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TE$\longleftrightarrow$TM mode conversion in an $Y_3Fe_5O_{12}$ anisotropic planar lightguide covered by a metal layer

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The possibility of conversion of TE $\leftrightarrow$ TM modes in four-layer lightguiding structure which is covered with metal and contains the anisotropic layer on isotropic substrate is proved in the paper. Theoretical solutions are verified experimentally using the structure with anisotropic $Y_3Fe_5O_{12}$ lightguiding layer.

1. Introduction

Among many multilayer structures analysed in integrated optics the structures covered with metal coating draw a special attention. These structures exhibit many specific features, among others, the presence of the metal coating may cause a degeneracy of the TE and TM modes in the lightguide [1]. The phenomenon of mode degeneracy may be exploited to produce the mode conversion of the TE $\leftrightarrow$ TM type.

In order to produce the effect of TE $\leftrightarrow$ TM mode conversion, which may find practical application in the systems of integrated optics two basic conditions must be fulfilled. The first is the degeneracy of both TE and TM modes, due to which they propagate with the same velocity in the lightguide. The second-coupling between these modes of vibrations realized along a definite interval of propagation. In the isotropic lightguides such a coupling does not occur, the TE and TM modes being orthogonal and propagating independently of each other. In anisotropic lightguide layers, described with the help of the dielectric permittivity tensor having non-zero out-of-diagonal terms, the modes being close to those of TE and TM type in anisotropic lightguide, may propagate, however, they are not orthogonal [2].

In accordance with the above, the effect of mode conversion in the structure covered by a metal coating may be expected in the case when the isotropic lightguide layer is replaced by the anisotropic layer (fig. 1). The conditions which must be fulfilled to enable the effect to occur is the goal of the considerations presented below.

In order to determine the conditions of TE $\leftrightarrow$ TM mode degeneracy the four-layer structure having a metal cover of negative part $\hat{\varepsilon}_1$ of complex dielectric permittivity and anisotropic lightguide layer with components ε_{xz} and ε_{zx} of the dielectric permittivity tensor different from zero have been analysed.

The optimization of the conditions for the occurrence of TE $\leftrightarrow$ TM mode conversion effect was possible due to the acceptance of the proper form of the dielectric permittivity tensor in the lightguide layer. The assumptions that

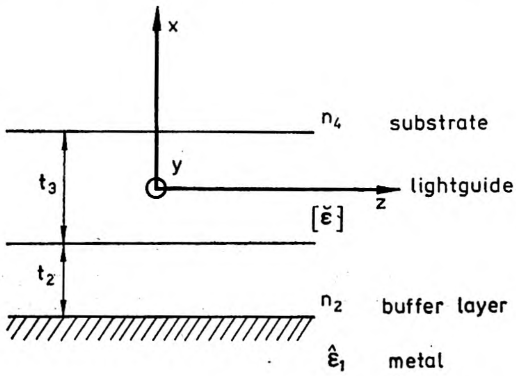

Fig. 1. The cross-section of the analysed lightguide structure (the direction of the electromagnetic wave propagation is defined by the z - axis)

the terms ε_{xy} and ε_{yx} are equal to zero made it possible to achieve the rigorous solutions in the form of orthogonal TE and TM modes. These modes are degenerated for definite parameters of the structure discussed, which fulfills the first condition of the mode conversion. Practically, in the obtained anisotropic lightguide layers the remaining components of the dielectric permittivity tensor are also different from zero. In particular, in the case of non-zero components ε_{xy} and ε_{yx} existing in the lightguide structure of the TE and TM modes do not appear as independent.

The third part of this paper presents the experimental results concerning the mode conversion effect realized on the base of an anisotropic lightguide layer of yttrium garnet $Y_3Fe_5O_{12}$. The results obtained have confirmed that the dispersion characteristics calculated for the case $\varepsilon_{xy} = \varepsilon_{yz} = 0$ are useful in analysis of practical lightguide layers, since they allow to determine the conditions of TE and TM degeneracy.

