Optica Applicata, Vol. XII, No 3-4, 1982

# Thin-film elements of structure containing wedge optical transition

Jerzy Kruszewski, Marek Gutkowski

Institute of Electron Technology, Technical University of Warsaw, Warsaw, Poland.

The concept of optical thin films elements presented in this paper is followed by fundamentals of thin-film optics, design and a review of both technology and materials used for thin film elements.

## 1. Introduction

For the functional systems of integrated optics both the active and passive structures are needed. The passive structures are: planar and strip (channel) waveguides, power splitters, directional couplers and the like, as well as a separate group of thin-film optical elements. This group comprises: lenses, prisms, reflectors and polarizers. These elements function similarly to their solid counterparts in classical optical instruments.

The said structures are realized in the planar lightguide. Their production consists in intentional change of the optical path at a definite place of the lightguide, most frequently by changing the effective refractive index or, more rarely, by changing the geometric path of the rays. The kind and extent of these changes is determined by the function attributed to the structure created.

Information about the works on thin-film optical elements appears in the literature since several years. Most publications are devoted to geodetic lenses. The systematics of these lenses as well as their characteristics may be found in paper [1]. The fundamentals of design and the mathematical methods of calculation of the line shape forming geodetic lenses of different type are reported in [2-4] among others. The last of the above works presents the newest achievements obtained at the Instituto Nazionale di Optica headed by Toraldo di Francia, who directed also the elaboration of some other types of thin-film focussing elements based on the expandable surfaces of jumped change in geodetic ourve, i.e., the so-called conflection doublets [5, 6].

Another group of the thin-film optioal element is formed by two-layer struotures. They may be used to produce such elements like: lens, prism, reflector and polarizer [7, 8].

In practice, the so-called wedge transition on the boundary optical element-waveguide is exploited for technological reasons. The majority of the thin film optical elements realized so far include such transitions in their struoture.

## 2. Wedge transition in the thin-film structures of optical elements

The light transitions by optical element involves overcoming of two medium boundaries, i.e., during entering the structure region, and during its leaving. In order to eliminate the losses for reflection and emission of light the change in optical properties (most frequently in the effective refraotive index) must by mild. For this purpose the so-called wedge transitions are employed, among others, to connect the lightguides of different thickness as well as to hybride coupling of two different lightguides. Both these ways of coupling are shown in Fig. 1 (after [9]).

As it may be easily noticed the mild change in the effective refractive index in the case (a) is of pure geometric nature, while in the oase (b) it is caused by geometry-material changes, typical of the hybride structure. There exists also a third way (o) - call it pure material way - of realizing a mild transition. It is realized by a continuous low gradient change in chemical composition of the substance at the border of

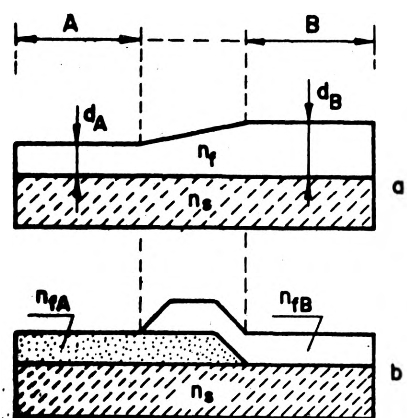



Fig. 1. Scheme of coupling with the help of a wedge: a, waveguides of different thickness ($d_A \neq d_B$), b. waveguides of different refractive indices ($n_{fA} \neq n_{fB}$), $n_s$ - refractive index of the substrate

the media. In the planar lightguide the wedge of this kind may be produced by the doping method, to create a suitable gradient of doping distribution at the border of the doped region [10].

The lightguide phenomena in the thin film transitions of the wedge type were examined first by Tien and Martin in the Bell Laboratory as early as in 1971. Next, in the years 1972-1976 the same authors carried out the examinations of applicability of the wedge transitions in the couplers [11] and connections [12]. From these examinations it follows that the length of the wedge should be great, compared to the film thickness, to enable a correct functioning of the wedge transition. The condition of slight change in effective refractive index along one wavelength path is then satisfied. This is a necessary condition to avoid the radiation modes causing the loss of power. In the case of geometrical transition (a) the wedge inclination should be contained within the limits 1:1 to 1:1000. For instance, if lightguide thickness is 1 μm the wedge length should range from 10 to 1000 μm, depending upon the light wavelength and the range of changes in effective refractive index. It has been also stated that such transition evokes no mode conversion.

