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Ta_2O_5 thin-film optical waveguide Luneburg lenses on SiO_2-Si substrate*

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The paper presents a brief survey of integrated-optical technology of planar lenses and the model of Luneburg-lens preparation. The model consists in the application of parabolic edge-profile of the shadow mask through which the Luneburg lenses are deposited with r.f. diode sputtering system. Based on this model the Luneburg lens has been designed and prepared in order to obtain a light beam expander in an integrated-optical real-time r.f.-spectrum analyser.

1. Introduction

The recent rapid development of communication has necessitated extensive research of faster and faster signal processing. The optical r.f.-spectrum analyser renders *real-time* signal processing possible. The last development of integration techniques allowed the optical r.f.-spectrum analyser to be integrated.

The integrated-optical real-time r.f.-spectrum analyser requires planar elements of near-diffraction-limited performance as they realize Fourier transform, collimation, focussing and imaging. There are a few methods for production of these elements in integrated optics, namely the preparation of the diffraction, geodesic and Luneburg lenses, illustrated schematically in Fig. 1.

Diffraction lenses have been fabricated by electron lithography in the form of a grating pattern on the waveguide surface. The lens effect is achieved by light diffraction from surface relief patterns. These lenses have been reported to give diffraction-limited performance [1], and angular field of view as low as 10°. They are very sensitive to ray's incidence angle. Unless light ray is incident at the Bragg angle or/and phase difference of two rays propagated through relief areas of different effective refractive indices is π, the efficiency is reduced significantly. The last reported diffraction-lens efficiency has attained only 23% at f-number equal to 5 [1].

Geodesic lenses of desired axially symmetric depression profile have been turned with a numerically controlled diamond turning machine with a very

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high accuracy. The waveguide is then fabricated on the substrate prepared in such a way. The lens performance depends neither upon optical-waveguide parameters nor on propagated-light mode-number. The lenses, being applicable to all substrate materials, require the relatively thick ones (high costs), and moreover, a precise and complex machining.

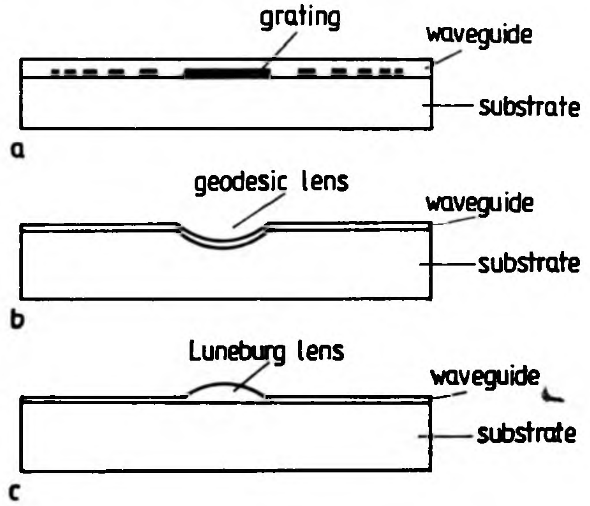


Fig. 1. Cross-sectional view of three guided-wave lenses: a – diffraction (Fresnell type) lens, b – geodesic lens, c – Luneburg lens

Luneburg lenses are free of all aberrations, except curvature of field in a focal plane, and have a 360°-field of view. This circular symmetric feature is of a particular interest in integrated optics, where the substrate area is limited, because by folding the optical axis, the lens may be used for several purposes at the same time. The Luneburg waveguide lenses are considered to be far more superior to the other ones, for all the refractive-index variations are continuous and smooth (which involves less scattering and lower mode conversion within the lens region).

