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Some elements of integrated optics circuits based on planar gradient glass waveguides

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The paper gives a short review of the working principles and the construction of some elements of integrated optics circuits basing on the planar gradient glass waveguides. It presents the following elements: grating beam deflector/mode converter, planar waveguide reflectors, hybrid circuit containing gradient glass waveguide and thin ZnO film, integration of two planar waveguides and integration of planar waveguide and multimode optical fibre.

1. Introduction

A number of investigations [1, 3] have been concerned with the technology of planar optical glass waveguides obtained by diffusion and ion-exchange methods. This technology is characterized by simplicity, satisfactory repeatability and accessibility to the main raw material (glass plates). The waveguides obtained in these ways have low mode attenuations (~1 dB/cm) and their surface refraction indices range from 1.520 to 1.605.

The mentioned features of the technology and the properties of optical glass waveguides predispose them to be used mainly in passive optical elements construction (such as: polarizers [3], filters [4], beam expanders [5]); these waveguides may be also used for active elements (such as modulators [6], switches [7]) of hybrid integrated optics circuits construction.

The paper presents the construction and treats of the working principles of some optical elements models based on the planar gradient (sode-lime type*) glass waveguides produced in molten salt baths: $AgNO_3$ and KNO_3.

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* Microscopic slides of the content given in [2].

2. Planar grating deflector converter

The grating structures are widely applicable [8] in integrated optics; they serve to construct the following optical elements: filters, mode converters, deflectors, grating couplers. One of the grating-forming techniques is electron beam litography. This method has been used for production of planar diffraction gratings in thin films of polymethylmethacrylate (PMMA) deposited onto the surface of optical glass waveguides formed in molten $AgNO_3$ bath.

2.1. Production technology of grating structures

The PMMA films of the thickness ranging within 0.3–0.6 μm were spin-coated onto the surfaces of some planar optical glass waveguides. The samples were baked at 393 K for 15 minutes, thereupon the surfaces of the samples were covered with 0.04 μm thick films of Au to prevent charge from building up during electron beam irradiation. The patterns of the periodic structures were formed using a scanning electron microscope (JOEL JSM-35). The exposing conditions employed were a 0.5 nA electron beam current and a surface density of charge ranging from 5×10^{-6} C/cm^2 to 2.5×10^{-5} C/cm^2. Maximum duration of exposure was 500 seconds. After exposing, Au films were etched and the patterns were developed.

Some gratings with typical sizes of 1×1.5 mm and a period Λ ranging from 0.9 μm to 5 μm were formed in this way; one of the gratings micrograph is shown in Fig. 1.

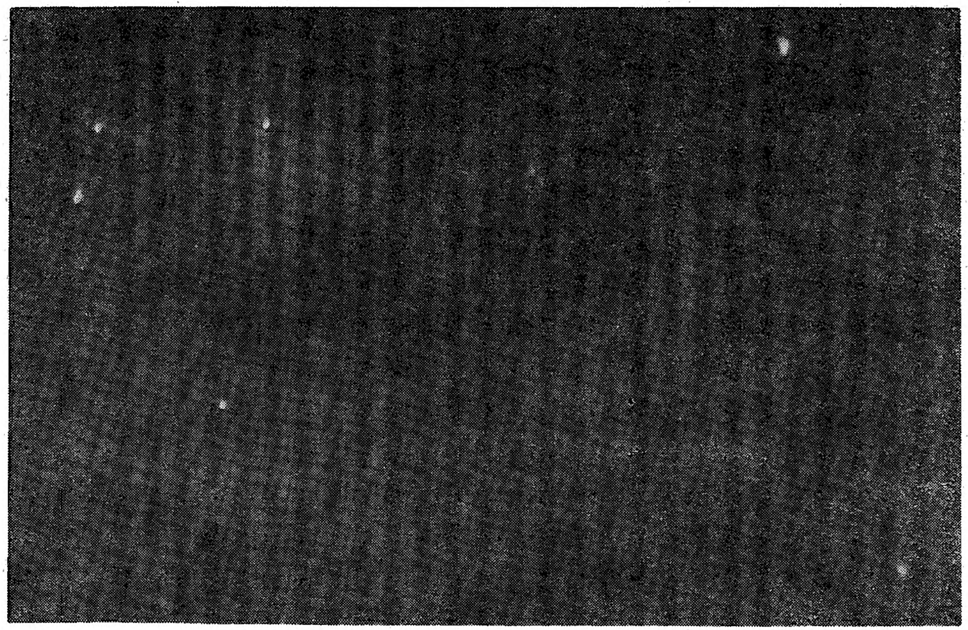

Fig. 1. Micrograph of the PMMA grating (with a period of 2 μm) formed by electron beam lithography

2.2. Optical properties of hybrid structures

Basing on the phase-matching condition [9] and using experimentally determined values of effective mode indices, the calculations were performed to find for which angles of light incidence at gratings isotropic or anisotropic Bragg diffraction of modes may occur.

