EVAPORATED As_2S_3 LUNEBURG LENSES FOR $LiNbO_3$:Ti OPTICAL WAVEGUIDES*

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SUMMARY

Because of their relative ease of fabrication, advanced state of design, and low aberrations, Luneburg lenses are attractive candidates as elements in integrated-optics devices, both for simple beam-forming applications and for information processing. Few materials, however, possess the combination of high refractive index, low absorbance, and ease of deposition required for making Luneburg lenses suitable for use on high-index optical waveguides, such as those formed by diffusion of Ti into $LiNbO_3$. We have found that Luneburg lenses of good quality can be formed on such waveguides by evaporation of arsenic trisulfide glass through simple masks. Using only two thin circular-aperture masks, we could readily obtain lenses with focal spots of a few times the diffraction-limited width at f/4. These lenses have been designed for and tested at both visible (633 nm) and infrared wavelengths. Losses are generally small in both wavelength regions, although much of the guided light is coupled into the lens region. There exist restrictions on the steepness of the lens profile near the edge if partial coupling to local modes in the lens region is to be avoided. Since an irreversible change in refractive index can be effected in the As_2S_3 glass by exposure to blue or ultraviolet light, the focal length of the lens can be shortened optically after fabrication. This technique permits in-situ optimization of lens characteristics with no apparent degradation in focal-spot quality. Procedures for the design, fabrication, and testing of lenses of this type will be described.

INTRODUCTION

Realization of integrated optics devices requires development of integrated analogs to the components familiar in conventional optics. Among the most important of such components is the lens. Integrated lenses can be useful not only for the usual focusing and beam-forming operations, but also as data-processing elements exploiting the Fourier-transform property of the lens. We have recently developed techniques for the design, fabrication, and evaluation of one type of integrated lens—the Luneburg lens—on planar optical waveguides formed by diffusion of titanium into $LiNbO_3$. The lenses are formed of overlayers of As_2S_3 glass deposited onto the $LiNbO_3$ surface by thermal evaporation through simple masks. Few materials other than chalcogenide glasses like As_2S_3 possess the high refractive index, low absorbance and ease of deposition required for making this type of lens on a high-index material like $LiNbO_3$. In the present paper we describe and exemplify our current procedures

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for making As_2S_3 Luneburg lenses. We also describe how the well-known short-wavelength photosensitivity of this material can be used to adjust focal length after lens fabrication.

BACKGROUND

Three principal classes of lenses have been investigated for use in integrated optics.

Geodesic waveguide lenses, figure 1a, are formed by creating a spherical depression in the waveguide substrate and then fabricating the waveguide by diffusion or film deposition (ref. 1). A ray of light encountering the depression enters it in a direction determined by the perpendicular distance of the ray from the center of the depression. It then proceeds along a geodesic curve until it encounters the edge of the depression again, whereupon it reenters the planar region of the guide. The index of refraction for the guided mode is practically unchanged in the depression, but the path length depends on the particular geodesic traversed by the ray; focusing occurs because of this differential path length. Since focusing in geodesic lenses is a geometrical effect, all waveguide modes are focused with the same focal length.

Spherical geodesic lenses suffer from spherical aberration which must be corrected for high-performance uses. This can be done by placing a carefully controlled layer of material in the depression, (ref. 2), or by using correcting layers external to the depression (refs. 3,4). Both these methods remove the mode-independence of the focal length. An alternative way to remove spherical aberration is to use an aspheric depression (ref. 5).

Geodesic lenses have several drawbacks. The fabrication techniques are slow and costly. Entrance edges must be rounded to prevent excessive losses and scattering from an abrupt transition from the planar guide into the depression. This rounding tends to lead to an uncertainty in the focal length. Finally, the waveguide in and around the depression must be made stronger because the curvature of the depression tends to introduce radiation losses in weak guides. This is a particular problem in $LiNbO_3$ devices, where crystal size and cost limitations often will necessitate use of short focal lengths.