In the structures of optical elements all the three (a), (b) and (c) types of transitions are used. The transitions of definite kind are situated at the (input and output) borders of the optical elements structure, except for the reflectors, in which only one transition is exploited.

Depending upon the chosen kind of wedge various optical structures are produced: for the cases (a) and (c) these will be single-layer structures, while for the case (b) - two-layer and waveguide structures.

## 3. Fundamentals of thin film optics

In the course of the examinations mentioned above the effects of refraction and total internal reflection were observed during tha passage of the light through the structure containing wedge elements. On the base of these effects, modified laws of refraction and reflection have been formulated (Tien and Ulrich, 1970).

To describe the lightguide phenomena as well as thin film optics it is possible to start with the wave equation written for the three-dimensional space. For an isotropic medium this equation takes the form

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) E = -k^2 n_f^2 E, \tag{1}$$

where $k = 2\pi/\lambda_0$ - wave-vector in the vacuum,
$kn_f$ - value of the wave-vector in the medium of refractive index $n_f$.

The equation (1) may be decomposed into two equivalent notations

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) E = -\beta^2 E \tag{2}$$

and

$$\frac{\partial^2}{\partial z^2} E = -b^2 E, \tag{3}$$

where $\beta$ and $b$ - are the components of wave-vector in the waveguides satisfying the relation $\beta^2 + b^2 = k^2 n_f^2$.

The relations (2) and (3) describe the zig-zag wave so that the first one describes this movement in the horizontal x-y plane and the other - the changes in the electric field vector in the direction perpendicular to the waveguide plane. Substitution of the mode indices of $N = \beta/k$ type for refractive index $n_f$ in the equation (2) gives an ordinary wave equation in the two-dimensional space. The quantity $N$ is called an effective refractive index and plays the same role in the thin-film optics at that performed by the refractive index in the geometric optics. The value of $N$ depends upon the lightguide film thickness and its refractive index. By changing the optical parameters of the light waveguide the value of the effective refractive index may be regulated. Due to the introduction of the parameter $N$ the Snell's and Fermat's laws which are valid in geometrical optics, preserve their validity also in the planar optics. This is very essential, especially for designing the thin-film structures.

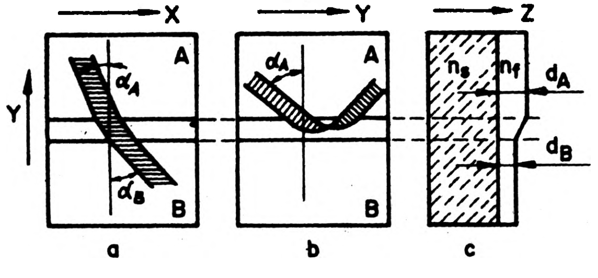



Fig. 2. Scheme of refraction (a) and total reflection (b) in the structure (c)

The effects of refraction and total internal reflection in the lightguide structure with the wedge transition are shown schematically in Fig. 2 (after [1]). The Snell's law for refraction may be written down in the form of relations

$$N_A \sin\alpha_A = N_B \sin\alpha_B \quad (4)$$

or

$$\beta_A \sin\alpha_A = \beta_B \sin\alpha_B, \quad (5)$$

where $N_A = \beta_A/k$, $N_B = \beta_B/k$, $\alpha_A$ - the incidence angle in the lightguide A, $\alpha_B$ - the refraction angle in the lightguide B.

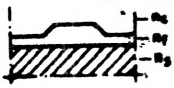
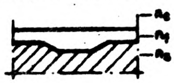
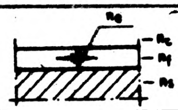
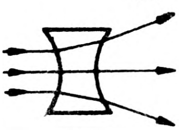
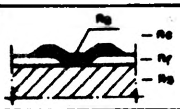
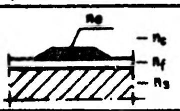
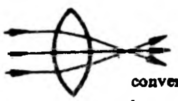
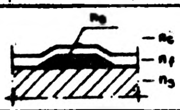
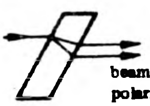
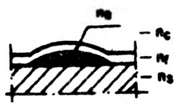
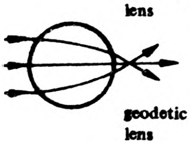
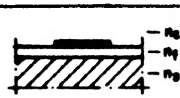
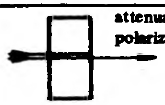
We assume that $N_A > N_B$. Hence, the light wave travelling in the lightguide A falls on the wedge transition under the angle $\alpha_A$ and enters the lightguide under the angle $\alpha_B$. Obviously, the condition $\alpha_A < \arcsin(N_A/N_B)$ must be fulfilled. Within the range from $N_A$ to $N_B$ the change of effective refractive index between the lightguides occurs gradually. For this reason the effects of refractive index and partial reflection may not appear simultaneously at the border of these lightguides. Consequently, the Fresnel formulae cannot be employed.