The Luneburg lenses require a spherically symmetric index distribution $n(r)$ in the following form:

$$n(r) = \exp[\omega(\varrho, s)] \tag{1}$$

where

$$\varrho = nr, \tag{2}$$

and s is a focal length normalized with respect to a lens radius, r_0; r is a distance normalized with respect to a lens radius, r_0, such that $0 \leqslant r \leqslant 1$; n is an effective refractive index normalized with respect to the effective index of the waveguide, N_0, such that $n \geqslant 1$ and

$$\omega(\varrho, s) = \frac{1}{\pi} \int\limits_{\varrho}^{1} \frac{\arcsin(x/s)}{(x^2 - \varrho^2)^{1/2}}\, dx. \tag{3}$$

In integrated optics the desired refractive index distribution may be obtained using homogeneous material by varying the waveguide thickness in the lens region. A thickness profile (further called the ideal one) of the Luneburg lens is achieved by a desired-index-distribution transformation with the transcendental mode equation. It is worth emphasizing that integrated-optical technology allows us to achieve inhomogeneous refractive-index distribution in homogeneous materials (which does not take place in bulk optics).

2. Mask design

A shadow-mask design is based on the model of YAO et al. [2] with some original improvements. R.f. sputtering deposition configuration useful for a presentation of the model is shown in Fig. 2.

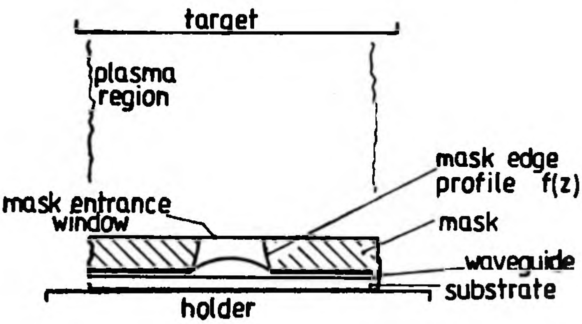


Fig. 2. R. f. sputtering desposition configuration

In the model it is assumed that: sputtered particles behave like optical rays within mask region, their source distribution from the target is Lambertian, mean free path length is a little greater than the mask dimension, target-to-substrate distance is much greater than the mean free path length.

Under these conditions a thickness profile deposited through the mask is given by the following integral:

$$T(x_0, y_0) = \iint_W \frac{A(\theta)G\cos\theta}{R^2}\, dx\, dy \tag{4}$$

where x_0, y_0 are coordinates in a substrate plane, θ is the particle incidence angle, R is the distance between point source of the particles in the mask entrance window and the place on the substrate, where these particles contribute to the lens thickness, W is the area of the mask entrance window seen from the substrate, G is the logic function, the value of which is zero when sputtered particle crosses the mask during its travel to the substrate, and 1 when it does not.

The model has been experimentally tested with deposition process through a simple mask illustrated in the inset of Fig. 3. The thickness profile measured with the diamond stylus probe is in a good agreement with that calculated over most of a central part of protrusion. YAO et al. [2] suggested the form of the mask edge as a series of conical sections and obtained near-diffraction-limited lenses. The modification employed here consists in using a parabolic shape of the mask edge in the algebraic form

$$f(z) = ax^2 + bx + 1. \tag{5}$$

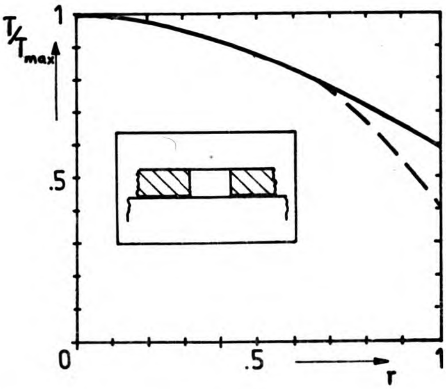


Fig. 3. Thickness profile calculated theoretically (solid line) and the experimentally obtained one (dashed line), both for the mask as illustrated in the inset

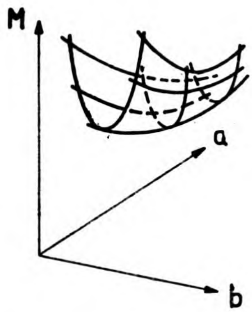


Fig. 4. Metric function vs. mask edge profile parameters

The modification has significantly lowered the computing time enabling the deposition of good enough Luneburg lenses. In the improved model we have established a certain metric function, M, being a ten-point mean-square-root deviation of the calculated thickness profile for a given mask from that (called