The computer program was used for the calculations; this program makes it possible to determine the angles θ_i and θ_d (shown in Fig. 2) for all the combinations of the incident and diffracted modes orders.

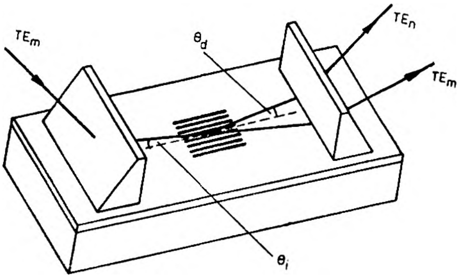

Fig. 2. Schematic layout of the Bragg diffraction experiment

The results of the calculations were checked experimentally; schematic layout of the experiment is shown in Fig. 2 (the examples of the calculations and measurements results were given in the description of Fig. 2). The isotropic and anisotropic Bragg diffraction cases were observed. The anisotropic Bragg diffraction of an optical wave propagating in one of the waveguides by the grating with $\Lambda = 2$ μm is shown in Fig. 3.

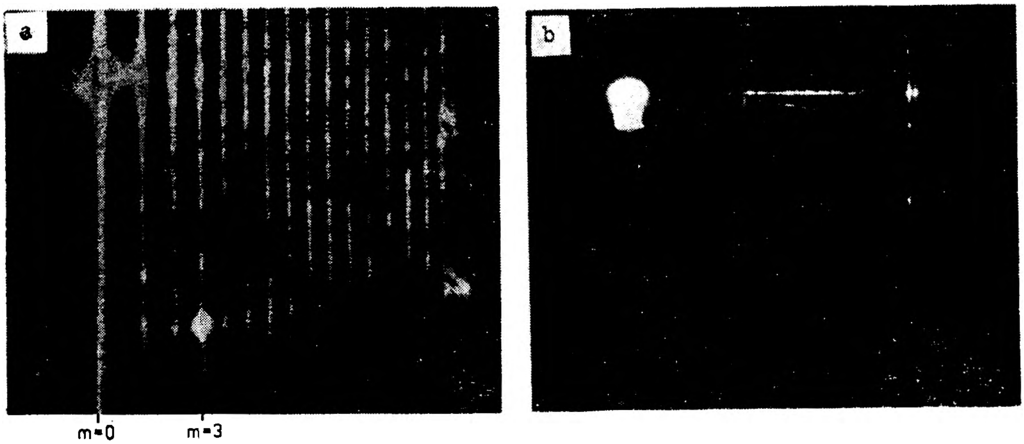

Fig. 3. Bragg diffraction of light (with mode conversion being: $TE_0 \rightarrow TE_3$) by the PMMA grating with a period of 2 μm. The diffraction pattern (a), the paths of the light waves propagating in the structure $(\Theta_i+\Theta_d)_{\text{measured}} = 0.201$ rad, $(\Theta_i+\Theta_d)_{\text{theoretical}} = 0.199$ rad (b)

The results of the experiments suggest that the presented devices may be used as deflectors, mode converters of optical power dividers.

3. Elements altering the direction of light propagation in a planar optical waveguides

The optimization of optical circuit geometry and of sizes may require the repeated changes of light propagation direction within this circuit. In the circuit the formation of which is based on a planar optical waveguide light propagation direction can be altered by using planar reflectors.

