

Bragg's grating coupler in planar optical sol-gel waveguides

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The aim of our investigation was to develop a technique of producing Bragg's grating couplers on planar waveguides obtained by means of the sol-gel technique. Introducing a light beam into the waveguide structure is in the case of planar optical systems always an essential technological problem, requiring simple and reproducible solutions without extending the waveguide structure too much. The paper deals with the technology of producing grating couplers by impressing the pattern of the network while forming the planar waveguide structure applying the sol-gel method. The results of investigation on grating couplers obtained in such a way have also been presented. Attention has been drawn to the possibility of using such structures in optoelectronic sensors, particularly gas sensors, including sensors of toxic gases.

Keywords: integrated optics, planar waveguides, grating coupler, sol-gel method.

1. Introduction

In integrated optoelectronics of vital importance are problems concerning the introduction and extraction of light beam from the planar waveguide. The excitation of plane waveguides is connected with volumetric transformation of the spatial wave into a surface optic wave.

- There are several means of exciting the light in optical waveguides, viz. [1], [2]:
- from the front (through the normal surface);
 - by means of the skew-cut edge of the waveguide;
 - prismatically;
 - by means of grating coupler.

The first two methods are characterized by a poor effective coupling (with efficiency of only some percentage). The prismatic coupler is generally applied in planar optical systems, although in this case the plane structure of the waveguide layer becomes three-dimensional, which may result in additional restriction of its application [3], [4].

The application of Bragg's gratings as couplers in planar optics was mentioned for the first time by WHITE *at al.* [5]. The grating coupler is a structure based on the waveguide, the refraction index of which varies periodically along the path of light propagation. The efficiency of the grating coupler amounts theoretically to 70% [6]. Actually, however, such couplers display practical efficiency of only 30%, because a large part of energy of the incident beam is refracted and fades in the glass substrate. A higher efficiency of coupling (up to 80%) can be achieved utilising the asymmetric profile of the coupling grating. The grating coupler is less effective than the prismatic one. Its obvious advantage is, however, its compatibility with the monolithic conception of integrated optoelectronic systems [7].

2. Periodical structures – methods of their production

Bragg's planar grates are produced mainly by means of three techniques of periodical perturbation [8]: electronic methods, optical methods and mechanical impressing of the grating sample.

From among the electronic methods the one utilizing the beam of electrons and the focused beam of ions is to be distinguished. The advantage of these methods is the possibility of getting structures smaller than 200 nm, their drawback being such that

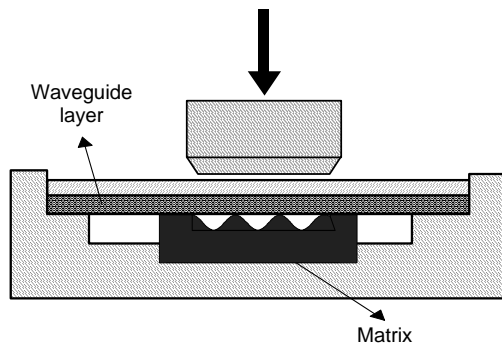


Fig. 1. Idea of the mechanical imprint method.

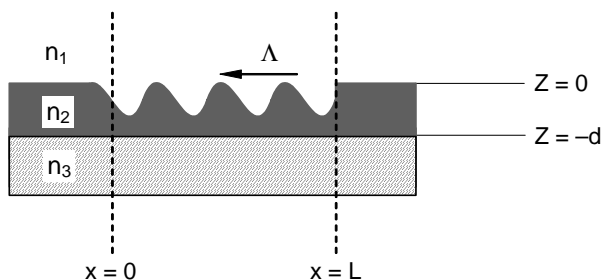


Fig. 2. Waveguide layer with periodically varying disturbances of the refracting index.

processes are expensive and time-consuming, so that the number of users applying them is rather limited [8], [9].

Optical methods of producing the pattern of the diffraction grating require photo-sensitive waveguide layers or coatings. Periodical structures are produced in these layers by exposing them to ultraviolet light [10]. By means of optical methods periodical structures are produced, being understood as periodical variations of the depth or variations of the refracting index of the exposed layers. They require the acquisition of specific (and expensive) devices.