Diffraction lenses, figure 1b, are waveguide analogs to the Fresnel zone plate. A diffraction lens is a grating whose pattern approximates the thick hologram formed by recording the interference pattern created by the intersection of a converging cylindrical wave and a plane wave. The lens consists of an overlayer of lines that follow the fringes of the interference pattern. In experimental work on such lenses (ref. 6), the line pattern was calculated by computer and replicated by e-beam lithography to generate a mask which was then used to fabricate the lens photolithographically.

The principal advantages of diffraction lenses are low cost, speed and simplicity of fabrication, and potential for automation. Their principal disadvantage is their extremely limited field of view.

The Luneburg lens (ref. 7), is one of the classical gradient-index lenses. It has found application in microwave antennas and beam formers, but until the advent of integrated optics it was impractical in optical systems since, in a bulk optical system, the refractive index at the edge of the lens must equal that of air. A

three-dimensional Luneburg lens is conventionally defined as a spherically symmetric refractive index distribution that perfectly focuses the surface of a fixed sphere onto the surface of a second fixed sphere. In the two-dimensional world of integrated optics the distribution is circularly symmetric and the spheres are replaced by circles. Ordinarily we consider the situation where one sphere becomes of infinite radius and the other, in the geometrical-optics approximation, shrinks to a point; so the lens behaves like a conventional lens, bringing a plane-parallel beam to a focus. For specific optical data-processing operations, though, other configurations, possibly not conforming to the conventional definition, might be desired.

The practicality of Luneburg lenses in integrated optics results from the circumstance that the index of refraction at the lens edge is simply that of the waveguide mode rather than that of air. The required refractive-index distribution can be produced in a waveguide by deposition onto the guide surface of an overlayer of material with a prescribed variation in thickness, as indicated in figure 1c. This thickness profile is produced by sputtering or evaporating the lens material onto the waveguide surface through a circular mask with shaped edges. Diffraction-limited Luneburg lenses (ref. 8) have been fabricated using a Ta_2O_5 overlayer on a 7059 sputtered glass waveguide.

Any material that is not highly absorptive can be used to make Luneburg lenses, but only materials with a refractive index higher than the surface index of the waveguide can produce mode-index changes large enough to make short-focal-length lenses. For $LiNbO_3$ waveguides, the surface index is in the range 2.1 to 2.3, depending on wavelength and polarization. Chalcogenide glasses have refractive indices in the range 2.3 to 2.5 and they can readily be deposited by sputtering or evaporation. One of the simplest materials to use is amorphous As_2S_3, which is readily available in the form of chunks of glass from which material yielding good quality films may be evaporated at 500-700°C. We have found this material quite suitable for the formation of Luneburg lenses on $LiNbO_3$.

It is important that the overlay film be tapered in thickness at the lens edges so that spurious modes in the lens region not be excited. These modes occur when the required overlayer thickness is sufficient to allow higher modes in the underlying waveguide to exist. As the film thickness is increased, the single mode of the waveguide is slowly "pulled" up in effective index, until a point is reached when the index rapidly increases beyond the waveguide surface value, toward the bulk index of the film. As this rapid change is occuring, a new mode appears in the waveguide, a mode that was cut off for thinner films. This mode replaces the original single mode of the guide; its index rapidly increases to the vicinity of that of the original guided mode, where it remains until it too is finally pulled up into the film. This process continues, with new modes being pulled up into the guide from cutoff to replace lower modes that have been pulled into the film. As a result, there is, roughly speaking, almost always a mode present having an effective index very near that of the original waveguide. If the film thickness changes too rapidly at the edge, then in the region where the original mode is lifted into the film, strong coupling can occur between the incoming mode and the spurious mode lifted from cutoff by the presence of the film. This coupling occurs because the effective index difference between the incoming mode and the spurious one is small and is changing more slowly than that between the incoming mode and its continuation in the film region. The result of such coupling is the appearance of multiple focused spots and increased apparent loss of transmission. The increased loss may not be too serious, but the transmission of the spurious modes through the lens is deleterious for most applications and can be disastrous for processing applications.