Laboratory models of two types of planar reflectors were produced. In the reflectors of the first type (Fig. 4a) the work principle is based on the reflecting properties [10] of a waveguide tapered edge. These reflectors were formed in molten nitrates baths: $AgNO_3$ and KNO_3. Before immersing in baths, parts of the surfaces of glass substrates have been marked by thin (~1 μm thick) Al films. After having taken the samples out of baths, the masking films were removed by mechanical polishing. The elements of such a type may also be

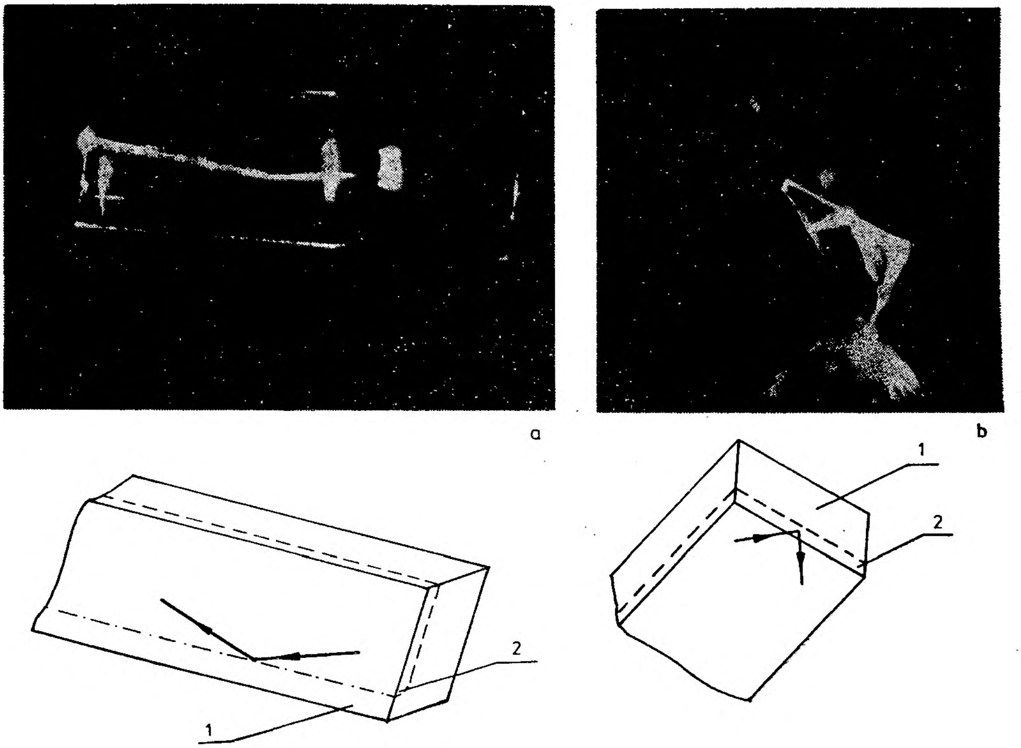

Fig. 4. Planar waveguide reflectors: first type (a); second type (b): 1 – glass substrate, 2– optical gradient waveguide

produced by partial dipping of the substrates in baths. The range of angles at which light on such a type of reflectors must be directed may be estimated basing on the Snell law

$$\theta > \arcsin \frac{n_b}{n_s} \tag{1}$$

where n_b — bulk substrate refractive index,
n_s — refractive index on the gradient waveguide surface,
θ — angle of incidence on the reflector (measured from the normal to tapered edge of waveguide).

In these reflectors for TE modes: $\theta > 1.45$ rad (molten KNO_3 bath) and $\theta > 1.23$ rad (molten $AgNO_3$ bath).

It is obvious that for waveguides having refractive index slightly greater than the substrate, this tapered-edge approach restricts its use to near-grazing incidence. Care must be taken to avoid the tapered edge acting as a coupler into the substrate.

In the second type reflectors (Fig. 4b) the light supported by the waveguides is reflected from the polished side surfaces of the glass substrate. To estimate the angles of total internal reflection (at the interfaces waveguides-air), in reflectors of this type, formula (1) may also be used, where $n_b = 1.0$. In this case a much wider range of total internal reflection may be obtained, for TE modes: $\theta > 0.72$ rad (molten KNO_3 bath), and $\theta > 0.67$ rad (molten $AgNO_3$ bath). The polished surfaces may be metallized permitting an efficient reflection at normal incidence.

In both types of devices presented the reflecting surfaces irregularities cause energy transfer from the excited modes to all other waveguide modes and also to media surrounding the waveguides.

