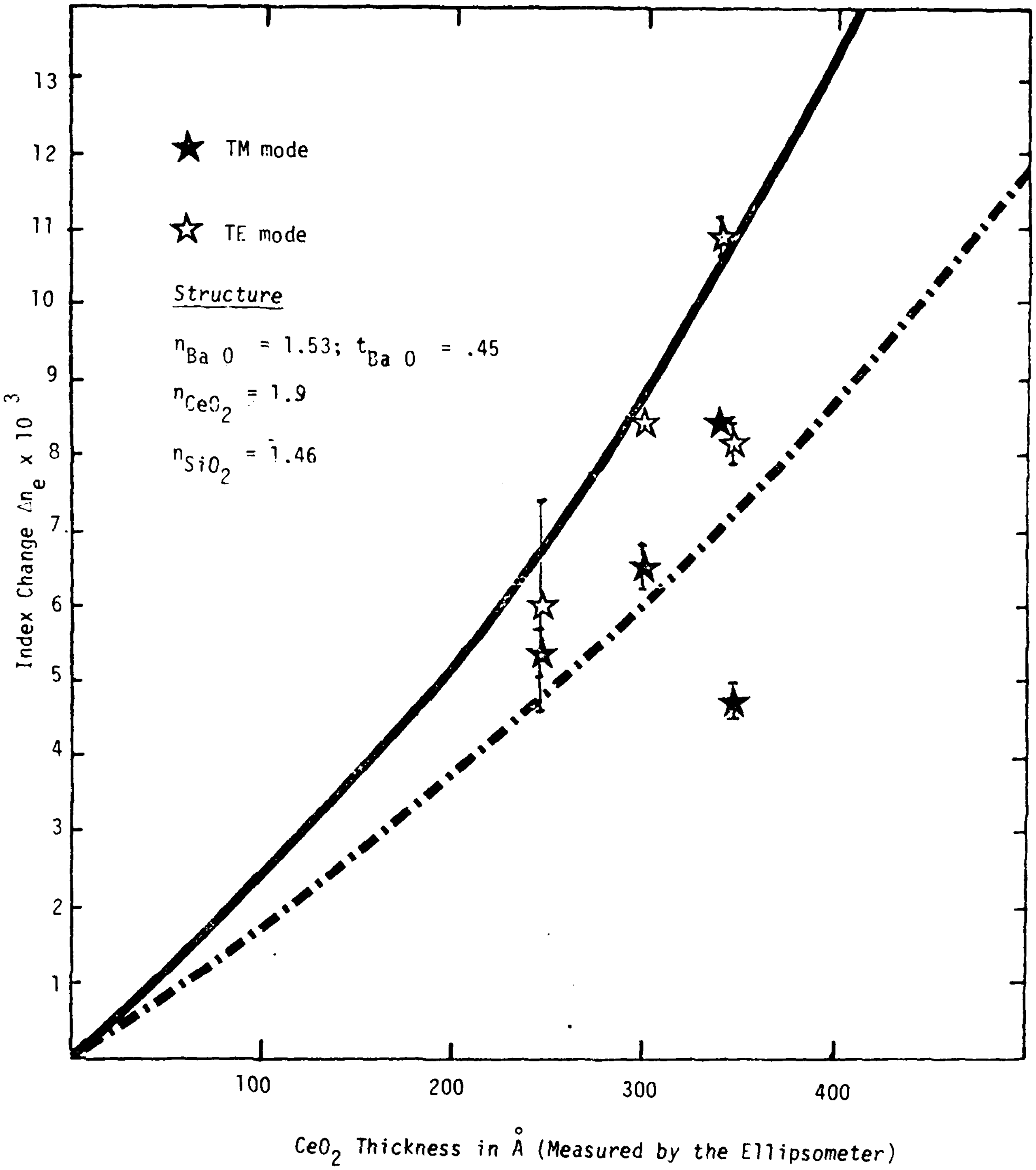


Figure 3 Index Change (Δn_e) as a Function of Ba O Glass Waveguide Thickness with CeO_2 Overlay Thickness (τ) as a Parameter.



The waveguides are obtained from the same wafer and the n_e is measured by the same prism.