2. Theoretical part

2.1. Lightguide configuration and the basic assumption of analysis

In accordance with the theoretical assumptions formulated in the introduction we shall consider the lightguide as shown in fig. 1. The anisotropic light guide layer of thickness t_3, for which the dielectric permittivity tensor takes the form

$$[\varepsilon] = \varepsilon_0 \begin{bmatrix} \varepsilon_{xx} & 0 & \varepsilon_{xz} \\ 0 & \varepsilon_{yy} & 0 \\ \varepsilon_{zx} & 0 & \varepsilon_{zz} \end{bmatrix}, \tag{1}$$

is deposited on an isotropic substrate of refractive index n_4. Here ε_0 is the dielectric permittivity of vacuum and the out-of-diagonal terms, while ε_{xz} and ε_{zx} are of pure imaginary type. The buffer dielectric layer of thickness t_2 and the refractive index n_2 separates the lightguide layer from the metal coating.

We assume that the direction of electromagnetic wave propagation is parallel to the z axis, while the structure is uniform in the y direction ($d/dy = 0$).

We look for solutions of the Maxwell equations in the anisotropic light-guide, as shown in fig. 1, in the form of plane wave propagating in the direction of the z axis:

$$\boldsymbol{E} = \boldsymbol{E}(x)\exp j(\omega t - k_z z),$$
$$\boldsymbol{H} = \boldsymbol{H}(x)\exp j(\omega t - k_z z), \tag{2}$$

where $k_z = \beta - j\alpha$ is a complex propagation constant in the z direction.

Under the condition that $d/dy = 0$ the Maxwell equations may be separated into two groups:

$$\left.\begin{aligned} jk_z H_x - \frac{dH_z}{dx} &= -j\omega\varepsilon_0\varepsilon_{yy}E_y \\ -k_z E_y &= \omega\mu_0 H_x \\ \frac{dE_y}{dx} &= j\omega\mu_0 H_z \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} jk_z E_x - \frac{dE_z}{dx} &= j\omega\mu_0 H_y \\ k_z H_y &= \omega\varepsilon_0\varepsilon_{xx}E_x + \omega\varepsilon_0\varepsilon_{xz}E_z \\ \frac{dH_y}{dx} &= j\omega\varepsilon_0\varepsilon_{zx}E_z + j\omega\varepsilon_0\varepsilon_{zz}E_z \end{aligned}\right\} \tag{4}$$

From (3) we obtain the wave equation for the waves of TE type in the form

$$\frac{d^2E_y}{dx^2} + (k^2 - k_z^2)E_y = 0, \tag{5}$$

where

$$k^2 = \omega^2\varepsilon_0\varepsilon_{yy}\mu_0 = \varepsilon_{yy}k_0^2,$$
$$k_0^2 = \omega^2\varepsilon_0\mu_0.$$

In the case of equations of second group determining the modes of TM type the H_y component is obtained by solving the wave equation

$$\frac{d^2H_y}{dx^2} - jk_z\left[\frac{\varepsilon_{xz}}{\varepsilon_{xx}} + \frac{\varepsilon_{zx}}{\varepsilon_{xx}}\right]\frac{dH_y}{dx} + \left[\frac{\varepsilon_{zz}}{\varepsilon_{xx}}(\omega^2\mu_0\varepsilon_{xx} - k_z^2) - \omega^2\mu_0\varepsilon_{xz}\frac{\varepsilon_{zx}}{\varepsilon_{xx}}\right]H_y = 0. \tag{6}$$

The wave equations in the isotropic layers (fig. 1) are of similar character as the equation (5). The analysis allowing to obtain the wave equations in these layers was omitted due to limited space of this paper. The reader may get the needed information on the subject in the commonly available literature ([3, 4], for instance.

2.2. The dispersion equations

The dispersion equations for the modes propagating in the lightguide discussed may be obtained by using a method widely applied in the analysis of the electromagnetic wave propagation in the dielectric waveguides [3, 4].