DESIGN

The design of the Luneburg lens involves the following steps:

1. Select the desired operating wavelength, lens aperture and focal length; calculate the f/#.

2. Select the overlay material, waveguide profile, and waveguide parameters.

3. Select the operating mode and polarization.

4. Solve the wave propagation equation for the specified conditions and for an overlay of arbitrary thickness to find mode indices required for propagation both inside and outside the lens region. (As noted by Southwell (ref. 9), it is easier to calculate the overlay thickness as a function of the mode index).

5. For the given f/# evaluate the Luneburg-Morgan integral, which gives the mode index required at a given radius in the lens region to obtain proper focusing.

6. Using the results of 4, determine the lens thickness needed to obtain the desired mode index.

7. From the results of 5 and 6, tabulate the required lens profile.

8. Design a mask arrangement which will produce a lens having a profile close to the specifications of 7.

The first three steps require little discussion. The lenses discussed in this paper are designed for a wavelength, exterior to the guide, of 633 nm. They have apertures of 6 mm and design speeds of f/4.3 for full aperture. Since rays passing very close to the lens edge are not always well focused, we often design for a restricted aperture a little smaller than the lens diameter. The lenses are generally made on single-mode waveguides, for which we assume a Gaussian index profile with a diffusion length of 2 μm. Our design equations are strictly correct only for TE modes; but since for highly asymmetric waveguides the only distinction between TE and TM modes is in the substrate index, good designs for TM modes can also be obtained by simply using the appropriate value for that parameter.

To find the overlay thickness required to obtain a desired mode index (step 4), we have made a straightforward extension of the calculation in reference 9 for a uniform waveguide layer to the case of an inhomogeneous guide characterized by a Gaussian refractive index profile - that is, $n(y) \simeq n_b + (n_s - n_b)\, e^{-y^2/\Lambda^2}$, where n_b is the bulk index of the lithium niobate, n_s is the index at the surface of the waveguide layer, Λ is the diffusion length, and y is depth below the surface into the waveguide. We used the WKB approximation (ref. 10) to determine the mode propagation characteristics of the guide. Since most of the guided light in the lens region propagates in the overlay material rather than in the original waveguide, the exact characteristics of the diffused waveguide do not influence the calculated lens profiles greatly; but this is not to say they do not need to be known with some accuracy. As an example, in one calculation a change of 40% in the assumed surface index n_s led to a change of 10% in the calculated lens thickness at the center.

The required mode-index to obtain focusing at a given lens radius is obtained (step 5) from the solution of the Luneburg-Morgan integral equation.

$$\ln \frac{N(r)}{N_{ext}} = \frac{2}{\pi} \int_0^{(t - z)^{1/2}} \frac{\sin^{-1} (u^2 + z)}{(u^2 + 2z)^{1/2}} \, du. \qquad (1)$$

In this equation, N(r) is the mode index at radius r in the lens region, while N_{ext} is the mode index outside the lens. The parameter t is the reciprocal of twice the f/number of the lens, and z = tR, where R = 2r N(r)/A N_{ext}. A is the lens aperture. In the form presented here, the integral is easily evaluated to 5 decimal place accuracy by a single 16-point Gaussian quadrature.

Steps 6 and 7 merely involve tabulation and possibly interpolation.

Given the lens profile required for a particular focusing requirement, we need to determine apertures and positions of masks suitable for depositing a lens with this profile on the waveguide. As stated earlier, we have found that fairly good approximations to profiles of interest to us can be obtained using only two thin masks. Our model for the deposition system is a simple generalization of that described in reference 8, and our present design procedure might be termed computer-aided guesswork.

The model for the evaporation system, and the system itself, are illustrated schematically in figure 2.

The evaporation source is modeled as a uniform distribution over a circle of radius b of point sources, each emitting As_2S_3 molecules uniformly into the hemisphere above the source. The extent to which this simple model describes actual evaporation from a crucible has not been investigated experimentally. It is possible that the geometric radius b' of the top of the crucible or the top of the melt differs from the effective source radius b that must be used in the model.