Mechanical impressing of the pattern of periodical structure is applied in the case of layers susceptible to deformations. This method may be used for the activation of periodical disturbances in layers deposited by means of the sol-gel method and also in polymeric layers.

The method of mechanical imprinting for producing periodical structures in a planar waveguide of the type $\text{SiO}_2\text{-TiO}_2$ was applied by LUKOSZ and TIEFENTHALER [11], [12]. The obtained structures were used by the authors as Bragg's grating couplers and mirrors. Based on this method, as suggested by SZANDRO [13], periodical structures of the type: SiO_2 , TiO_2 , Ta_2O_5 , $\text{SiO}_2\text{-TiO}_2$ were obtained. Figure 1 presents the idea of activating a periodical disturbance on a planar sol-gel waveguide by impressing the pattern of the grating [14]. The matrix which is the pattern of the imprinted grating has been produced during the process of electronic or ionic etching on a steel or silicon substrate.

By imprinting the pattern of the matrix in the waveguide layer we cause a periodic disturbance of the waveguide layer (Fig. 2).

3. Realization of the system for the mechanical imprinting of grating structures

In order to obtain periodical structures an adequate mechanical system has been constructed permitting the realization of the imprint method. This system consists of

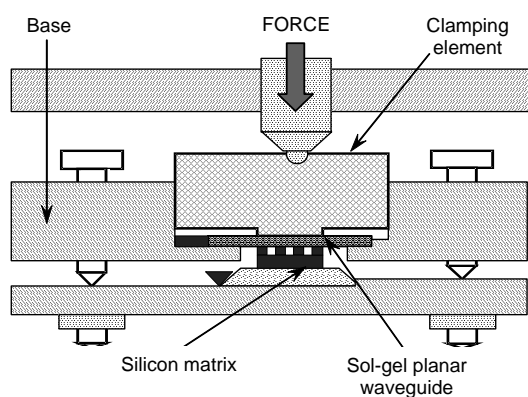


Fig. 3. Diagram of the system for the mechanical imprinting of a periodical structure.

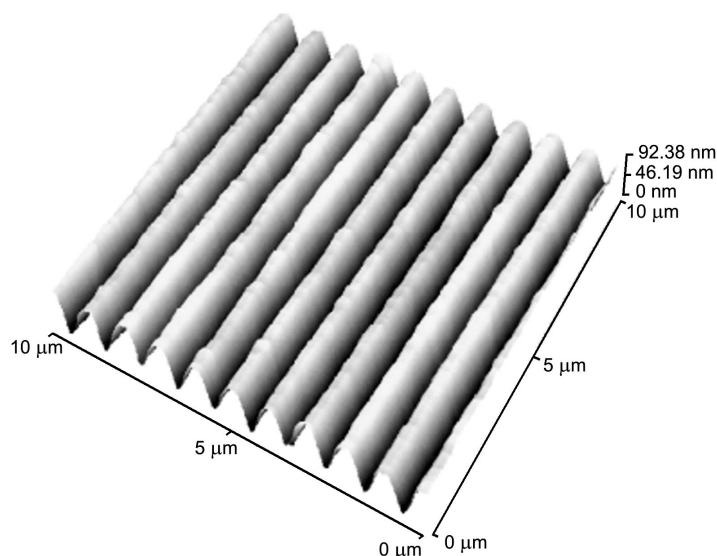


Fig. 4. Presentation of the matrix visualized by means of the AFM.

three basic elements (Fig. 3): a base with a chuck fastening the matrix, a clamping element and an element fastening the silicon matrix to the system. In practice, for the realization of grating couplers a silicon matrix was applied. Figure 4 shows such a matrix, visualized by means of the atomic force microscope (AFM).

The silicon matrix was produced at the Institute of Electronic Technology in Warsaw. The length of one disturbance in the matrix amounted to about 1000 nm. The size of the matrix is a square of 4×4 mm.

4. Process of obtaining periodical waveguide structures

The production of Bragg's grating structures by means of the mechanical imprinting of the grating pattern became possible after the technology of producing single-mode planar waveguides by means of the sol-gel method had been mastered. The sol-gel method [15]–[18] is a low-temperature method of synthesizing organic material or synthesizing organic and inorganic material. Sol is a colloidal solution, *i.e.*, a system composed of the dispersive phase (liquid) and the dispersed phase (solid). Gel is a macroscopic particle taking up the entire volume of the solution.