2.2.1. TE modes

After taking account of the boundary conditions in accordance with fig. 1 and comparing the respective vectors for modes of TE type we obtain the dispersion equations in the form [5]:

$$u_3 t_3 = \arctan\left[\frac{\frac{ju_1}{u_3} - \frac{u_2}{u_3}\tan(u_2 t_2)}{1 + \frac{ju_1}{u_2}\tan(u_2 t_2)}\right] + \arctan\left[\frac{ju_4}{u_3}\right] + m\pi. \tag{7}$$

where

$$u_1 = (k_z^2 - \hat{\varepsilon}_1 k_0^2)^{1/2}.$$
$$u_2 = (u_2^2 k_0^2 - k_z^2)^{1/2},$$
$$u_3 = (\varepsilon_{yy} k_0^2 - k_z^2)^{1/2},$$
$$u_4 = (k_z^2 - n_4 k_0^2)^{1/2},$$
$$am = 0, 1, 2, 3, \ldots \text{ (denotes mode order).}$$

2.2.2. TM modes

In the case of TM modes the finding of solution is more complex. It is impossible to obtain the dispersion equation in such a simple form as it was the case for TE modes. After taking account of the boundary conditions and in accordance with notations used in fig. 1, a system of six linear equations with six unknown is obtained. The propagation constants in particular regions are

$$u_1 = (\hat{\varepsilon}_1 k_0^2 - k_z^2)^{1/2},$$
$$u_{21} = u_{22} = (u_2^2 k_0^2 - k_z^2)^{1/2},$$
$$u_{31} = \frac{-k_z\left(\frac{\varepsilon_{xz}}{\varepsilon_{xx}} + \frac{\varepsilon_{zx}}{\varepsilon_{xx}} - \sqrt{\Delta}\right.}{-1}, \tag{8}$$
$$u_{32} = \frac{k_z\left(\frac{\varepsilon_{xz}}{\varepsilon_{xx}} + \frac{\varepsilon_{zx}}{\varepsilon_{xx}}\right) - \sqrt{\Delta}}{-2},$$
$$u_4 = (u_4^2 k_0^2 - k_z^2)^{1/2},$$

where

$$\Delta = k_z^2\left(\frac{\varepsilon_{xz}}{\varepsilon_{xx}} + \frac{\varepsilon_{zx}}{\varepsilon_{xx}}\right)^2 + 4\left[\frac{\varepsilon_{zz}}{\varepsilon_{xx}}(\omega^2 \mu_0 \varepsilon_{xx} - k_z^2) - \omega^2 \mu_0 \varepsilon_{xz}\frac{\varepsilon_{zx}}{\varepsilon_{xx}}\right].$$

In order to make this system of equations solvable its determinant must be equal to zero, i.e.:

$$\begin{bmatrix} \exp(ju_1x_1) & -\exp(ju_{21}x1) & -\exp(-ju_{22}x1) & 0 & 0 & 0 \\ \frac{u_1}{E_1}\exp)ju_1x1) & -\frac{u_{21}}{E2}\exp(ju_{21}x1) & \frac{u_{22}}{E2}\exp(-ju_{22}x1) & 0 & 0 & 0 \\ 0 & \exp(ju_{21}x2) & \exp(-ju_{22}x2) & -\exp(ju_{31}x2) & -\exp(-ju_{32}x2) & 0 \\ 0 & \frac{u_{21}}{E2}\exp(ju_{21}x2) & -\frac{u_{22}}{E2}\exp(-ju_{22}x2) & -S\exp(ju_{31}x2) & -W\exp(-ju_{32}x2) & 0 \\ 0 & 0 & 0 & \exp(ju_{31}x3) & \exp(-ju_{32}x3) & -\exp(ju_4x3) \\ 0 & 0 & 0 & S\exp(ju_{31}x3) & -W\exp(ju_{32}x3) & -\frac{u4}{E1}\exp ju_4x3) \end{bmatrix} = 0 \tag{9}$$

Notations:

$$E1 = n_1^2, \quad x1 = -[(t_3/2)+t_2], \quad S = \frac{\varepsilon_{xx}u_{31}-\varepsilon_{zx}u_2}{\varepsilon_{xx}\varepsilon_{zz}-\varepsilon_{xz}\varepsilon_{zx}},$$

$$E2 = n_2^2, \quad x2 = -(t_3/2),$$

$$E4 = n_4^2, \quad x3 = t_3/2, \quad W = \frac{\varepsilon_{xx}u_{32}-\varepsilon_{zx}u_2}{\varepsilon_{xx}\varepsilon_{zz}-\varepsilon_{xz}\varepsilon_{zx}},$$

which gives the sought dispersion equation determining the TM modes. In the case of complex constant of propagation $k_z = \beta - j\alpha$ the solution of both the dispersion equations (7) and (9) requires an application of complex numerical calculations based on respective minimizing programmes.