Also, the phenomenon of total internal reflection takes here another course than in the geometrical optics. The light wave from the part A of the structure falling under the angle $\alpha_A > \arcsin(N_A/N_B)$ on the wedge transition will be totally reflected under the angle equal to the incidence angle. This is in accordance with the Snell's law. Simultaneously, the wave reflected will be shifted by a small distance with respect to the point of incidence. This is caused by the continuous change of the direction of wave propagation in the gradient region of the effective refractive index until the reflected wave is formed. This is the well-known effect of Goos-Häenchen. From the Snell's law it follows that the total internal reflection depends exclusively upon the value of the coefficient N on both the sides of the wedge transitions.

## 4. The structures of the thin-film optical elements

The thin-film optical elements are of small sizes. External sizes of few to several mms are typical when measured in the lightguide plane. Figure 3 shows several examplified elements. As it is well-known the structure of the discussed elements depends mainly upon the way in which the wedge transition is produced. The already mentioned methods

**T a b l e.** Structures and technologies used in production of optical elements

| Item | Structure | Ray-tracing in elements | Technology | Remarks |
|---|---|---|---|---|
| 1 |  |  prism | Evaporation + selective etching | $n_f > n_s$ Element realized on simple wedge transition |
| 2 |  |  reflector | Diffusion, rediffusion, ion exchange | $n_f > n_s$ |
| 3 |  |  diverging lens | Evaporation, high frequency sputtering, centrifuge deposition + irradiation, ion implantation | $n_e > n_f > n_s$ Continuous change of refractive index in selected region of the layer |
| 4 |  | | Diffusion, rediffusion + + selective etching + high frequency sputtering | $n_e > n_f > n_s$ Only slight changes in refractive indices $n_e$, $n_f$, $n_s$ |
| 5 |  |  converging lens | Epitaxy + high frequency sputtering | $n_e > n_f > n_s$ Refractive index $n_e$ must be much higher than the indices $n_s$ and $n_f$ |
| 6 |  |  beam-splitting polarizer | Evaporating, high frequency sputtering + deposition | $n_e > n_f > n_s$ Refractive index $n_e$ must be much higher than the indices $n_s$ and $n_f$ |
| 7 |  |  Luneburg lens | Evaporation, high frequency sputtering | $n_e > n_f > n_s$ Continuous profile. Luneburg lens shows neither spherical nor chromatic aberration |
| 8 |  | geodetic lens | Substrate grinding + + diffusion, ion exchange, ion implantation, evaporation | $n_f > n_s$ Continuous profile in layer of constant thickness. The geodetic lens shows no spherical aberration |
| 9 |  |  attenuating polarizer | Evaporation, diffusion + + evaporation | $n_f > n_s$ Design used only in construction of polarizers working on the base of higher order mode attenuation |

(a), (b) and (c) of the transition creation as well as the other methods have been applied in practice and a number of structures of different optical elements have been produced (for instance [7, 8, 12-15]).

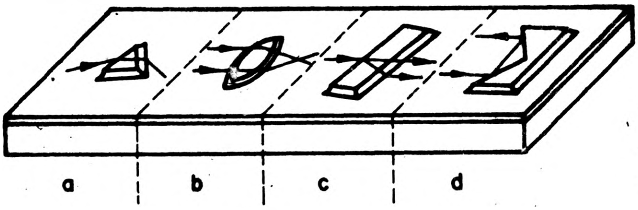



Fig. 3. Schemes of thin-film optical elements: a. prism, b. lens, c. polarizer, d. reflector

The structures shown schematically in the setup may be divided into the following groups (see Table):

i) Single-layer structure produced by the: geometric (items 1 and 2) and blending and doping (item 3) methods.