The sol-gel method is based on hydrolysis and condensation of the initial components – the precursors in an alcoholic solution. The precursors are those substances which participate in the first stage of the reaction. The precursors applied in the sol-gel technology affect the optical properties as well as the porosity and hardness of the dielectric waveguide layers obtained. Of special interest are the optical properties of the layers obtained, particularly the refractive index.

In optoelectronic sol-gel processes the most often applied silicon precursors are tetraethoxysilane (TEOS) and tetramethoxysilane (TET). In this technology the precursors were solved in water and ethyl alcohol (EtOH). The solvents prevent the separation of two liquid phases during the initial hydrolysis and permit to control of the silicon and water concentration, which affect the kinetics of the gelling process. The rate of the process is affected by the presence of a catalyst, which in our case was HCl acid. The gel is the result of polymerization [15], [16]. Processes of the production of waveguide layers by means of the sol-gel method have been dealt with in detail in [14]. In our case, the waveguide layer structures were layers of $\text{SiO}_2\text{-TiO}_2$, obtained as a result of controlled extraction of the sodium-calcium glass lamella (plate) from the gel solution. The wave layers on which later periodical structures were produced were initial processes with the following proportions [14]: $\text{TEOS:EtOH:H}_2\text{O:HCl} = 1:4:1.5:0.08$. This solution was then placed for 60 minutes in an ultrasonic washer at a temperature of 50°C (323 K). In the course of the following stage the TET-solution was added to the partially hydrolyzed TEOS-solution in molar proportions of $\text{TET:EtOH:H}_2\text{O} = 1:10:1.5$, so that the molar proportion would be $\text{TEOS:TET} = 1:1$. The final solution was placed in an ultrasonic washer at 50°C . After 1.5, 3 and 4.5 hours, respectively, the portions of solutions denoted as A, B and C were poured off. From the moment when the formation of the gel was completed, waveguide layers were produced from solution A after 1.5 hour, from solution B after 2 hours and from solution C layers were deposited after 3 hours. These layers were then dried for several hours at a temperature of 20°C , after which the layers were held for 2 hours at temperatures of 200, 250 and 300°C . Next the waveguide layers were properly placed in a mechanical system (Fig. 3) and the periodical structures were imprinted on them.

Numerous grating couplers have been made on many varying substrates with a deposited waveguide layer at various rates of extracting the substrate glass plates from the gel solution. The imprints were applied with various pressure forces. A part of the obtained structures was then kept for two hours at temperatures of 200, 300 and 400°C .

These tests have made it possible to determine the approximate time interval in which the waveguide layer is elastic enough to permit the periodical structure to be imprinted. We may distinguish three stages of hardness of the obtained layer, depending on the time which has elapsed since the deposition of the sol-gel layer on the glass substrate:

- i) the layer being too soft – fragments of the sol-gel layer adhering to the matrix can be torn off;
- ii) optimal layer – imprints are possible reproducing the form and amplitude of the disturbance;
- iii) hard layer.

The investigation has proved that if the layer is too hard, imprinting is either impossible or the structure obtained will be deformed.

Based on tests that have been carried out it can be assessed that in the system presented the periodical structure can be imprinted in about 3–4 minutes after the

waveguide layer has been deposited on the glass substrate by means of the sol-gel method. It has been found that after the elapse of about 4 minutes the layer has become too hard for getting a periodical structure satisfying the optical properties.

In our situation, up to three minutes after the deposition of the waveguide layer the periodical structure was imprinted.

The quality of the surface of the periodical structure obtained is affected by the force with which the matrix is presented onto the layer. If the exerted force is too great (per surface unit), the layers adhere to press the matrix and their fragments are torn off together with the matrix, which leads to a permanent deformation of the periodical structure. In our first processes the applied pressure amounted to about 0.1 MPa.

The periodical structures obtained were subjected to investigation in order to determine the constant Λ (Λ is the length of the deformation period of spatial disturbances).