The lens-profiling mask is modeled as a simple circular hole in an infinitesimally thin sheet parallel to the waveguide surface. The distance h_1 of this sheet from the surface and the radius s of the hole are varied by trial and error to optimize the fit to the desired profile. The fits are to a lens profile normalized to unity at the center; we rely on a separate measurement of the central thickness to obtain the proper lens thickness. To obtain a good fit near the edge of the lens, an additional mask very close to the substrate is used. It is positioned experimentally to reduce the lens thickness to zero at the desired aperture.

Presumably with the use of enough additional masks one can approach the design thickness within an arbitrarily small error. More important, though, is the question of how small deviations from the ideal profile affect the operating characteristics of the lengs. We intend to investigate this in future work.

FABRICATION AND CHARACTERIZATION

The As_2S_3 lenses are fabricated in a conventional bell-jar high-vacuum evaporation system. The system is typically pumped down to a pressure of about 1.0×10^{-5} torr by the oil diffusion pump. The source is As_2S_3 fused glass which has been hand

ground to form a fine powder. The As_2S_3 powder is thermally evaporated from a quartz crucible held by a conical tungsten basket. The crucible temperature (unmonitored) is estimated to be between 500 and 700°C. The As_2S_3 molecules travel through the series of masks illustrated in figure 2 and are deposited onto the $LiNbO_3$ substrate. Evaporation times vary from 15 seconds to 1 minute and are controlled by a hand-operated shutter. Film thicknesses were estimated during the evaporation process by the weight of the As_2S_3 used as the source and the evaporation time. After the lenses were removed from the system, their thickness profiles were verified by Talysurf. We have recently installed a quartz crystal thickness monitor into the system so that we can accurately monitor the evaporated film thickness in-situ. Care is taken to remove any fumes generated by the evaporation system from the room.

To characterize the optical quality of the Luneburg lenses we have made, we examined the light distribution in the focal plane. The experimental arrangement is shown in figure 3. The input beam was directed through a variable-width aperture and then coupled into the waveguide with a rutile prism. The guided beam passed through the lens and then was coupled out with another rutile prism. The focal plane was external to the waveguide and output coupler. An f/2 imaging lens was used to re-focus the focal region onto a diode-array scanner. The scanner consists of 128 photodiodes, each 15 μm wide and 26 μm long, spaced 25 μm apart. The scanner output was directed into an oscilloscope where it was displayed as a plot of detected intensity in the focal plane as a function of position.

EXAMPLES

A lens designed to focus the TM_0 mode of an in-diffused waveguide supporting only one mode of each polarization was fabricated. The source was 0.36 g of As_2S_3 glass in an 18.3 mm diameter quartz crucible positioned 100 mm below the waveguide. The profiling mask had an aperture of 4.7 mm and was placed 22 mm below the waveguide, while the edge-defining mask, with an aperture of 5.9 mm, was 0.5 mm below the guide. A 20 second evaporation yielded a lens with a central thickness of 0.74 μm, close to the design value of 0.75 μm. The measured lens profile as determined by Talysurf is compared with the design profile in figure 4. Although the lens as fabricated was about 20% too thick near the edge, it focused a TM_0 beam only slightly smaller than the full aperture with a focal length of 2.5 cm, close to the design value of 2.58 cm. The flatness of the fabricated lens relative to the design can be alleviated by introducing additional profiling masks. This lens was designed assuming values of 2.293 for the refractive index at the waveguide surface and 2.40 for the As_2S_3 film. More recent measurements indicate that the refractive index of the as-deposited film at 633 nm is at least 2.42 and may be higher. This will not affect the calculated profile greatly, but will have an effect on the design overall thickness.

An example of the focusing qualities of one of these lenses, as determined by the focal-spot scanning procedure previously described, is shown in figure 5. This lens had a central thickness of 0.67 μm and after exposure to an undetermined amount of ultraviolet light had a measured focal length of 2.67 cm. For a one-dimensional lens, the half-power diffraction-limited spot size is given by:

$$S = 0.8859 \frac{\lambda_o \quad f}{N_{ext} \; w} \tag{2}$$

where λ_o is the external wavelength of the light used, N_{ext} is the mode index outside the lens region, f is the lens focal length in the waveguide, and w is the input aperture. We used a 4 mm aperture in this experiment; consequently the minimum half-power spot size is 1.63 μm. The measured value is 5.4 μm; so at this aperture this lens is about three times diffraction-limited. Figure 5 shows that the lens is quite symmetrical with little of the focused beam energy outside the central peak.