ii) Two-layer structure - according to the hybride method (items 5-7). A characteristic feature of this structure is that the medium creating the optical element is of higher refractive index $n_e$ than the refractive index of the lightguide layer $n_f$.

iii) Waveguide structure - according to the hybride method (item 4). In this case the junction of two remote (and not necessarily the same) planar lightguides by the wedge transitions is employed.

iv) Substrate structure - a mild change in optical path is obtained by sinking (of required profile) in the substrate before producing a lightguide (item 8). This structure is typical of the so-called geodetic lenses.

v) Structure with metallic layer - realized by deposition of a metallic layer on the lightguide (in a definite place) - item 9. This is the structure evoking an effect of attenuation of the TE and TM modes of the wave propagated in the lightguide. This structure is used in so-called attenuating polarizers (mode selectors).

## 5. Technological methods and materials used for production of the planar optical elements

The structures of the optical elements discussed may be produced by using the methods employed in thin-film technology. Two groups of methods most frequently applied in the integrated optics may be mentioned:

1. Epitaxy, ion sputtering, evaporation, and deposition of organic layers followed by their polimerization. These are the deposition methods enabling the production of a jumping change of refractive index at the layer-substrate border.

2. Diffusion, ion exchange, ion implementation, bombardment by elementary particles and exposure to radiation. These are the methods modifying the optical properties at the near-surface substrate layer by changing its chemical composition and (sometimes) crystal structure. The created layers are immersed in the substrate, while the refractive index is modified to produce a typical profile connected with the applied technological method. The simplest single-layer structures (items 1 and 2 in Table) are produced in one technological cycle. The realization of the others (items 3-9 in Table) requires usually two processes.

The application of the above technological methods to produce the optical elements creates the problems known also in other cases. However, there appear also some special problems. One of them is to preserve the definite chemical composition of the condensate. It is connected directly with the value of the refractive index, which is sometimes specified with the accuracy to the second or even third decimal place. The next problem is to obtain an exactly defined thickness of the layer. This thickness has a direct influence on the value of the effective refractive index as well as on the transmission properties of the lightguide. Finally, the most typical problem here is the required shape and quality of the wedge. In the course of the technological processes the wedge transition should be realized by changing suitably the value of the effective refraction index, to assure a proper geometry of the transition in some cases and to produce a suitable gradient of the doping concentration in the other ones. The production of a proper edge of the structure is the most essential. This edge - the edge of the wedge transition - must be very smooth and regular. The smoothness requirements, necessary to avoid the scattering, define the admissible surface roughness to be less than 50 nm. The above requirements cause that the production of the high quality structures is difficult. All the technological processes must be both carefully and rigorously controlled. The production of the masks with "ideal" edge must be done with the highest care. Also, their imaging must be very precise. Frequently, it is necessary to employ the electro- and X-ray-radiography.

In order to produce the thin-film optical elements a relatively wide group of materials is used. Any structure contains two or three material components for substrate, lightguide and the modified region. The composition of this material depends, of course, on the system functioning. In this respect four groups of materials useful for the structures discussed may be mentioned:

1. Semiconductors materials of $A^{III}B^{V}$ and $A^{II}B^{VI}$ types, with wide forbidden band and high refractive index reaching the value 3 *. The used compositions are: GaAs, AlAs, GaP and ZnS.

2. Family of glasses and glazes of low refractive indices - of order of 1.4–1.6 are usually used as substrate materials.

3. Group of oxides of high refractive indices within the range of 1.9–2.4. $Ta_2O_5$, ZnO, $LiNbO_3$ belongs to this group.

4. Very numerous group of organic materials (among others, photoresists, like AZ 1350 Shipley, n = 1.618), monomers (like VTMS and GMDS, n = 1.47 - 1.53), and many others.

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* This value of the refractive index is for $\lambda = 0.63$ µm

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Received May 17, 1981
in revised form January 28, 1982

## ТОНКОПЛЕНОЧНЫЕ ОПТИЧЕСКИЕ ЭЛЕМЕНТЫ СО СТРУКТУРОЙ, СОДЕРЖАЩЕЙ ОПТИЧЕСКИЙ КЛИНОВОЙ ПЕРЕХОД

Представлены понятие тонкопленочного оптического элемента, основы тонкопленочной оптики, правила конструкции элементов, а также обзор технологии и материалов, применяемых при осуществлении этих элементов.