For the determination of the length Λ the diffraction grating method was applied [2]. The measurements have shown that in the case of the investigated periodical structures obtained by means of this technique the constant of the diffraction grating amounts to $\Lambda = 996 \pm 5 \mu\text{m}$. The results obtained comply fully with the value of the constant determined by means of the AFM amounting to $998 \pm 3 \mu\text{m}$.

5. Test stand for investigation of grating couplers

The obtained grating couplers were tested in the set-up presented in Fig. 5 [2]. In order to arrange the periodical waveguide structure versus the direction of the laser beam radiation precisely, a goniometric table was used. The structure tested was illuminated by a laser diode (LD) with a wavelength of 677 nm and modulated by a signal from a generator with a frequency of 1000 Hz. The applied generator permitted the introduction of a light beam with a known polarization into the waveguide. The rotation of the goniometric table was forced by the step motor, controlled by a computer. The

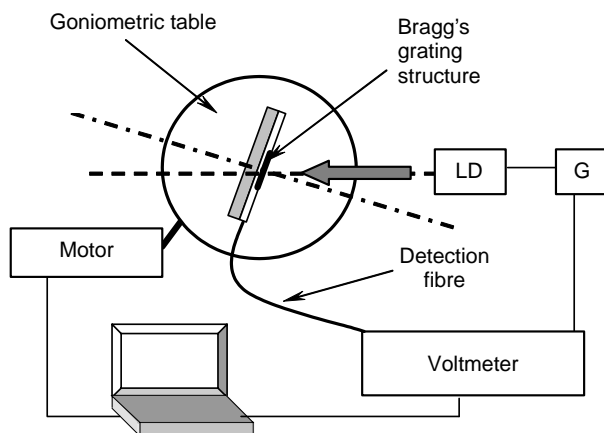


Fig. 5. Diagram of the set-up for the testing of grating couplers (LD – laser diode, G – generator).

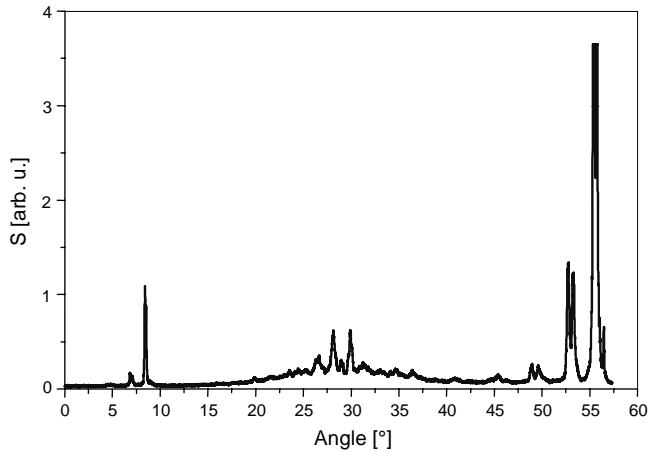


Fig. 6. Transmission characteristics of a waveguide with a grating coupler.

accuracy of rotation of the goniometric table was 1.8" angle. The optical modes which propagated in the waveguide with the periodical structure were transmitted by the optical fiber to the photodiode. The testing of the waveguide consisted in measurements of the light propagating in it as a function of the angles of its activation. In the detection system a homodyne nanovoltmeter was used, from which the output signal was directed to the measurement card in the computer.

Figure 6 gives an example illustrating dependence of the signal obtained as a function of the introduction angle of the light beam to the periodical structure illuminated by the laser with $\lambda = 677$ nm.

As may be seen in Fig. 6, various modes can propagate in the structure. Besides waveguide modes also other substrate modes propagate in it. The peaks registered for