Figure 4 The Δn_e of the Glass Waveguide

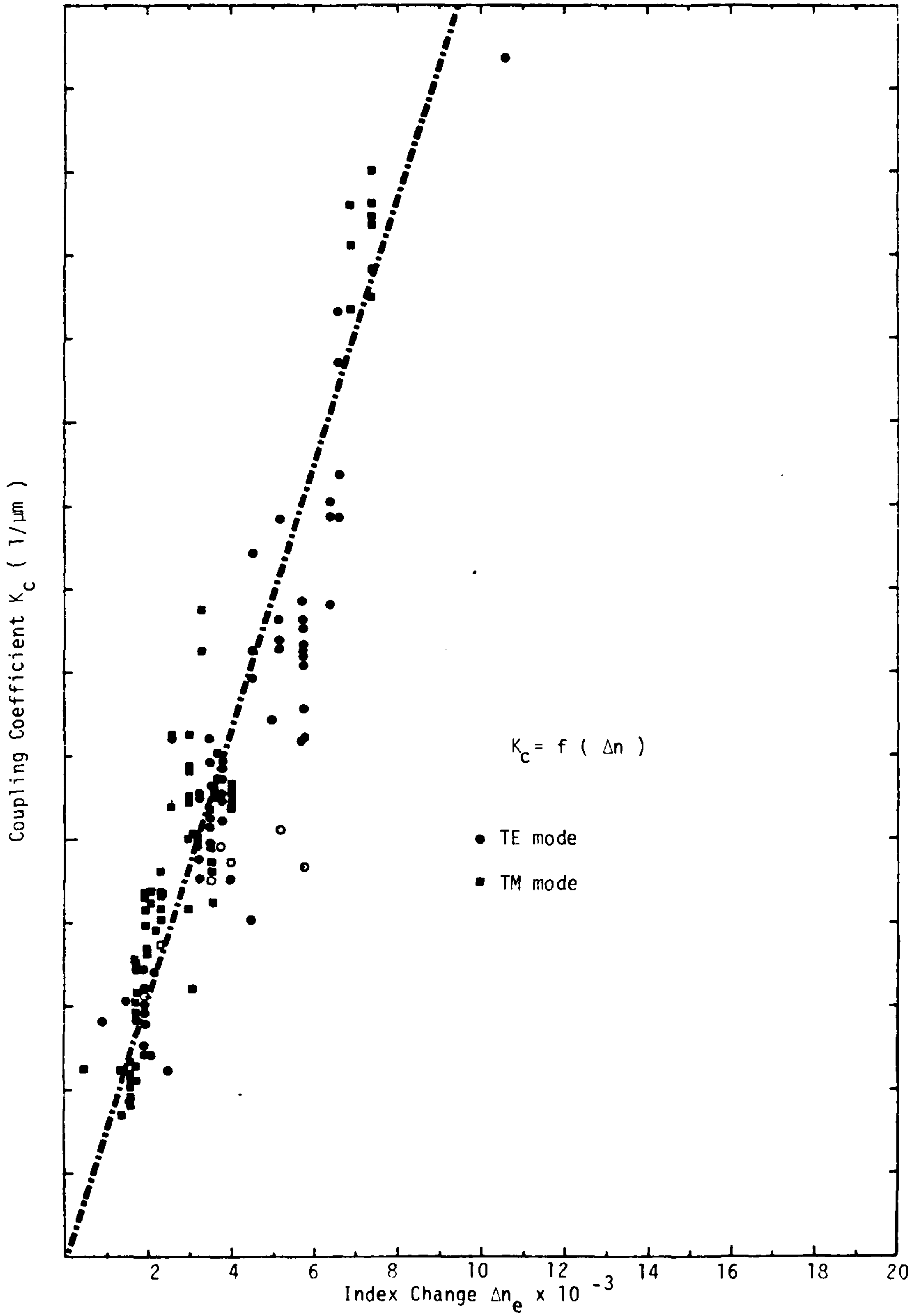


Figure 5 The Coupling Coefficient as a function of Δn_e