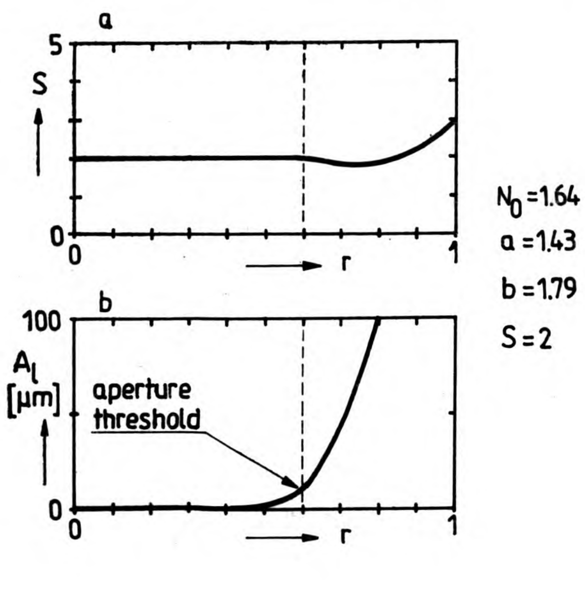


Fig. 5. Normalized focal length $S = f/r_0$ vs. radial position of incident light ray (a), lateral aberration vs. radial position of the incident ray (b)

ideal) of the theoretical Luneburg lens. The behaviour of metric function with respect to parabolic-function parameters is illustrated in Fig. 4. It helped to estimate roughly these parameters for the further numerical analysis, in which the mask shape has been optimized by searching the parameters which would give the minimal value of the metric function. Optimizing procedure consisted in analysis of the changes of metric-function numerical-derivatives with respect to each parameter (the search for zero point of the metric function derivative by the Newton method). For the mask profile obtained in such a way the lens aberration has been numerically calculated with a ray-trace procedure suggested by MONTAGNINO [3] and improved by SOUTHWELL [4]. Focal-length dependence upon ray position with respect to the lens optical axis is shown in Fig. 5a, and in Fig. 5b. There is a relation between the aberration and radial position of incident ray. Special attention should be paid to the choice of mutual incremental-step-sizes of parameters for the numerical calculations.

3. Technology

The lens material to be chosen should satisfy the following requirements:

- low light attenuation for a given wavelength,
- well elaborated preparation technique [5],
- compatibility with the waveguide technology,
- high deposition-parameter-insensitive performance of the lens (see Fig. 6).

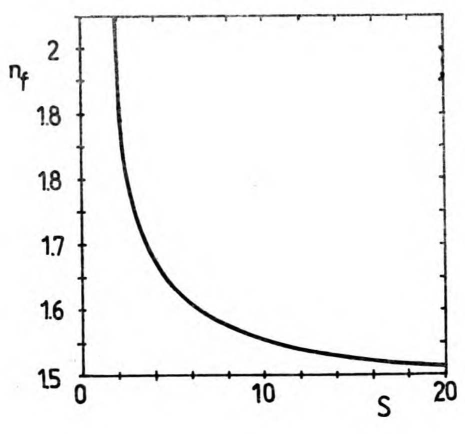


Fig. 6. Optimum material index for waveguide lens which minimizes the sensitivity of focal length to the thickness variation [6]

To obtain a compact package the Luneburg lens for beam expanding should have a short focal length. To this end, as it can be seen in Fig. 6, a high refractive-index material is required. Based on the criteria mentioned above, we have chosen Ta_2O_5 as a deposited material. It exhibits light losses as low as 1 dB/cm and waveguide-material refractive-index as high as 2.1 The configuration of the Ta_2O_5 waveguide and lens on SiO_2-Si substrate is shown in Fig. 7. Both the waveguide and the protrusion are made of Ta_2O_5 material enabling the preparation of the lens for $s \geqslant 2$ (i.e., f-number $\geqslant 1$). The ideal thickness-profile for such a configuration is presented in Fig. 8 (curve 2). For comparison the analogical profile for widely used Ta_2O_5-DC 7059-SiO_2-Si configuration is plotted in the same figure (curve 1). The latter configuration requires a more abrupt profile within the lens edge region. A higher slope of the lens edge causes a more intensive scattering and mode conversion, whereas the use of Ta_2O_5-SiO_2-Si configuration gave lower losses.