4. Optical coupling between gradient glass waveguide and thin ZnO film

When the complex circuits of integrated optics are being constructed, there appears a problem of selecting the materials useful for waveguides production and having other useful properties (for example: electro-, magneto- or acoustooptic properties). One deals with such problems in the case of thin ZnO films which, considering their piezoelectric properties, are applicable [11] to acoustooptic modulators/deflectors construction. Thin ZnO films deposited by RF sputtering are characterized by good acoustic properties (according to [12] the value of effective coupling constant may be greater than 10 percent) but rather high optical losses (according to [13] the mode attenuation for TE_0 mode of He-Ne laser light is $\sim$20 dB/cm). One of the possible solutions of this problem is to minimize the region of high optical losses, i.e. the construction of the hybrid structure in which light would be led (and taken off) to the region of acoustooptic interaction (i.e. ZnO film) by low loss waveguides formed in another material. The scheme of such a (multimode) construction (produced by the authors) is shown in Fig. 5. The c-oriented polycrystalline (1.08 μm thick) ZnO film was deposited by RF sputtering onto te surface of planar (low loss $\alpha \sim 1$ dB/cm) sode-lime glass waveguide formed in molten KNO_3 bath. During the film deposition process, the substrate was covered partially by mechanical mask. The spacing between the mask and the top surface of the glass plate was 1 mm; the mask substrate geometry resulted in formation of tapered ZnO film edge. The value of ZnO film refractive index n_f was defined

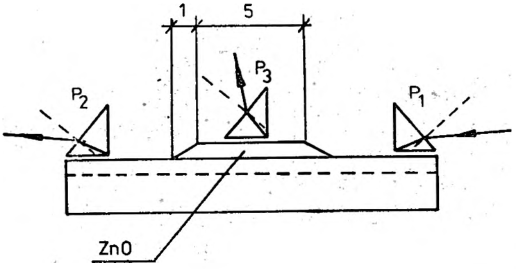

Fig. 5. Scheme of the chip consisting of planar gradient glass waveguide and thin ZnO film (P_1, P_2 – glass prisms, P_3 – rutile prism; sizes in mm)

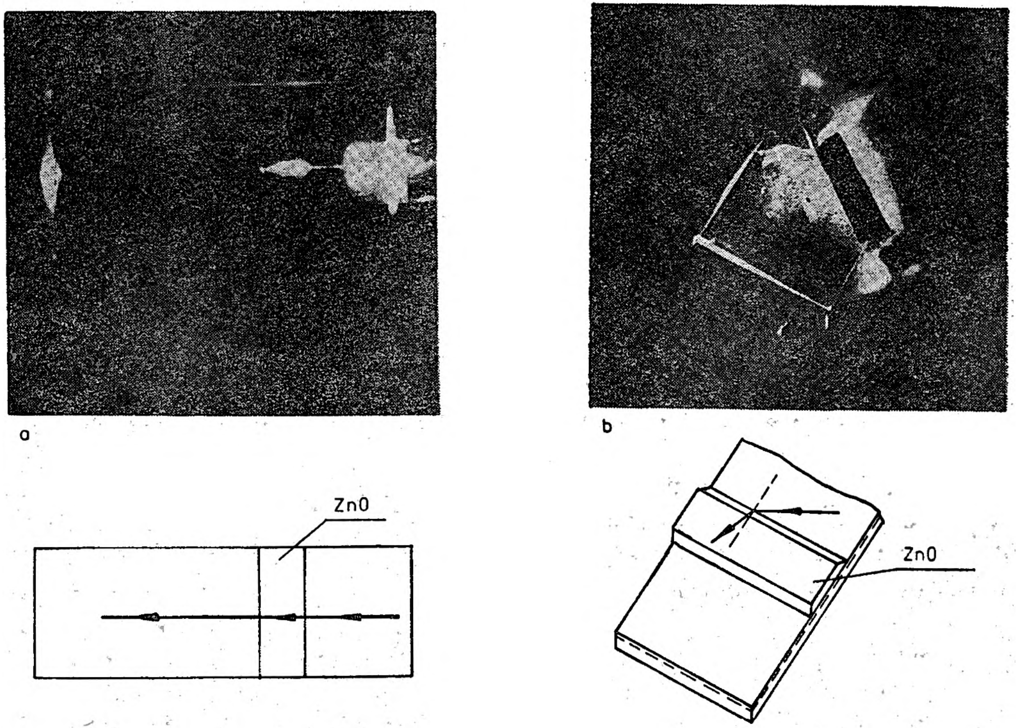

Fig. 6. The paths of the light waves propagating in the chip shown in Fig. 5: normal incidence (a), oblique incidence – optical wave refraction on the boundary of thin ZnO film (b)

basing on measurements (effective TE mode indices determination) and calculation (characteristic mode equation [9] solution) related to the structure which had been produced previously; it was a thin ZnO film waveguide deposited onto the surface of soda-lime glass plate. The above was obtained (for He-Ne laser light) $n_f = 2.059$.

