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Design and numerical analyses of the planar grating coupler

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Abstract. The paper presents the results of numerical analyses of the structures of integrated optics in the form of planar waveguides made of materials with high values of the refractive index $n = 2.00$ and with an input-output system in the form of Bragg grating couplers. The numerical investigations were carried out by using the FDTD method (Finite Difference Time Domain method).

Key words: FDTD method, grating coupler, planar waveguide.

1. Introduction

In systems of integrated optics of much importance is the way in which light is introduced into and out of the optical waveguide. One of the possible solutions is the application of the input-output system in the form of Bragg grating couplers [1]. The advantage of such couplers is the possibility of producing them as an integral part of the system of integrated optics. In the case of waveguide structures they are obtained in the form of periodical disturbances of the refractive index of the planar waveguide with a period Λ [2, 3]. Periodical disturbances are induced among others, by chemical etching or ion etching the periods in the waveguide layer [4] and mechanical impressing of the diffraction pattern in the waveguide layer [5]. Planar grating couplers are also applied in sensor systems. An equally important matter is the choice of the adequate numerical method for the purpose of analyzing the integrated optics structure. In such analysis the FDTD method has found wide application [6].

2. Theory

If a planar grating coupler can serve as an input-output element of the energy of light for the waveguide structure, the following condition ought to be satisfied (1) [2, 7, 8]:

$$\beta_c \sin(\theta) = \beta_w + \frac{m 2\pi}{\Lambda}, \tag{1}$$

where β_c, β_w – propagation constant in the environment and in the structure, respectively; n_c, n_w, n_s – refractive index of the environment, the waveguide layer and the substrate; Λ – spatial period of the grating, m – diffraction order.

Equation (1) permits to determine the input and output angles of the light going into or coming out of the structure as a function of the effective refractive index and the order of diffraction. This relation is also the basis of the effectiveness of sensor systems produced basing on grating couplers [9]

$$\theta = \arcsin \frac{1}{n_c}\left(N_{eff} - \frac{m\lambda}{\Lambda}\right). \tag{2}$$

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The propagation geometry is presented in Fig. 1.

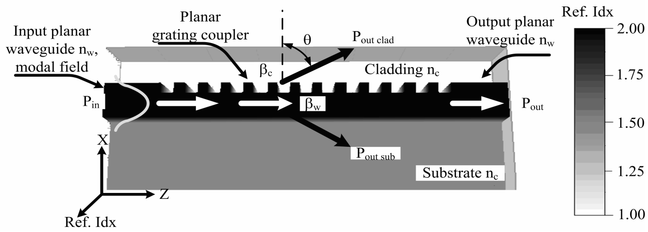

Fig. 1. Structure of a grating coupler and the idea of its modelling

The fundamentals of the FDTD go back to the year 1966, when Kane Yee's paper [7] was published, in which the author suggested the mechanism of solving Maxwell's equations in the form of the so-called time steps [6, 10, 11]. He also proposed a method of discretization of the electromagnetic field. In the case of 2D structures, two modes are considered, viz. TE (Transverse Electric) and TM (Transverse Magnetic). Below, the idea of the analysis of the TE mode is presented. The geometry of propagation is to be seen in Fig. 1.

$$\begin{gathered}\frac{\partial Ex}{\partial t} = 0, \qquad \frac{\partial Ey}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial Hx}{\partial z} - \frac{\partial Hz}{\partial x}\right), \\ \frac{\partial Ez}{\partial t} = 0, \qquad \frac{\partial Hx}{\partial t} = \frac{1}{\mu_0}\frac{\partial Ey}{\partial z}, \\ \frac{\partial Hy}{\partial t} = 0, \qquad \frac{\partial Hz}{\partial t} = -\frac{1}{\mu_0}\frac{\partial Ey}{\partial x}.\end{gathered} \tag{3}$$

In the FDTD method the central difference approximation [6] is used to determine the components of the electric and magnetic fields. Assuming that the electric field *Ey* is calculated for the entire time step, and the magnetic field (*Hx*, *Hz*) for only a half of this, the component *Ey* of the field is calculated basing on the following equation (Eq. 4) [11].