2.3. Solution of dispersion equations

The dispersion equations have been solved numerically on CDC 360 CYBER computer by using the minimizing programme POWELL 1 with a minimizing subroutine in direction MINK 6 [6]. The choice of the gradientless method to seek for minimum was due to the dispersion equation in the form of the determinant (9). The structure based on lightguide layer of ferrum-yttrium garnet $Y_3Fe_5O_{12}$ was taken for calculations. At the presence of magnetic field magnetizing the sample until saturation in the x direction the components of the dielectric tensor defining the material are different from zero [7]. For the calculations the tensor of the form ($\lambda = 1.152$ μm):

$$[\varepsilon] = \varepsilon_0 \begin{bmatrix} 4.743 & 0 & j0.025 \\ 0 & 4.743 & 0 \\ -j0.025 & 0 & 4.743 \end{bmatrix} \tag{10}$$

was accepted. By neglecting the terms ε_{xy} and ε_{yx} it was possible to determine the pure TE and TM modes. The values of ε_{xz} and ε_{zx} were assumed to be the greatest possible which may occur in the layer under test.

At the absence of magnetic field the tensor (10) is reduced to the expression

$$[\varepsilon] = \varepsilon_0 \begin{bmatrix} 4.743 & 0 & 0 \\ 0 & 4.743 & 0 \\ 0 & 0 & 4.743 \end{bmatrix} \tag{11}$$

The gadolinium-gallium garnet (GGG) taken for the substrate is an isotropic material of refractive index $n_4 = 1.945$ (for $\lambda = 1.152$ μm), while the light sensitive KPR-2 emulsion of refractive index $n_2 = 1.580$ (for $\lambda = 1.152$ μm) was chosen for the buffer layer. This value of the refractive index was assumed on the base of the measurement carried out on a sample emulsion ($n_2 = 1.580 \pm 0.005$). As a material for metal coating the silver was considered which is a metal of negative real part of the complex dielectric permittivity in the infrared region. In calculations it has been assumed for $\hat{\varepsilon}_1 = -58.3 - j2.842$ at $\lambda = 1.152$ μm [8]. All the calculations were performed as a function of the buffer layer thickness t_2.

2.3.1. The influence of the buffer layer thickness (at the absence of the internal magnetic field)

The effect of the buffer layer thickness on the modes propagating through the analysed lightguide structure is shown in the graphs (changes of β/k – fig. 2, and changes of α – fig. 3). For the calculations the lightguide layer thickness $t_3 = 5$ μm was assumed.

In accordance with the expectation the degeneracy of TE and TM modes (graph in the fig. 2) is achieved. For the assumed lightguide layer thickness

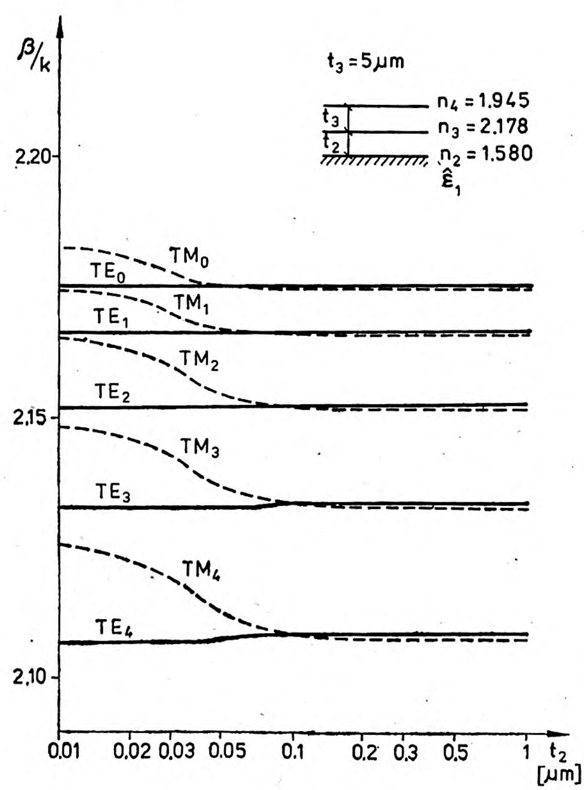

Fig. 2. The changes of β/k as the function of the buffer layer thickness t_2 for the analysed structure containing the isotropic lightguide layer (the graph is limited to represent the five lowest orders of modes)

the waveguide may transfer 9 orders of TE and TM modes. For each order the intersection of TE and TM modes is observed. In accordance with the fig. 2, the higher the mode order the more the point of intersection is shifted in the direction of increasing thicknesses t_2. This point is enclosed within the limits 0.07–0.2 μm. In the graph in the fig. 3 the run of the damping coefficient