In the gradient glass waveguide (being part of hybrid structure) refractive index profile $n(x)$ was calculated basing on the procedure followed by I.W.K.B. [2] method; $n(x)$ profile was approximated by erfc function. The value of refractive index (for TE polarized light) on the surface of this waveguide was $n_s = 1.524$.

The propagation of light (coupled by P_1 prism) in the hybrid structure is shown in Fig. 6. Selective modes excitation by P_1 prism was accompanied by collective appearance of all mode lines in the light decoupled from the structure through others prisms. Similar effect could be observed when light was coupled into the structure through P_3 prism.

The described effect is probably connected with the parasitic modes excitation (waveguide modes being of orders different from the primary mode) caused by light scattering in ZnO film. The phenomenon of collective appearance of mode lines should not occur in monomode hybrid structure but one may still expect energy losses related to a partial transfer of light energy from the waveguides to their surrounding media (to prevent this loss, it seems to be necessary to polish the surface of ZnO film).

5. Integration of two planar glass waveguides. Coupling between planar glass waveguide and multimode optical fibre

Complex optical circuits may be constructed by coupling discrete chips formed on different substrates; this coupling may be realized in a direct way (evanescent field coupling [14]) or using intermediate elements – optical fibres.

The authors have performed the preliminary test of direct coupling between two planar gradient glass waveguides and the tests of coupling between planar waveguide of this type and multimode step index optical fibre. Planar waveguides were coupled together in two configurations shown in Fig. 7. In both configurations one deals with distributed or evanescent wave coupling. For such a coupling, phase matching condition [9] must be fulfilled; it may be fulfilled for pairs of modes (from both coupled waveguides) of the same or different orders. It seems that coupled planar waveguides may be used as mode filter or mode converter.

According to [15], in the configuration shown in Fig. 7a, 70 percent efficiency of coupling is limited, whereas in the configuration shown in Fig. 7b it may be greater than 90 percent. In experiments two identical waveguides (two halves of a single waveguide) and also two different waveguides were coupled with each other. The example of two identical waveguides coupling is shown in Fig. 8.

The coupling between a planar optical waveguide and an optical fibre

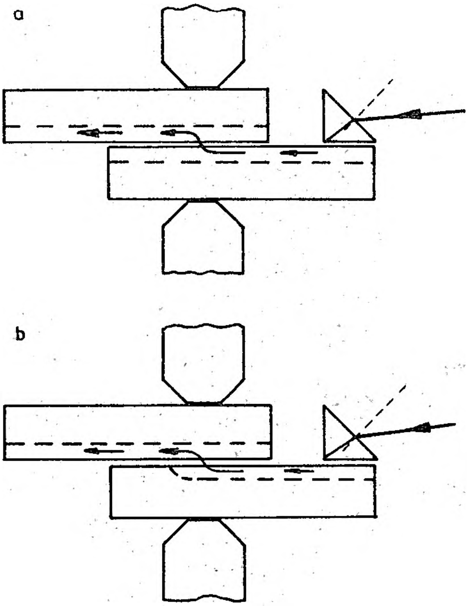

Fig. 7. Configurations schemes of coupled planar waveguides

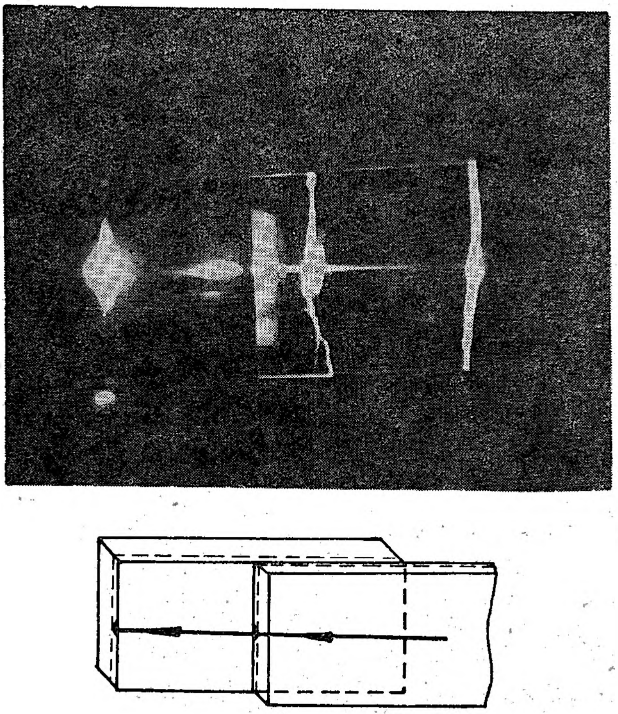

Fig. 8. Coupling (in configuration shown in Fig. 7a) between two identical glass waveguides formed in molten $AgNO_3$ bath ($T = 523K$, $t = 30$ minutes)