$$E_y(i,k) = E_y^{n-1}(i,k) + \\ + \frac{\Delta t\left[H_x^{n-\frac{1}{2}}\left(i,k+\frac{1}{2}\right) - H_x^{n-\frac{1}{2}}\left(i,k-\frac{1}{2}\right)\right]}{\varepsilon_0\varepsilon_r\Delta z} - \\ - \frac{\Delta t\left[H_z^{n-\frac{1}{2}}\left(i,k+\frac{1}{2}\right) - H_z^{n-\frac{1}{2}}\left(i-\frac{1}{2},k\right)\right]}{\varepsilon_0\varepsilon_r\Delta x}. \tag{4}$$

Analogically, the remaining components of the electromagnetic field (light) for the polarization *TE* and *TM* are determined. In the case of the FDTD method an adequate magnitude of the step must be assumed, by means of which the modelled structure can be discretisized. In the case of the 2D structure, the following conditions have been suggested in literature [7, 10, 11]:

$$\Delta x_{\min} \leq \frac{\lambda_{\min}}{10 \cdot n_{\max}} \quad \text{and} \quad \Delta z_{\min} \leq \frac{\lambda_{\min}}{10 \cdot n_{\max}} \tag{5}$$

where Δx, Δz – magnitude of the calculation step in the direction x and y, respectively.

The step of the mesh determines the maximum time step, at which the calculations can be accomplished. In order to warrant stable solutions of the FDTD method, the stability condition CFL (the Courant-Friedrichs-Levy condition) has been considered, which for the 2D structure takes the form [10]:

$$\Delta t \leq \frac{1}{\nu}\left(\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta z)^2}\right)^{-\frac{1}{2}}, \tag{6}$$

where Δt – time step, v – velocity of light in the analysed medium.

3. Numerical experiments

For the purpose of numerical analysis, the waveguide structure was designed and optimized in the system of integrated optics composed of a planar waveguide and an input-output system in the form of planar grating coupler. In the course of the first phase the thicknesses of the waveguide layers of mono- and several-mode planar waveguides were determined, after which the parameters of the grating couplers were optimized. The modelled structures were then excited by a mode field corresponding to the given waveguide mode TE00 and TE01 (Fig. 1 and Fig. 2). Within the range of the grating coupler with the spatial period Λ, the optical energy is passed both into the waveguide layer and its environment as well as into the substrate (Fig. 1). The effect of the optical energy rating, radiated by the structure of a grating coupler with a depth of grid period ds was analyzed. For the purpose of numerical modelling the following initial parameters have been assumed: optical wavelength $\lambda = 677$ nm; refractive index of the environment $n_c = 1.000$; refractive index of the waveguide layer $n_w = 2.000$; refractive index of the substrate $n_s = 1.456$. The numerical modelling was accomplished making use of the software OptiFDTD 8.0 elaborated by the firm Optiwave Systems Inc.

a)

b)

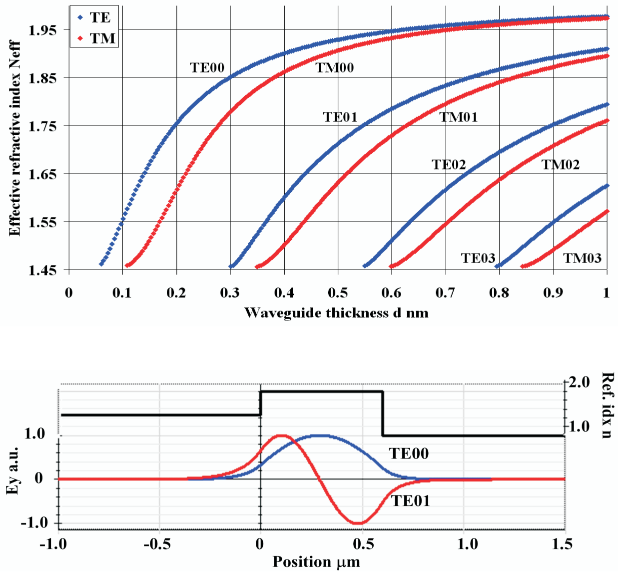

Fig. 2. a) The effective refractive index as a function of the thickness d_w of the waveguide layer for TE00 and TE01 modes; b) Distribution of the field Ey exciting the structures for TE00 and TE01 modes

4. Results

The characteristics of the effective refractive index of a planar structure in the function of the thickness dg of the waveguide layer permit to determine the number of modes which can propagate inside it. At a thickness of the waveguide layer amounting to $d_w \leq 300$ nm the planar waveguide is a single-mode one, whereas in the case $d_w > 300$ nm we obtain multimode planar waveguides (Fig. 2a).