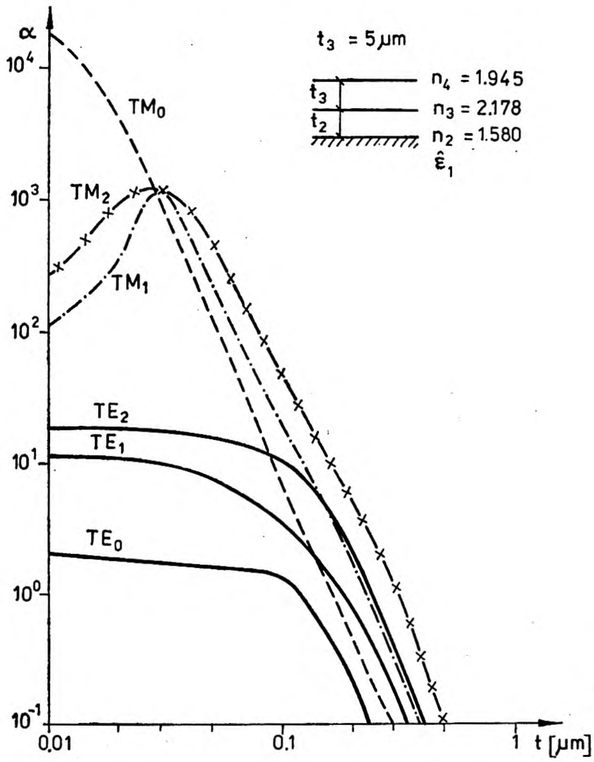

Fig. 3. The run of the damping factor a as a function of the buffer layer thickness t_2 for the lowest TE and TM modes

is given as a function of the buffer layer thickness t_2. As it was expected, the mode damping of TE modes is definitely less than that of TM modes and substantially decreases with the increase of t_2. In conformity with the expectations the higher TE mode the higher the losses, although the character of damping reduction is equally quick as for TE_0 mode. The damping of the modes of TM type is definitely higher although the character of changes remains similar. The high damping connected with the interaction of the TM_0 type wave with the metal coating diminishes rapidly with the increase of t_2, it may be explained by diminishing interaction of the electromagnetic wave propagating in the lightguide layer with the metal coating occurring with the increasing distance t_2. For the other TM modes the increase of damping is observed at $t_2 = 0.03$ μm.

2.3.2. The effect of external magnetic field creation

In the case when external magnetic field is applied the lightguide layer becomes an anisotropic medium. For numerical calculations the tensor of dielectric permittivity of the lightguide layer was assumed in the form (10). The assumed values of the terms ε_{xz} and ε_{zx} gave eventually small changes in the run of reduced factors of propagation.

Table. The comparison of β/k and α for TM_1 modes in the case of isotropic and anisotropic lightguide layer: $t_3 = 5$ µm

t_2	Isotropic layer		Anisotropic layer	
µm	β/k	α	β/k	α
0.01	2.174589	129.3706	2.174545	136.8166
0.03	2.171002	573.6677	2.170807	1403.3335
0.05	2.167944	223.0127	2.167892	221.8821
0.07	2.167328	73.2967	2.167294	71.6335
0.09	2.167093	33.7983	2.167064	33.2272
0.2	2.166811	2.7245	2.166786	2.6986
0.4	2.166775	0.0953	2.166750	0.0945
0.6	2.166774	0.0037	2.166749	0.0037
0.8	2.166774	0.0001	2.166749	0.0001
1.0	2.166774	0.0001	2.166749	0.0001

In the table β/k and α for the structures with isotropic and anisotropic layers are compared. The TM_1 mode was selected as an example. As it follows from the table the changes in β/k and α, evoked by the appearence of the out-of-diagonal terms in the tensor of dielectric permittivity characterzing the lightguide layer at the presence of external magnetic fields, are small. This is a valuable property from the viewpoint of desing of devices, which enables to exploit the effect of mode conversion in the magnetic layer covered with the metal coating.