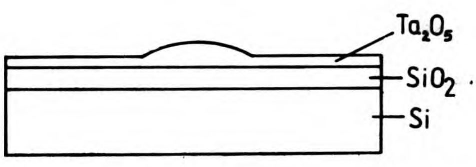


Fig. 7. Cross-section of Luneburg lens

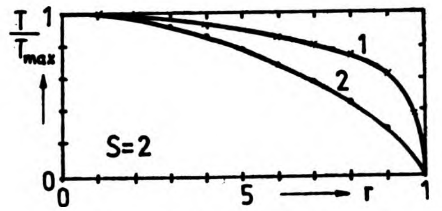


Fig. 8. Ideal thickness profile for $S = 2$ Luneburg lens: 1 – Ta_2O_5-DC 7059-SiO_2-Si, 2 – Ta_2O_5-SiO_2Si

As mentioned in the Introduction an r.f. diode sputtering system has been chosen for preparation of the Luneburg lenses and the waveguide [5]. Silicon wafers chosen as substrates have been chemically polished and oxidized in presence of $O_2 + H_2$ gases. The oxidation depth should be sufficient to neglect attenuation of the laser light penetrating the silicon substrate. Figure 9 shows the relation between losses due to absorption in a silicon substrate and SiO_2 thickness for the given Ta_2O_5 waveguide thickness [5].

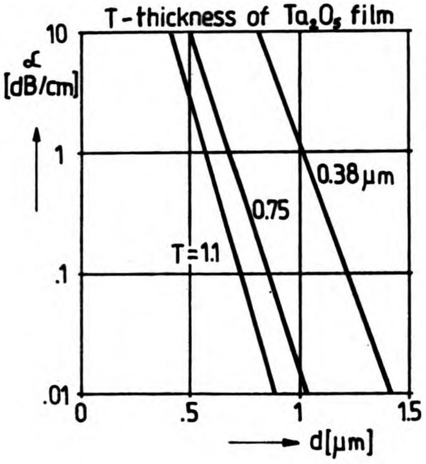


Fig. 9. Losses due to absorption in silicon substrate vs. SiO_2 thickness [5]

In order to form a base waveguide layer of the thickness corresponding to the desired effective refractive index, Ta_2O_5 single mode film has been deposited by sputtering Ta 3N target in 90% Ar + 10% O_2 atmosphere under the pressure of $5\cdot10^{-2}$–10^{-3} Torr in the presence of magnetic field. The substrates have been cooled with water throughout the technological process. After the waveguide film was deposited a desired protrusion has been deposited through a shadow mask of the earlier calculated shape.

4. Results

Figure 10 shows Newton rings of the obtained Luneburg lens seen in 6328 Å He-Ne laser radiation. Observations of the lens in monochromatic light within a wide range of wavelengths allows us to calculate the thickness profile. The profile has been compared with the diamond-stylus profilometer data to improve