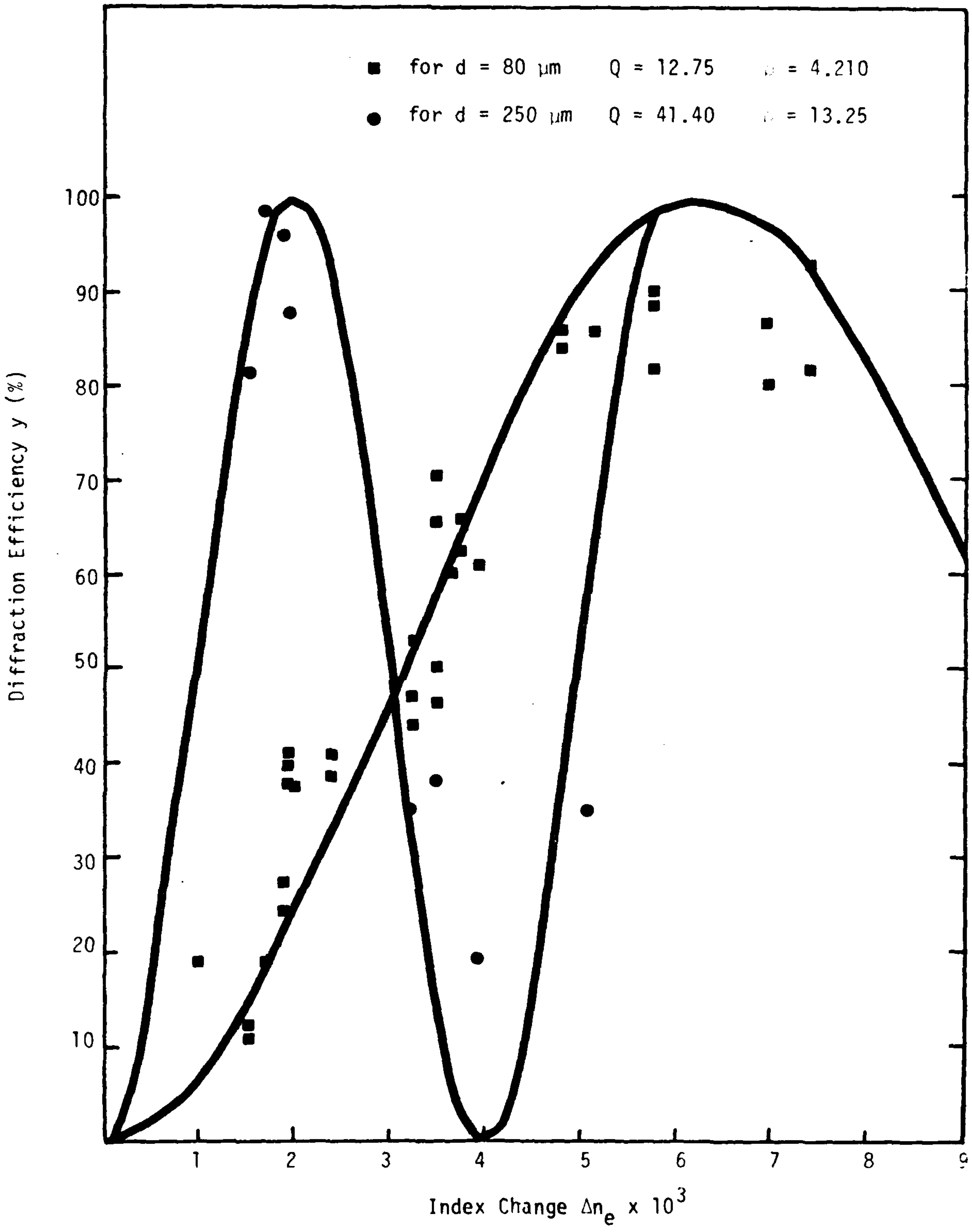


Figure 6 The Measured Efficiency of the Λ = 4 μm Constant Periodicity Grating

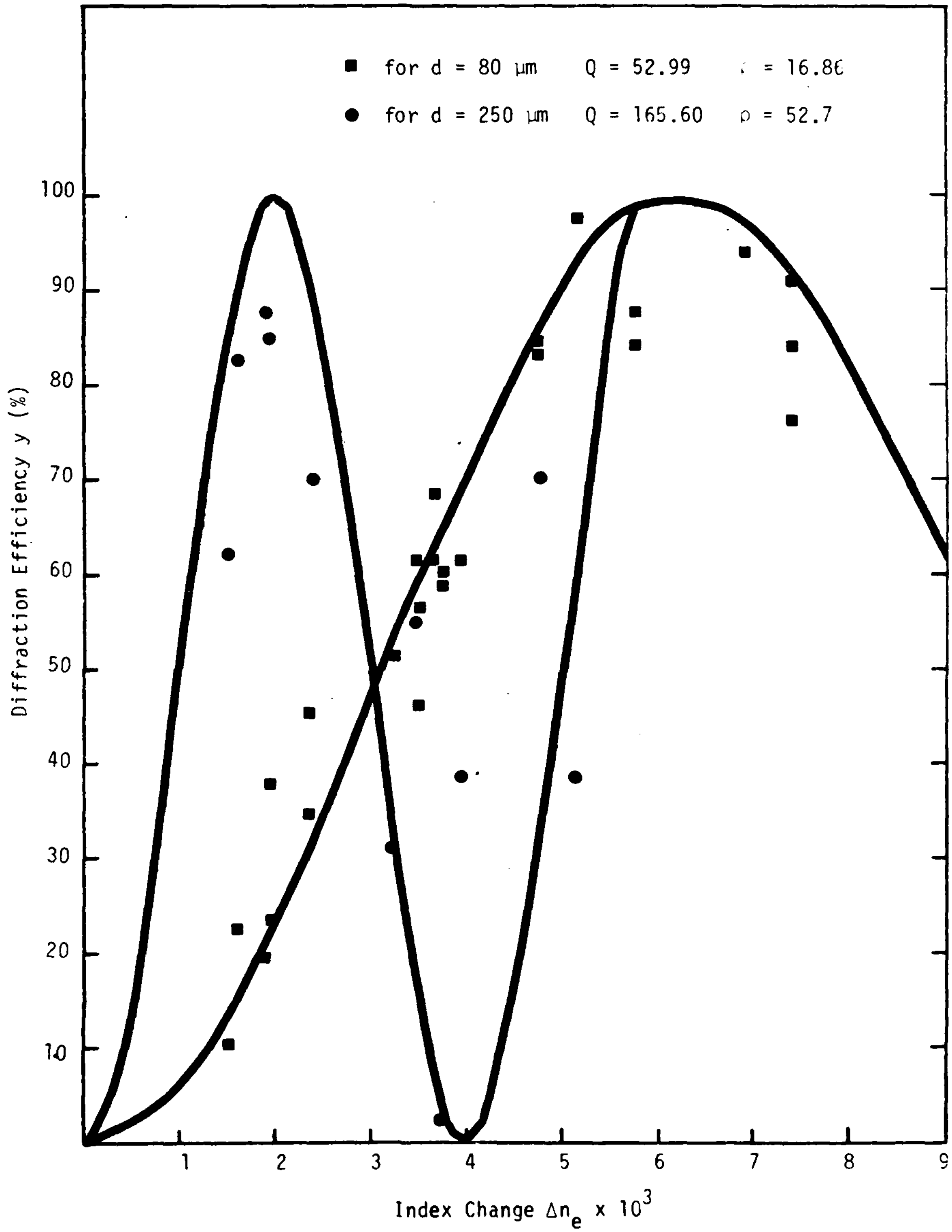