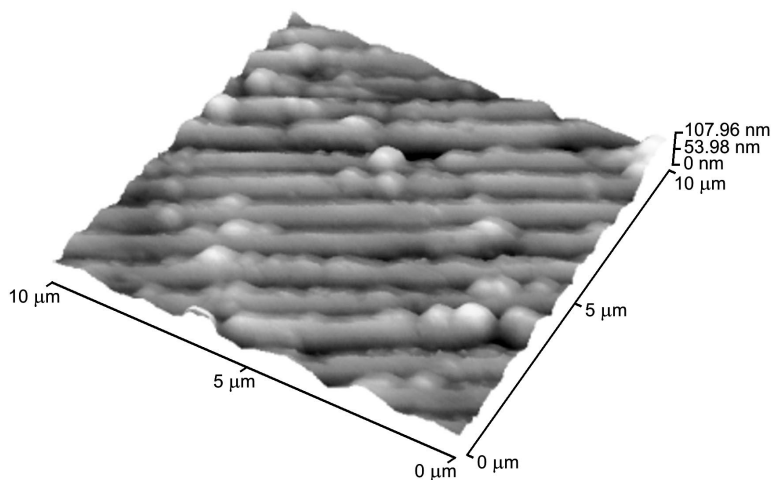


Fig. 7. Image of a periodical structure with dissatisfying optical properties obtained by AFM.

angles 53° and 56° , respectively, correspond to the modes TE and TM of the zero order. The peaks for angles of about 7° and 8° correspond to the modes of the first order. Peaks which have been observed for an angle of about 30° represent the so-called substrate modes propagating in the substrate plate. For the other waveguides the mode characteristics were similar. Because the elaborated structures ought to be one-mode waveguides we may say that the quality of the obtained waveguide structure with a coupler were rather unsatisfactory. Such a conclusion was later confirmed by investigations carried out on AFM. The image of the structure obtained by AFM is to be seen in Fig. 7.

6. Results of investigation of grating couplers

In order to continue further attempts at getting grating couplers again the technological process described above was applied. An adequate solution was prepared, whose partial TEOS hydrolysis lasted 75 minutes. The final solution, after the addition of TET, was obtained after 3 hours. From this solution the waveguide layers were extracted and deposited on glass substrates. Next, by means of the so designed system the structures of the grating couplers could be imprinted. Twenty grating systems were made on twenty different substrates with a deposited waveguide layer of the same gel solution, applying pressures by one order higher than the preceding ones (about 1.0 MPa). The samples obtained were divided into three similar series, differing in the final stage merely by the time of their heating. The samples were held at temperatures of 200, 250 and 300°C for 2, 2.5 and 3 hours.

Due to the fact that the TE_0 and TM_0 modes propagating in the structure display various effective refraction indices, various synchronical angles (angles of incidence

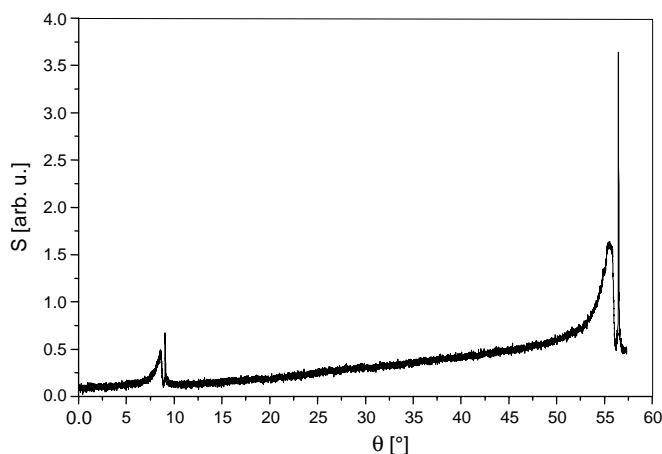


Fig. 8. Characteristics of a grating coupler (sample S6).

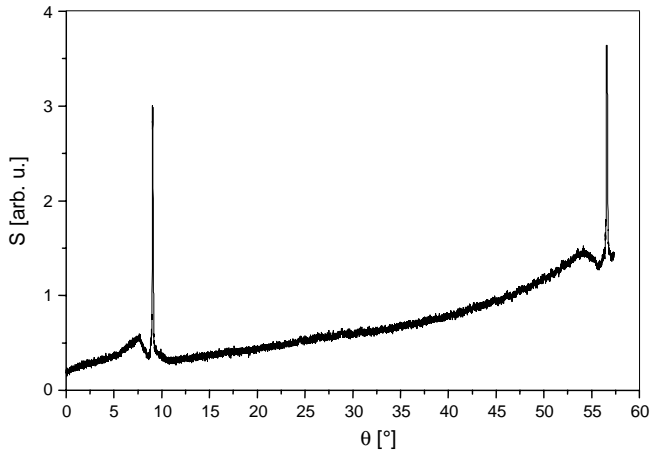


Fig. 9. Characteristics of a grating coupler (sample S17).