Below, the analysis of the Bragg gratings presented for the thicknesses of waveguide layers: $d_w = 300$ nm and $d_w = 600$ nm has made it possible to optimize the effectivity of introducing the light into the structure and its output as a function of the periodical depth. The results of numerical analyses of couplers with the spatial period $\Lambda = 1.0$ μm, and the thickness of waveguide layers $d_w = 300$ nm and $d_w = 600$ nm are presented in Fig. 3 and Fig. 4, respectively: In the case of the structure with the thickness $d_w = 300$ nm and the mode TE00 the optical periodical depth is $d_g = 60$ nm. At such a depth ds maximum values of the optical power rating educed to the substrate layer and the environment are attained (Fig. 3).

In the case of the structure with the thickness $d_w = 600$ nm and the modes TE00 and TE01 the optical periodical depths are in the range: 130 nm$< d_g <$200 nm (Fig. 4). At such depths the maximum optical power output to the covering layer (environment) is attained Fig. 4b. For the mode TE01 the optimal periodical depth amounts to about $d_g = 70$ nm (Fig. 4e).

The elaborated grating coupler has been presented in Fig. 5. The modal characteristics of the grating coupler has been presented in Fig. 6. The grating coupler was made by using nanoimprint technology. The measurement setup and manufacturing technology used in the research of the grating coupler was described in the publication [9].

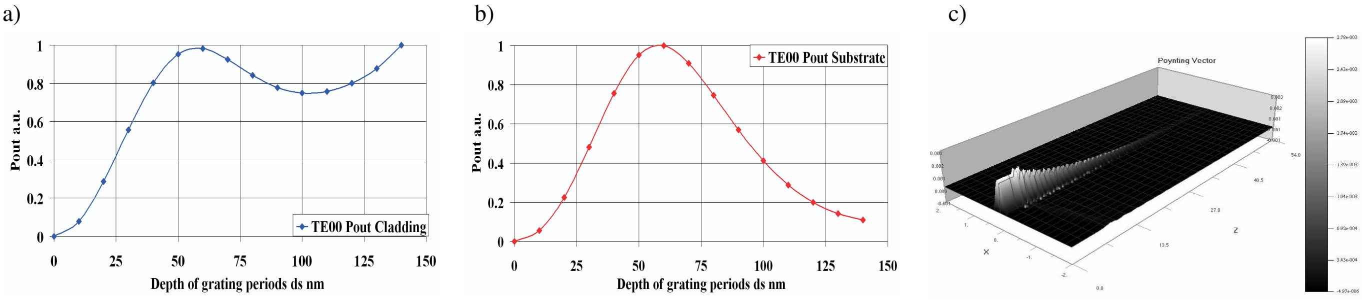

Fig. 3. Optical power rating as a function of the periodical depth d_g of the grating coupler radiated to: a) the light going into environment; b) the substrate; c) Pointing vector along the propagation of light in the grating structure