Figure 7 The Measured Efficiency of Λ = 2 μm Constant Periodicity Grating

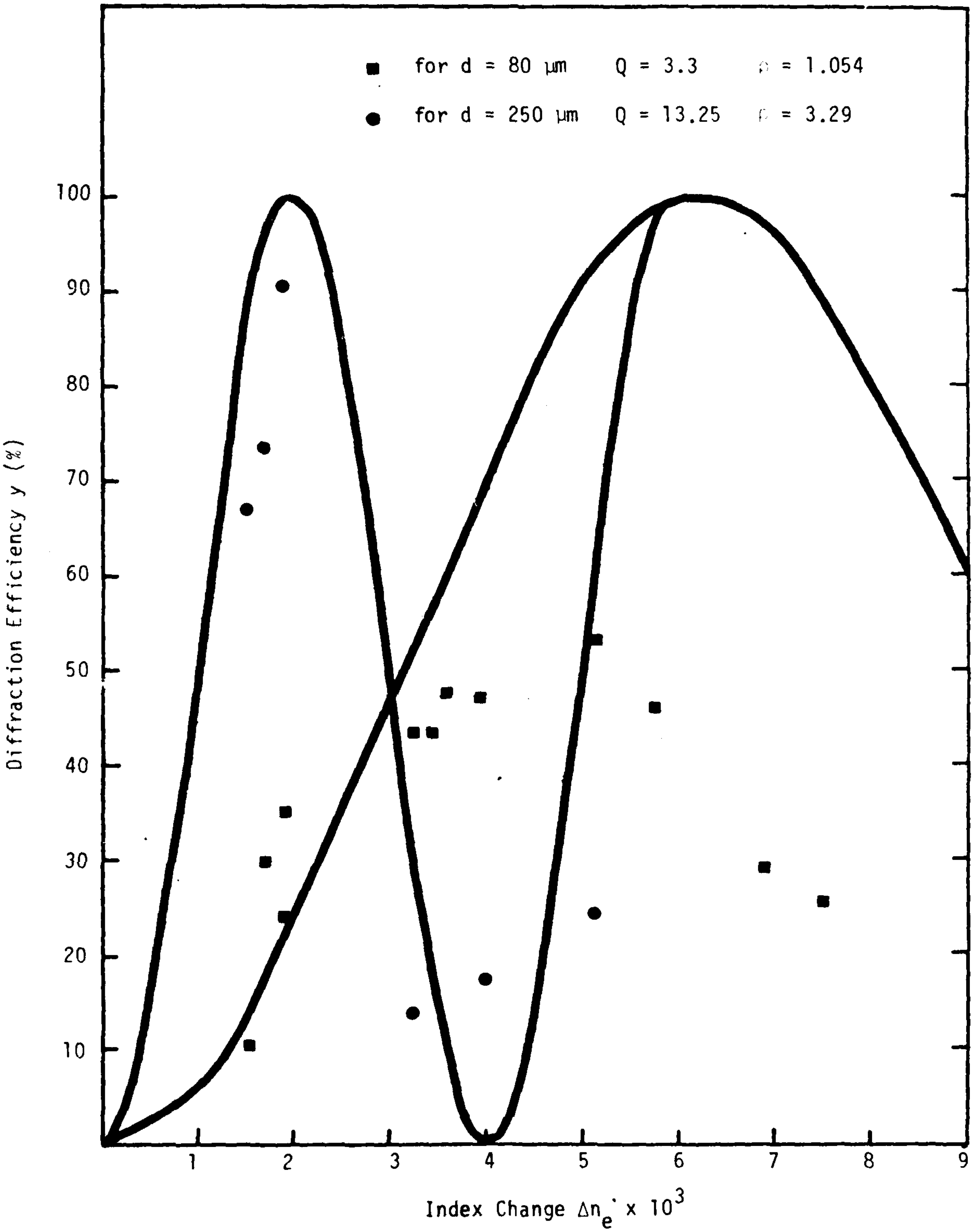


Figure 8 The Measured Efficiency of the Λ = 8 µm Constant Periodicity Grating

The Refractive Index Profile of Sample N fabricated by Ion Exchange of Lithium Niobate in Benzoic Acid.