3. Experimental part

3.1. Measurement system

The system used in measurements is presented in fig. 4. Since the tested magnetic specimens are transparent for the infrared light the He-Ne LG-600 laser retuned to the line $\lambda = 1.152$ µm was used as a light source. The light beam emitted from the laser pass through the modular and next, being polarized in the plane corresponding to the TE mode and focussed by the lens, fall onto the sample positioned vertically on the goniometric table. To let the light into and out of the specimen the prism couplers made of the rutil were used. The laser radiation lead out of the lightguide fell onto the infrared radiation detector. The detector with an analyzer was mounted on a rotating arm, which could rotate concentrically around the goniometric table axis. The steady magnetic field magnetizing the sample in the direction of x axis was produced by electromagnet made of transformer, the core cross-section of which was about 1 cm^2. The slit of electromagnet being about 3 mm wide, was absolutely sufficient for shifting the pole pieces of the magnet over the sample fixed vertically. Due to the sizes of the pole pieces the distance between the prisms was about 18 mm. In order to adjust the system and visualize the propagation effect

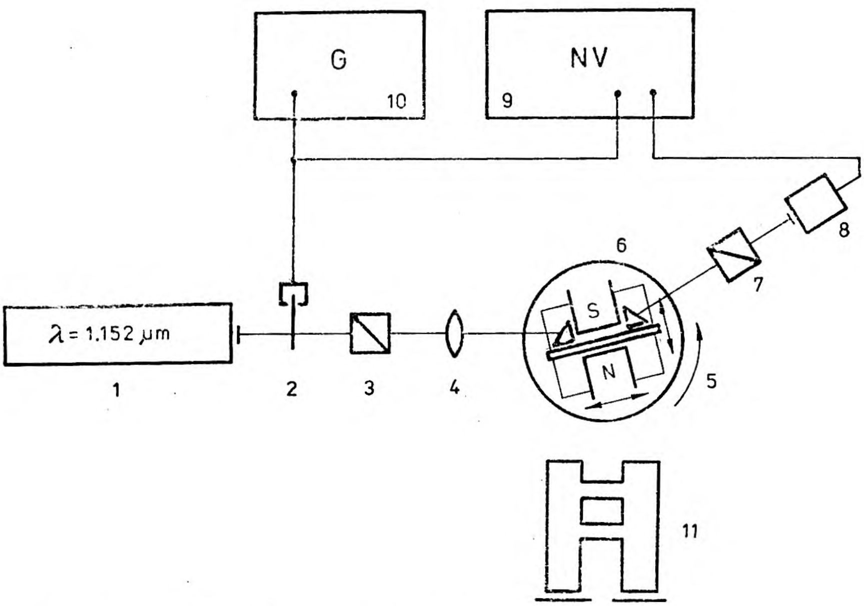

Fig. 4. Scheme of the measurement system:

1 – laser, 2 – modulator, 3 – polarizer, 4 – lens, 5 – goniometric table, 6 – magnet pole pieces, 7 – anal-yzer, 8 – detector, 9 – homodyne nanovoltmeter, 10 – modulator generator, 11 – noctoviser

a noctovision device was used. It should be emphasized that all the characteristic effects connected with the wave propagation through the planar lightguide are of similar character both in the infrared and visual ranges. This allows to transfer the measuremental experience, gained during the measurement of lightguide in the red light ($\lambda = 0.6328$ μm), to the infrared region ($\lambda = 1.152$ μm).

3.2. Sample preparation

The magnetic specimens of diameters of about 25 mm were cemented to the microscopic 50×25 mm slides. The sample surface was washed with the mixture of ethyl alcohol and ether. The KPR-2 emulsion deposited on the sample with the help of a centrifuge, was applied as the buffer. After drying out at the room temperature (for about 60 min.) and annealing (at about 373 K, and for 5 min.) a silver layer was produced through a mask on so created buffer layer. Before evaporating the layer the thickness of the deposited KPR-2 emulsion layer (being a buffer layer) was measured with the help of an ellipsometer. In accordance with the graph in fig. 2, a buffer layer was attempted to be deposited in the range 0.08–0.10 μm, so that the degenerace occur in the case of the lowest modes ($m = 0.1$).