of the laser beam on the structure, at which the corresponding mode is excited) are obtained in the case of various polarizations. The structures of grating couplers were tested in the system presented in Fig. 6. Preliminary showed the structures of the grating couplers to be characterized by much better optical properties when they were produced with a pressure of about 2 MPa. Figures 8 and 9 illustrate the characteristics of two selected grating couplers obtained on planar waveguides applying the sol-gel

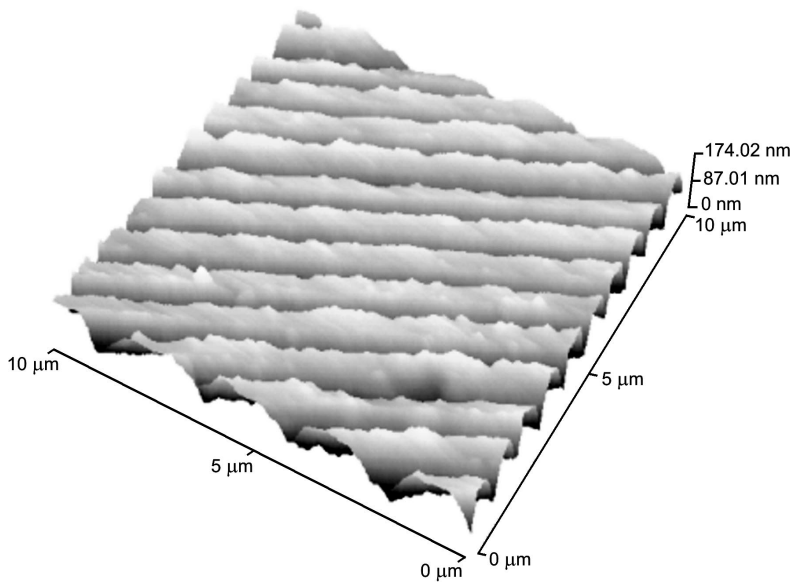


Fig. 10. Periodical structure – sample S6 (image by an AFM).

method. For this purpose pressures of the order of 2.0 MPa were exerted. The obtained structures differed in the temperature T and the time of their heating t_w . The sample S6 was held at a temperature of 250°C for 3 hours, the sample S17 at 300°C for 2 hours.

The planar waveguides obtained by applying the sol-gel method were in the case of all the previously described processes single-mode waveguides, keeping one mode of the type TE_0 and one mode TM_0 . After the application of grating couplers as a way of introducing light into the waveguide, also the mode of the first orders may propagate (Fig. 9)

Figure 10 shows the image of the structure S6, obtained while using the AFM.

7. Conclusions

A method for the mechanical production of grating couplers by a mechanical periodical disturbance of the waveguide surface has been developed.

It has been shown that it is possible to obtain grating couplers and single-mode waveguides in the course of one technological process. As a result of our investigation the parameters of the process were determined, in which it is beneficial to produce periodical structures by mechanically impressing the pattern of the mask on the surface of the waveguide. Experimental investigation has been carried out concerning the influence of the stress exerted in a specially designed system of imprinting the pattern of the mask on the waveguide substrate upon its optical properties and on the geometrical shape of the structure, as well as on the degree of its damage. The mechanical pressure permitting the performance of high-quality periodical structures exerts a stress of the order 2×10^6 Pa.

A grating coupler in the form of a periodical structure on the waveguide surface displays a high selectivity of the coupling angle, whereas in the case of applying a prism as a coupler the angle at which the coupling of the laser beam to the waveguide is observed, amounts to several degrees; in the case of well-made couplers, the range of this angle does not exceed one arc minute.

In the course of our investigation we observed that even a small change in the composition of the atmosphere surrounding the structure, affects a change of the coupling angle. This is an essential and very favourable property of the structure from the point of view of future gas sensor applications [19]–[21].

Assessing the results of our investigation the grating couplers developed proved to be characterized by a high effectiveness of coupling, amounting to a score of percent.

Investigation will be continued in order to utilize the developed waveguide structures with grating couplers in optoelectronic sensors. Such couplers will be applied in gas sensors, including sensors of toxic industrial substances.

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