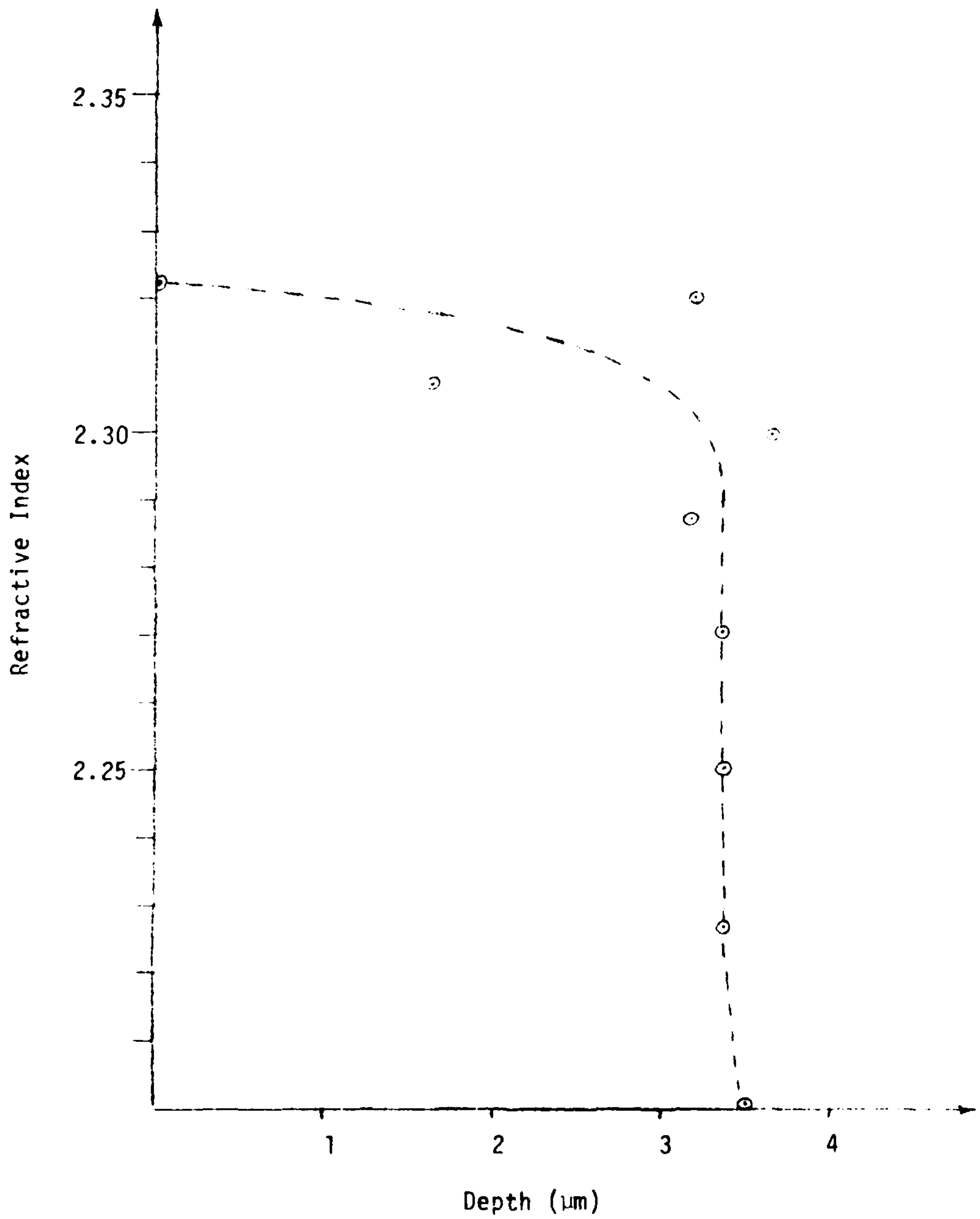
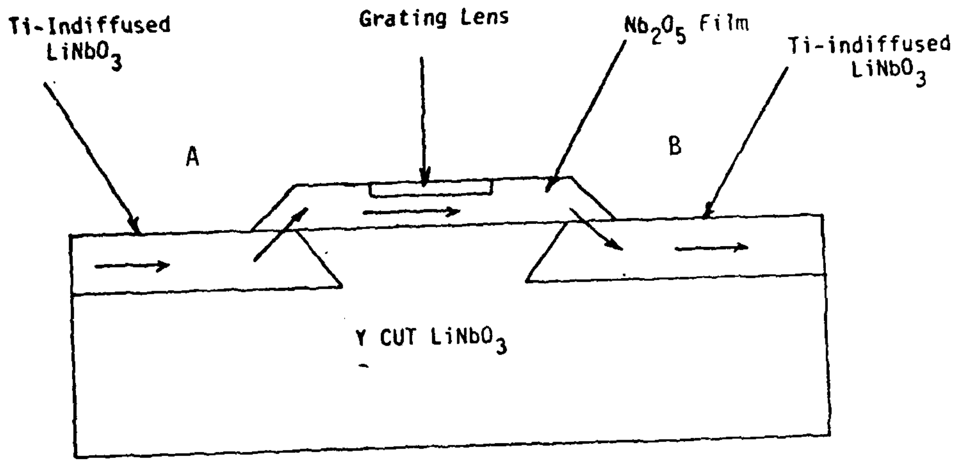
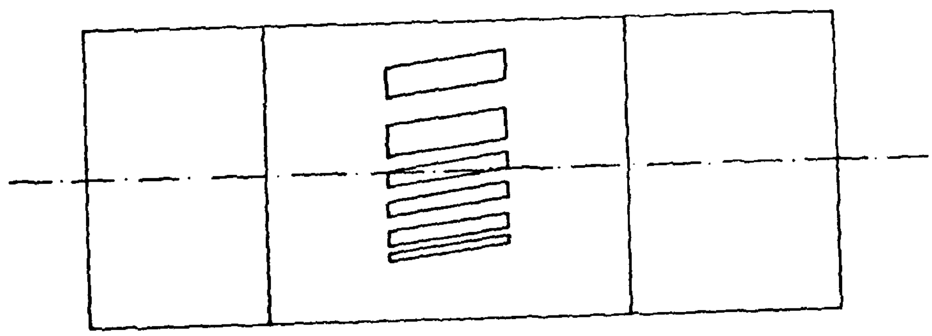