The post-fabrication optical shortening of the focal length of the lens by exposure to blue or ultraviolet light is illustrated by the following two examples.

The first lens was fabricated by evaporating from an 81.6 mg charge of As_2S_3 glass for 15 seconds. This 8 mm diameter lens had an original TM_0 focal length of 12.5 cm. After a 60 mJ exposure to ultraviolet light the focal length decreased to 10.5 cm. Subsequent exposures of 30 mJ and 60 mJ shortened the focal length to 9.3 cm and 8.2 cm, respectively. After a total ultraviolet exposure of 540 mJ, the TM_0 focal length had decreased to 5.4 cm.

The second lens was fabricated by evaporating from an 80.6 mg charge of As_2S_3 glass for 20 seconds. This 8 mm diameter lens had an original TM_0 focal length of 5.6 cm. The exposure source was the 4880 Å line of an argon laser. An exposure of 600 mJ shortened the focal length to 4.5 cm. After a total exposure of 2.4 J, the TM_0 focal length had decreased to 3.8 cm, with no apparent aberrations induced by the exposure process.

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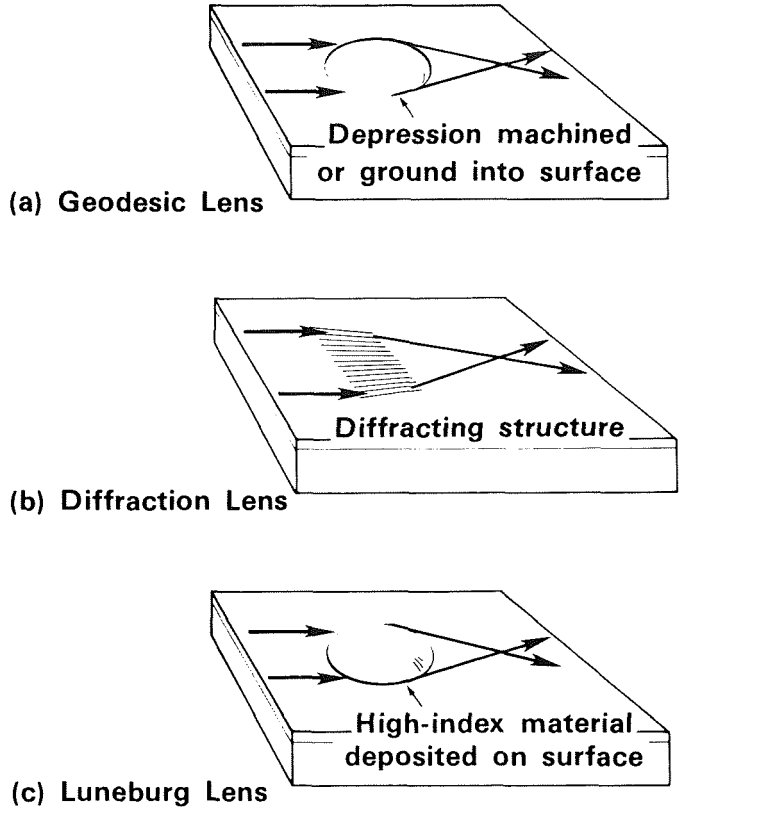

Figure 1.- Three types of waveguide lenses.