3.3. Measurement results

The prepared specimen was located on a goniometric table, the optical coupling of the laser light beam with the lightguide layer being achieved with the help of mechanical pressing of the rutil prisms to the specimen (fig. 5).

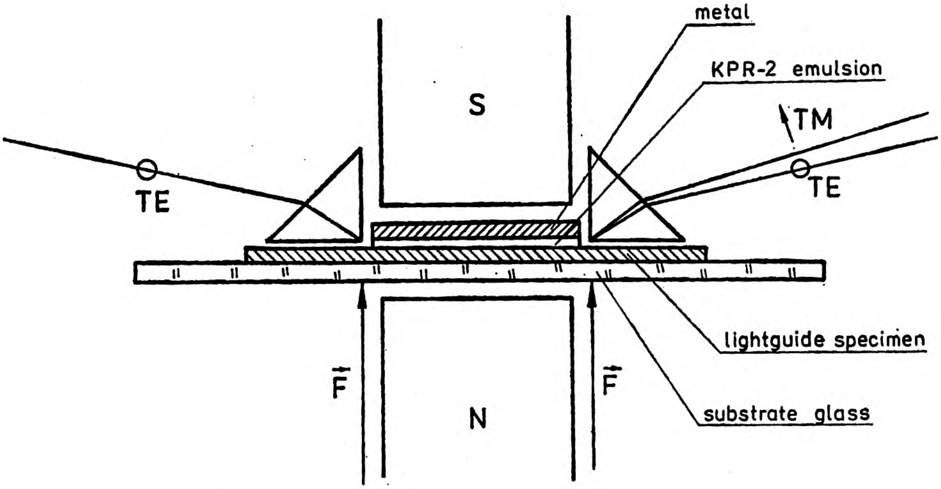

Fig. 5. The way of specimen mounting on the goniometric table

Due to the application of birefringent material (rutil) as a coupler the emerging radiation of polarization TM was shifted with respect to the TE beam by a few degrees of arc (fig. 5). For example, in the specimen described below this shift amounted to 7°23′ for the zero order. This angle tended to diminish as the higher orders were excited.

For constructional reasons the feeding voltage of 100 V was never exceeded. This corresponded to the maximum magnetic induction B equal to 132 ± 2 mT measured in the slit. An eight-mode specimen was taken for experiment, for which the thickness of light guiding layer equal to 4.8 μm has been estimated from the measurements of β/k propagation factors. The measurements of the structure produced once were repeated many times. Since each time the point of pressure application to the prism was changed, a high degree of the measurement results averaging could be achieved.

The results obtained for mode conversion, calculated as a ratio of radiation TM/TE intensity depending on the magnetic induction B produced in the slit of the electromagnet, are given for first five modes in the graph in fig. 6. For the other modes it would be difficult to detect any radiation of TM polarization. As it follows from the graph in fig. 6, for the buffer layer thickness equal to 95.1 ± 1.0 nm the mode conversion amonting to $9.27\% \pm 0.38\%$ was obtained for TE_1 at the maximal achievable magnetic induction in the slit. This result should be compared with the results of measurements carried out for the plate

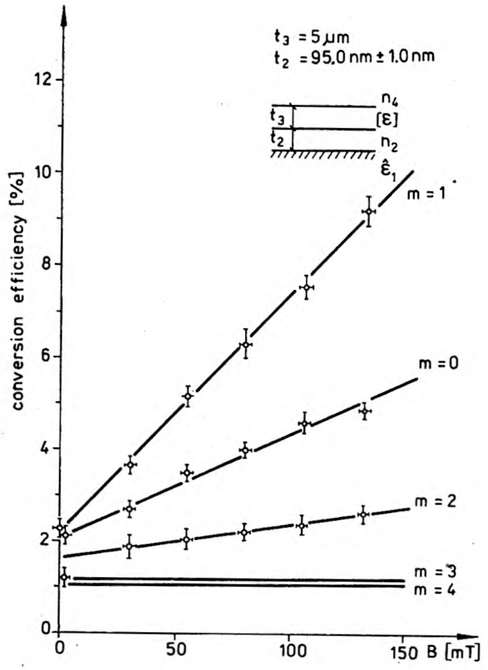

Fig. 6. The percentage change in the mode conversion efficiency for the examined structure as a function of the magnetic induction *B*