Figure 9



SIDE VIEW OF MODE-LIFT-OFF STRUCTURE



TOP VIEW OF MODE-LIFT-OFF STRUCTURE

Figure 10 THE Nb_2O_5 TRANSITION WAVEGUIDE

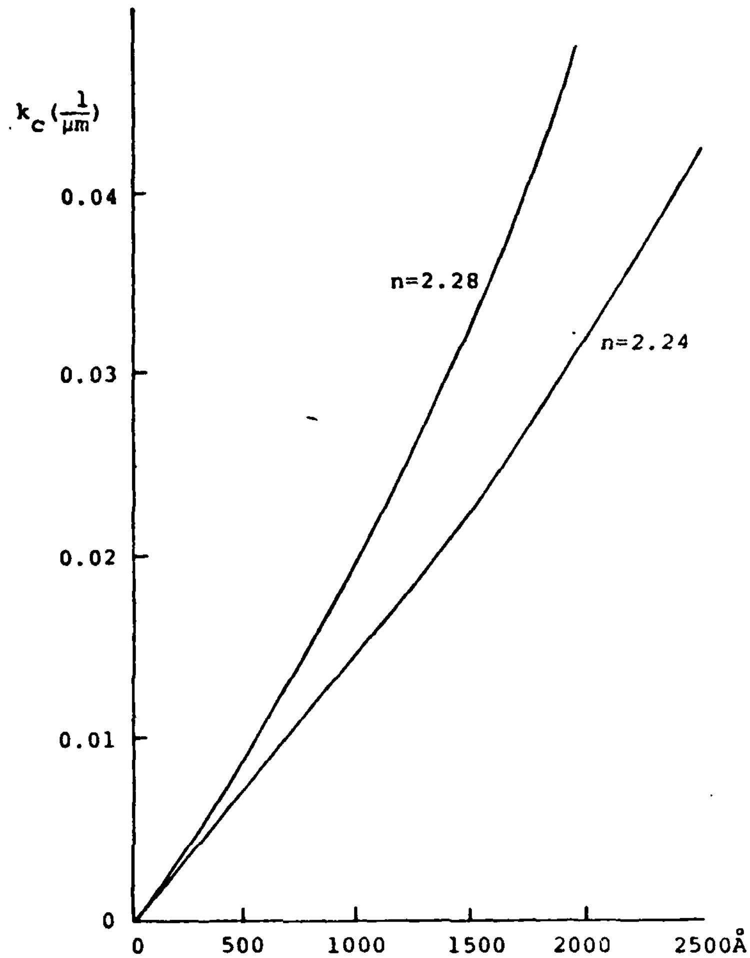
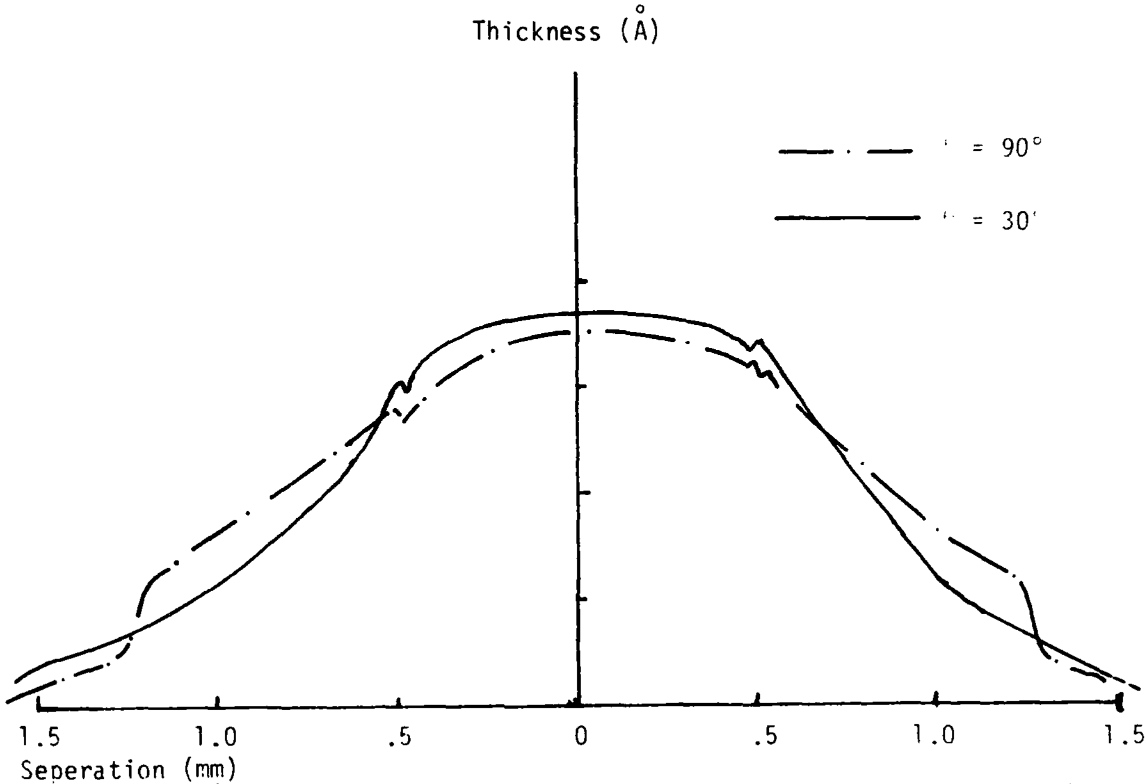
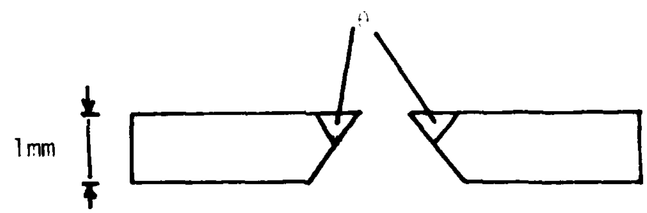


Figure 11 COUPLING COEFFICIENT VS. ETCHING DEPTH OF A Nb_2O_5 FILM ON $LiNbO_3$ WAVEGUIDE.

Two different refractive indeces of Nb O film are presented. The Nb_2O_5 film thickness of the waveguide is 7000Å in both cases.



(a) The Thickness Profile of the Nb_2O_5 Transition Waveguide



(b) The Configuration of the Shadow Mask

Figure 12 The Profile of the Nb_2O_5 Transition Waveguide

FILMED

5-8