was realized basing on the rule similar to the one described above. The planar waveguide (supporting three TE modes) formed in molten KNO_3 bath was coupled to the optical multimode step index fibre (fused-silica core with a diameter of 200 μm; plastic cladding). The exposed fiber core (the cladding had been removed on a distance of 1 cm) was mechanically pressed against the surface of the planar guide obliquely to the direction of light propagation in the planar guide (Fig. 9). The oblique position of the fibre assured the phase matching condition for electromagnetic waves to be fulfilled in both elements. Because of the large number of guided modes supported by the fibre, phase matching over a wide range of angles γ $(0 < \gamma < \pi/2)$ is possible. One should add that in a circuit, as the one described above, the efficiency of optical energy transfer from planar guide to fiber may exceed 90 percent [16]. One may also suppose that a more practical glue link may replace the mechanic pressing device used in the construction.

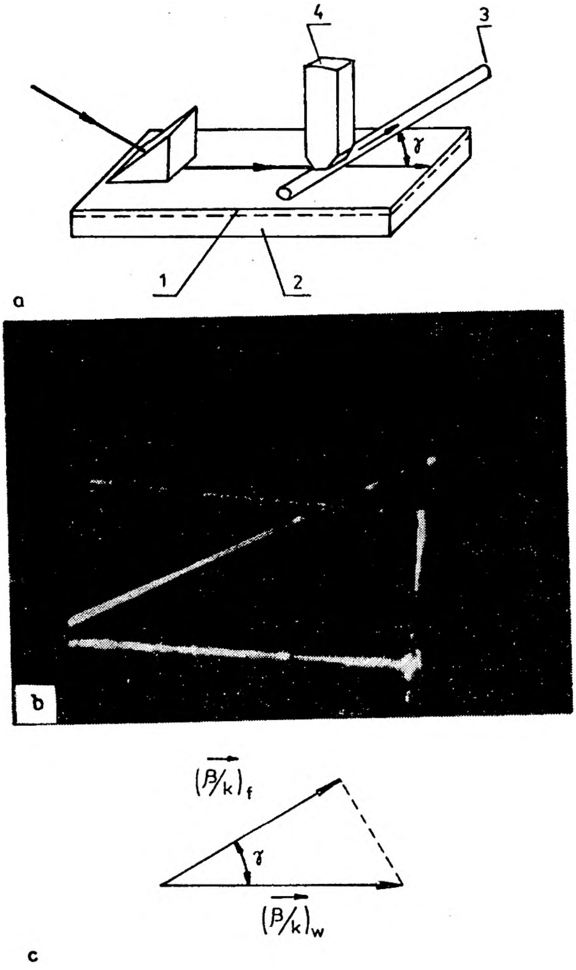

Fig. 9. Coupling between planar gradient waveguide and multimode step index fibre: a – scheme of experimental arrangement (1 – planar gradient waveguide, 2 – substrate, 3 – optical fibre with cladding removed, 4 – chisel-ended steel rod), b – example of coupling, c – wave vectors diagram (subscript *w* – planar guide, subscript *f* – optical fibre)

6. Conclusions

The paper reviews briefly the results of the investigations concerned with the technology of some elements of integrated optics circuits based on the planar gradient glass waveguides. These investigations are of sounding character; their purpose was to reveal rather than to give the satisfactory solutions to the construction problems. The investigations of this subject matter will be continued.

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Некоторые элементы систем интегрированной оптики, образованных на основе планарных градиентовых стеклянных световодов

В работе обсуждены принципы действия, конструкция и некоторые оптические свойства нескольких элементов систем интегрированной оптики, образованных на основе планарных градиентовых стеклянных световодов. Представлены: сеточный отклонитель/преобразователь струи модов, планарные рефлекторы, система сопряженных световодов – градиентового и слоевого, системы попарно сопряженных градиентовых планарных световодов (фильтры/преобразователи модов), сопряжение планарного световода с оптическим волокном, состоящим из многих модов.

Перевела Малгожата Хейдрих