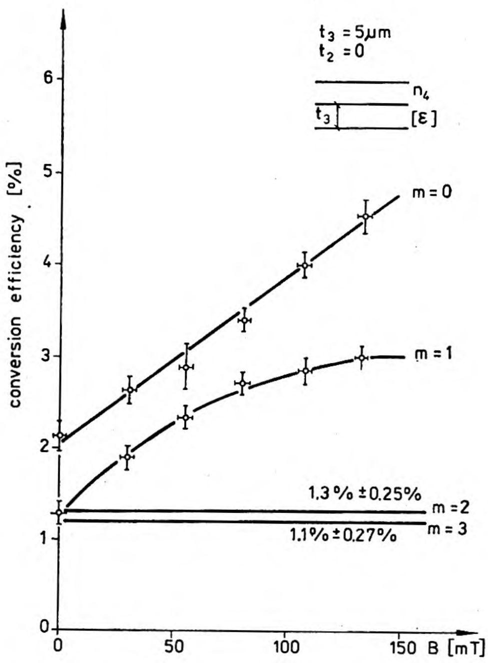

Fig. 7. The measured % of the mode conversion efficiency for the magnetic specimen without any buffer layer and metal coating

of magnetic material without the buffer layer and metal coating. Such measurements are presented in the graph in fig. 7.

The results obtained for the pure plate are quite obvious if the graph in fig. 2 is analysed for high values of t_2. For small difference $\Delta\beta$ occurring between the modes TM_0 and TE_0 the possible mode conversion may be expected. The dependence upon the external magnetic field is weaker than that for the zero order. For the remaining modes such a dependence was not confirmed.

In the four-layer structure, at the buffer layer thickness 95.0 ± 1.0 nm the occurrence of the strongest effect of mode conversion could be expected for the first order. This was confirmed by the experimental data presented in the graph in fig. 6. For this thickness of the buffer layer also $\Delta\beta$ between the TE_0 and TM_0 is less than that for the pure plate (whence a higher conversion of TM_0 and TE_0). The highest conversion for the first order may be explained by the appearence of the degeneracy of the TM_1 and TE_1 modes which was obtained by a proper matching of the buffer layer thickness t_2. This is in perfect accordance with the graph in fig. 2. The degree of conversion obtained for the second order is small. No dependence of the emerging TM type radiation upon the magnetic field was stated for the remaining orders. This is connected with the lack of degeneracy between the TM and TE modes for lower mode orders (graph in fig. 2). Lack of mode degeneracy excludes the possibility of conversion. It should be believed that for the matching of the buffer layer thickness t_2, such that the mode degeneracy conditions for one of the first orders be optimal, it is possible to achieve a higher mode conversion than that presented above. The examinations in this direction are being continued.

4. Final remarks

The paper includes the theoretical analysis of the four-layer structure possessing both a metal coating of negative real part $\hat{\varepsilon}_1$ of the complex dielectric permittivity and the anisotropic lightguide layer of components ε_{xz} and ε_{zx} of the dielectric permittivity tensor different from zero. As it was proved in the experiment in the third section the dispersion characteristics calculated for the case $\varepsilon_{xy} = \varepsilon_{yx} = 0$ appeared to be highly useful for analysis of the practical lightguide layers. These allowed to well define the conditions of degeneracy of TE and TM modes, which was one of the basic goals of the work presented.

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Конверсия модов TE↔TM в анизотропном планарном световоде Y_3 Fe_5 O_{12}, покрытом металлическим слоем

В работе представлена возможность выступления конверсий модов TE↔TM в четырёхслойной структуре, которая заключает металлическое покрытие, а также анизотропный слой на изотропной подложке. Теоретические решения были подтверждены экспериментом, проведённым со структурой, содержащей анизотропный световодовой слой $Y_3Fe_5O_{12}$.