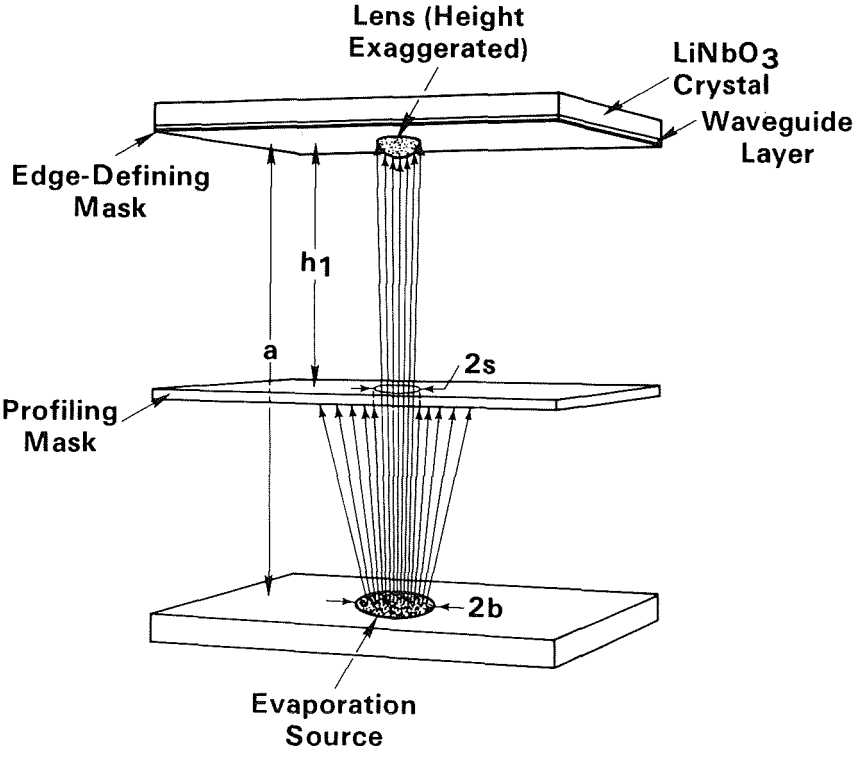

Figure 2.- Model of evaporation and masking system for fabrication of As_2S_3 Luneburg lenses.