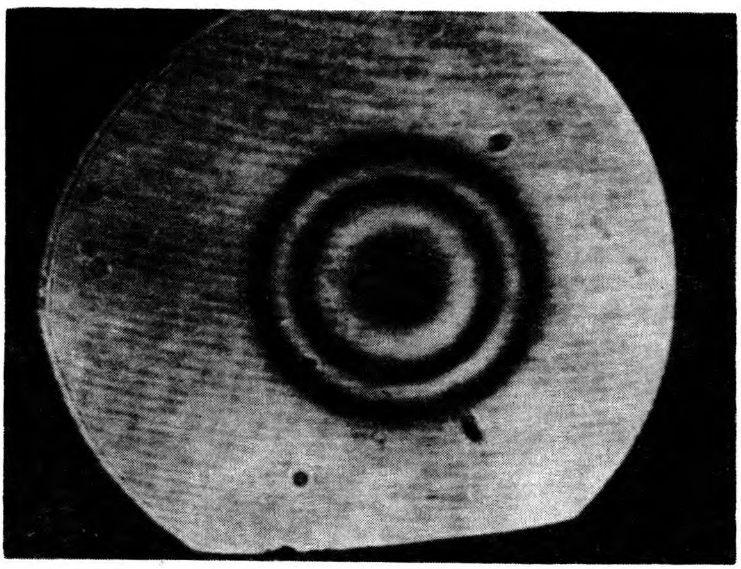


Fig. 10. Newton rings of the Luneburg lens seen in 6328 Å He-Ne laser radiation

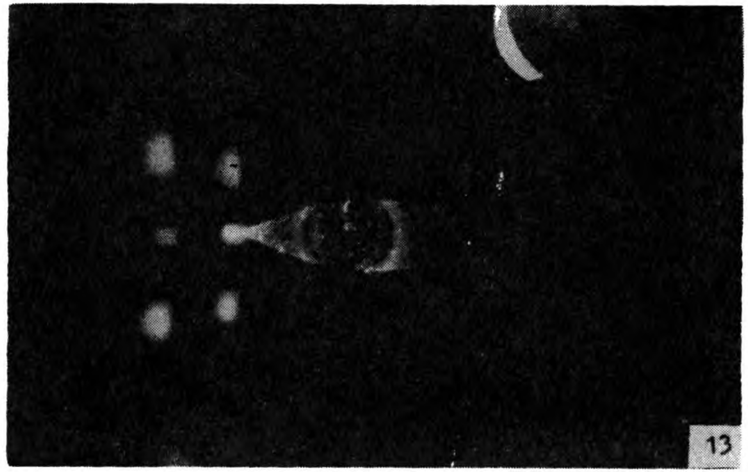
the measurement accuracy. The properties of the obtained Luneburg lenses have been evaluated in the set-up shown in Fig. 11. The light has been coupled to the waveguide cleaved edge with a microscope objective PZO 40/0.65. The objective, planar waveguide and the Luneburg lens constitute an expander of low-convergent laser beam. The expanded beam of the width at least a few millimeters is required for real-time frequency-analyser performance. Figure 12 shows light beam propagated in the waveguide after collimation by the Luneburg lens. The beam width equal to 4.2 mm is 60% of the lens aperture. It can be seen that aberrations occur when the input beam exceeds the threshold aperture.

To obtain collimation beam the waveguide should be cleaved close to the lens focus. Figure 13 shows a low expander preformance for which the substrate has been cleaved in a wrong place, a high expander performance for which substrate has bean cleaved in a right place being presented in Fig. 14.

Fig. 11. Testing set-up

5. Conclusions

By applying the presented calculations and technology it is possible to produce Luneburg lenses which can be used for construction of a light beam expander of a relatively good performance. The latter, in turn, can be a key part of a integrated-optical real-time r.f.-spectrum analyser. The deposition technology allows us to prepare the Luneburg lenses in a quite reproducible manner and at relatively low cost. Special efforts are paid to achieve diffraction-limited Luneburg lenses for Fourier transformation. The investigations are continued.



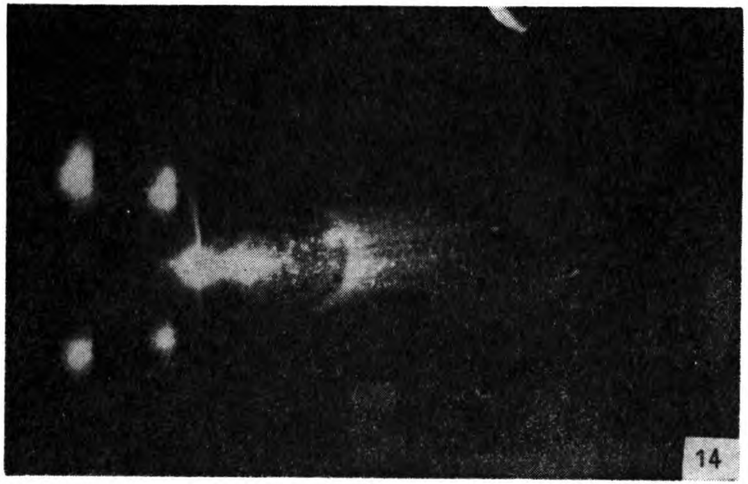


Fig. 12. Light beam propagated in the waveguide after collimation by the Luneburg lens

Fig. 13. Low expander performance, for which the substrate has been cleaved in a wrong place

Fig. 14. High expander performance, for which the substrate has been cleaved in a right place

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