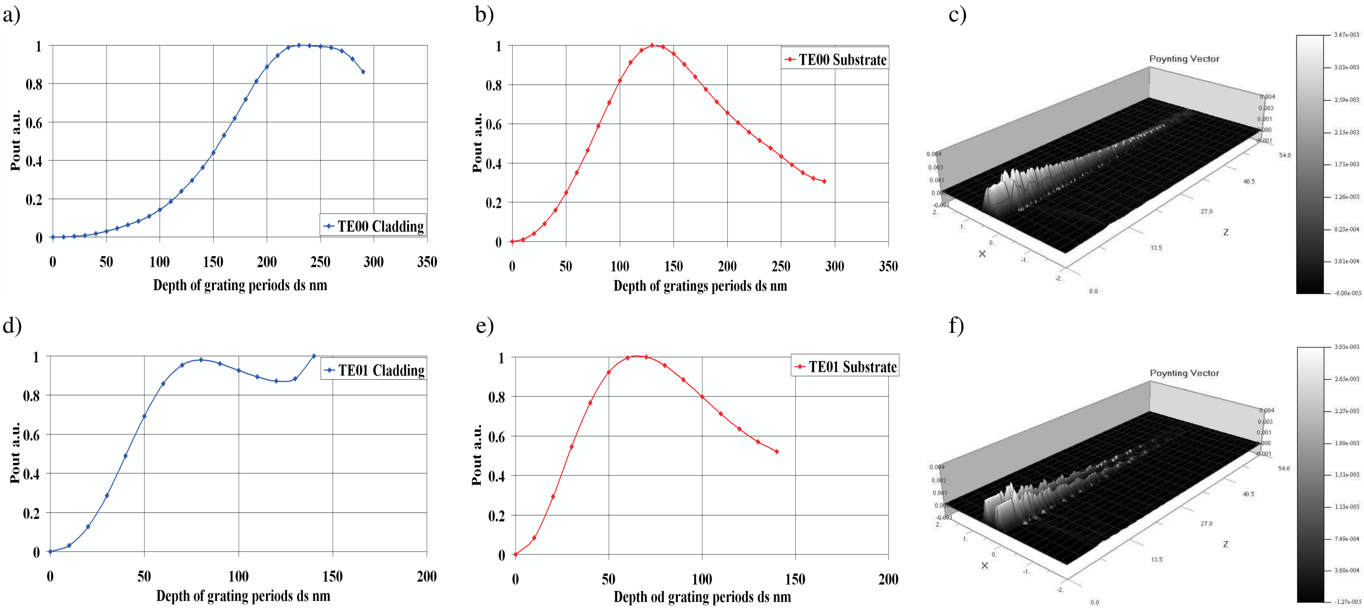

Fig. 4. Optical power rating radiated into the environment and substrate for: the TE00 mode a), b) and for the TEO1 mode: d), e). Pointing vector along the propagation of light in the grating structure c), f)

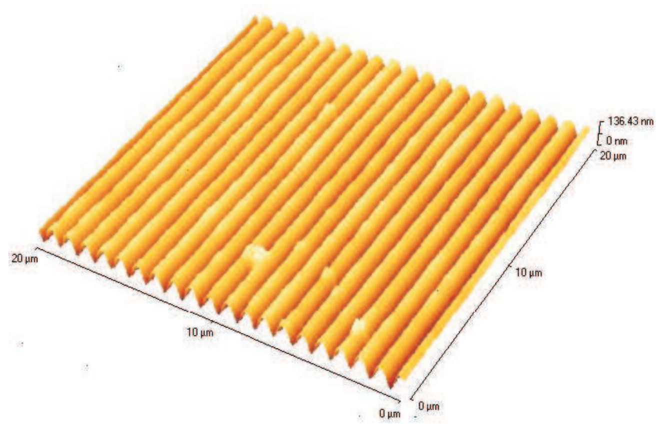

Fig. 5. The AFM picture of the practically made grating coupler

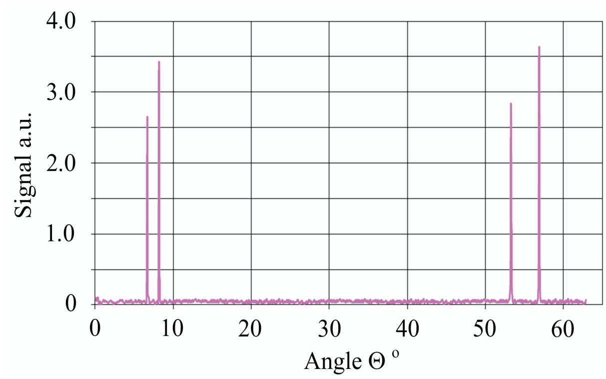

Fig. 6. The mode characteristics of the practically elaborated coupler

5. Conclusions

The main aim of the numerical investigation dealt with above was to optimize the grating coupler from the viewpoint of the input and output of light modes from the structure of the planar waveguide. Another aim was to test the possibilities of application of the Finite Diffraction Time Domain method for the purpose of modelling the structures of integrated optics. Numerical investigations lead to the conclusion that in the case of single-mode planar waveguides with the refractive index $n_w \approx 2.0$ the thickness of the grating couplers is on the level of about $d_s \approx 60$ nm for the TE00 mode. If the layers are thicker, the periodical depth of this mode, when the coupling reaches its maximum, is much greater, amounting to $d_s \approx 130$ nm. Numerical modelling has made it possible to find also out that in the case of modes of higher orders (TE01, TE02,...) the first maximum of coupling is attained at smaller periodical thicknesses of the grating couplers than in the case of modes of lower orders. The accomplished numerical investigations have also confirmed the applicability of the FDTD method in analyses of the structure of integrated optics – including grating couplers.

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