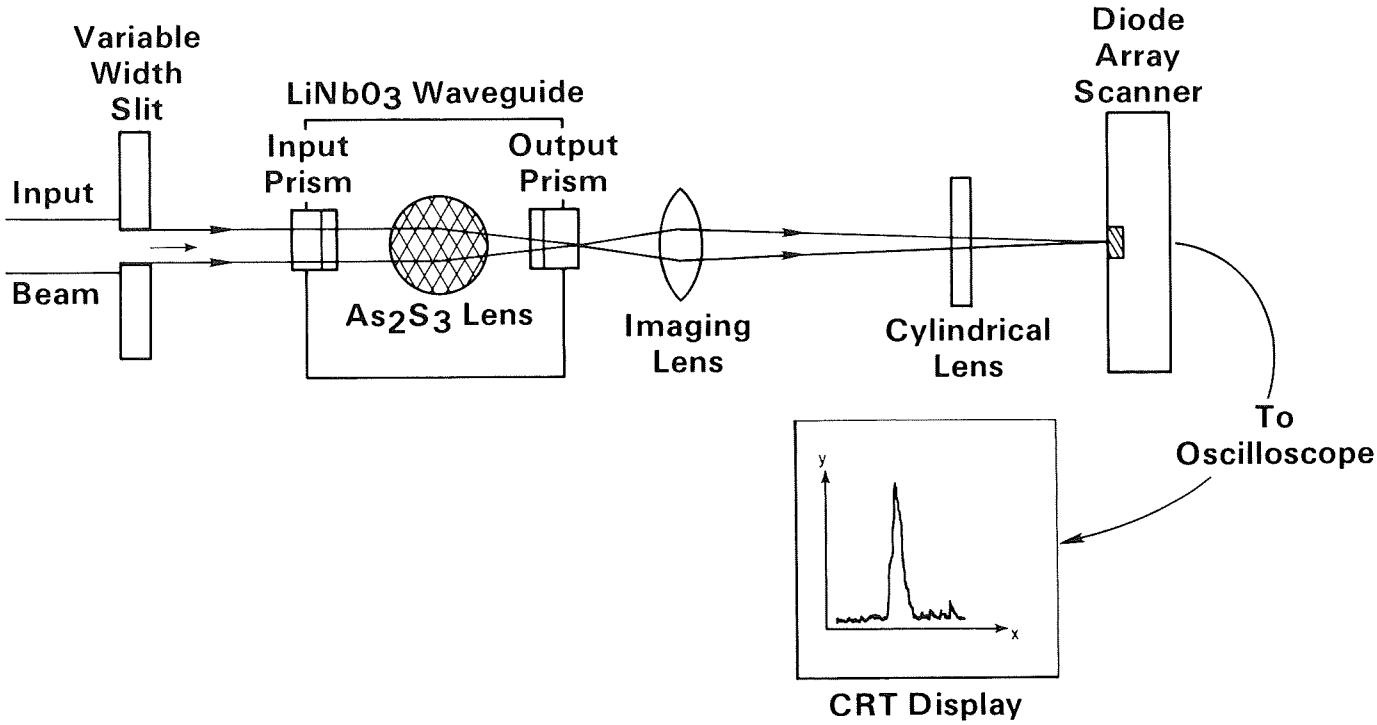

Figure 3.- Experimental arrangement for focal plane scan.

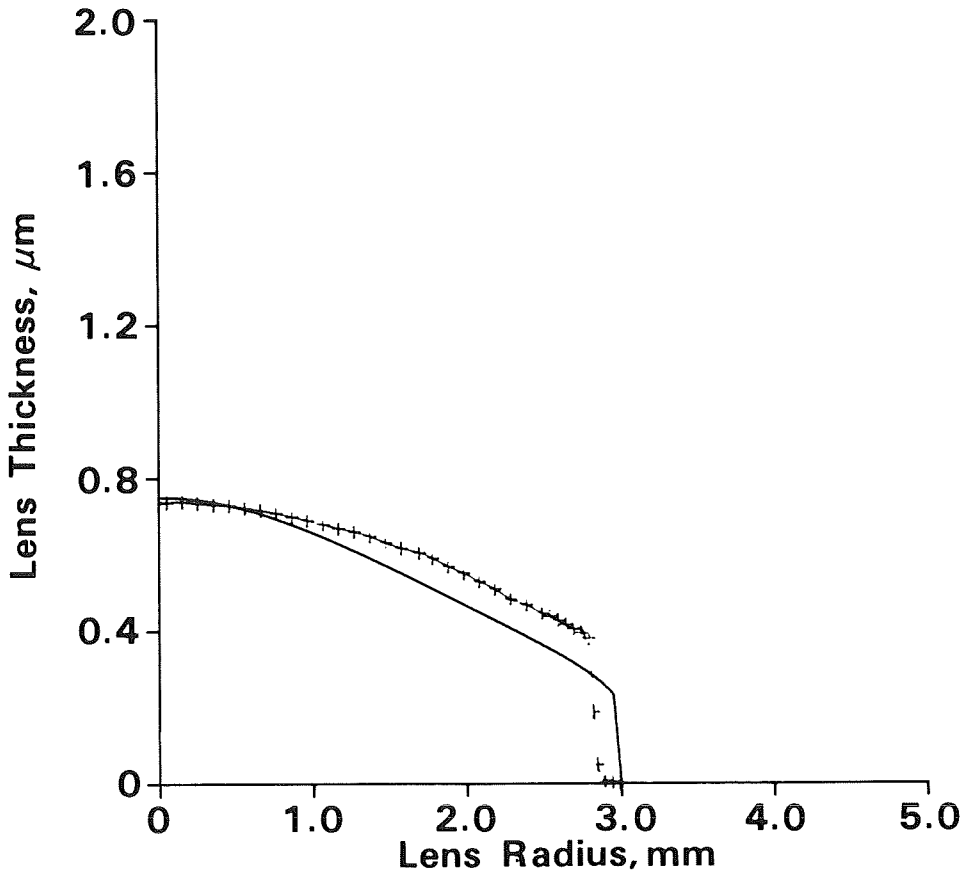

Figure 4.- Comparison of original design profile of Luneburg lens with that of actual lens determined by Talysurf (+'s).

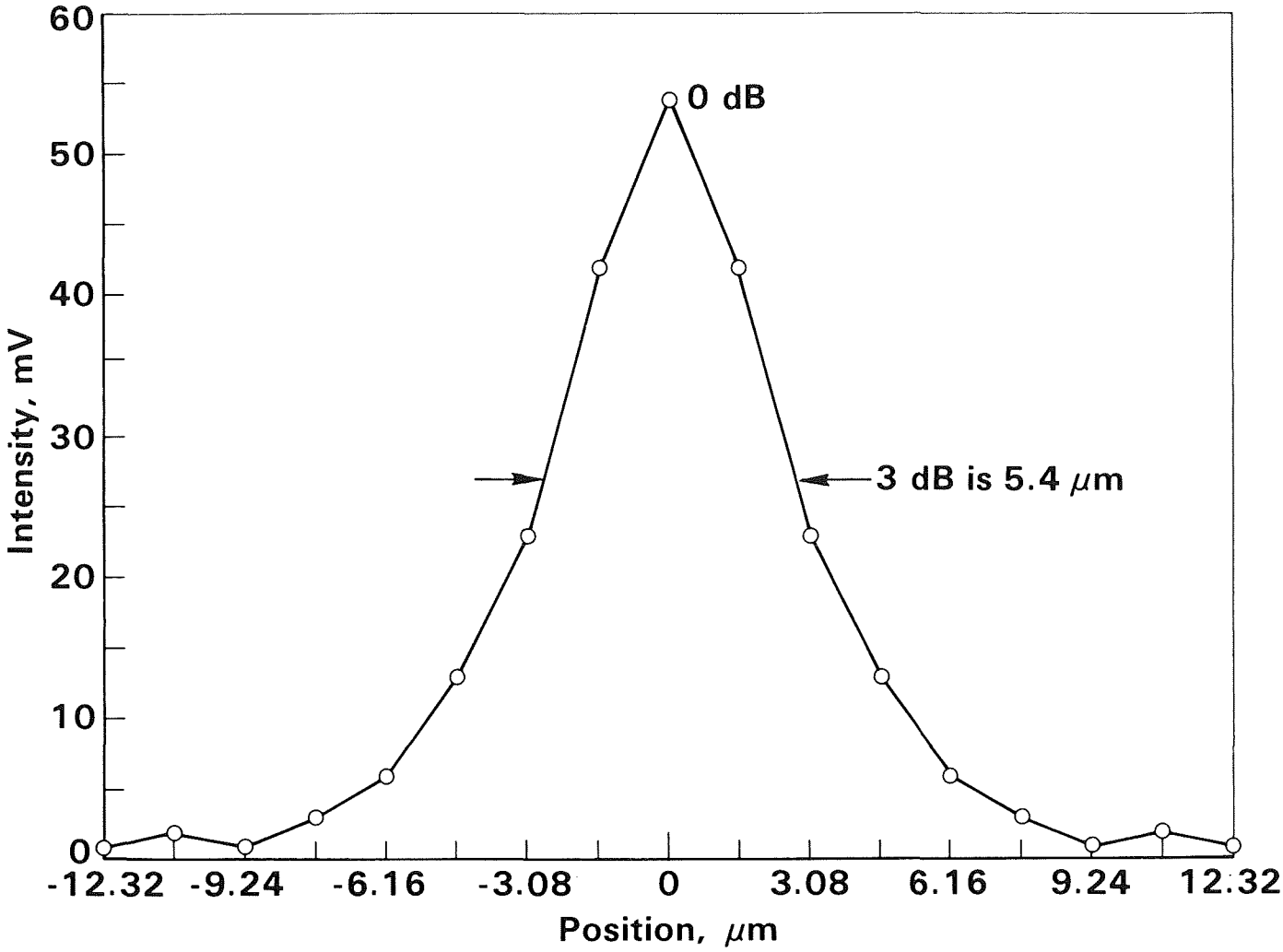

Figure 5.- Energy distribution in focal plane for an As_2S_3 lens of 26.7 mm focal length.