PLANAR WAVEGUIDES WITH DIFFRACTION GRATINGS

(review paper)

Iwona ZIELONKA, Paweł KARASIŃSKI

Institute of Physics
Silesian University of Technology
44-100 Gliwice, ul. B. Krzywoustego 2

In the paper the diffraction gratings are presented. One presented the technology fabrication methods of diffraction gratings as well as the possibility their applications.

The diffraction gratings are very important elements for devices of integrated optics and integrated acoustics.

Keywords: diffraction grating, interferometric methods, optoelectronics devices

1. Introduction

During the last few years very strong progress in integrated optics and acousto-optics has been observed. Nowadays, the very popular and important elements in the group of acoustooptic and optical devices are diffraction gratings [1].

The diffraction grating structures are made as:

- surface relief grating structures, [1]
- a periodic modulation of the refraction index on planar optic waveguides,
- a periodic modulation of the refractive index along the fiber core, called fiber Bragg grating [2,3],

Diffraction gratings are very important and useful elements in telecommunication devices as well as in sensing systems. The diffraction gratings in telecommunications systems have been working for multiplexion and demultiplexion signals, for wavelength division multiplexing into frequency division multiplexing (WDM/FDM) systems [1,4].

In the optical sensor techniques the gratings are mainly have used for coupling/outcoupling light from structure to sensor devices [5].

The planar waveguide diffraction gratings were used in semiconductor lasers, especially in distributed feedback (DFB) and tunable lasers. Now, the diffraction gratings are realized in planar technology in telecommunication systems and as distributed Bragg reflectors (DBR) in lasers [1].

In this paper different methods of fabrication of diffraction gratings on planar waveguide are described.

In Optoelectronics Department of Silesian University of Technology for some years the investigation of applying diffraction gratings for various practical applications are realized. Elaborated gratings in optics sensors of physical values will be applied.

2. Theoretical model

Diffraction gratings as periodical waveguide perturbation along the direction of lightwave propagation are produced. The perturbation may be physically realized by means of:

- the perturbation of the refractive index on planar waveguides,
- the corrugation of the surface in the region of lightwave propagation.

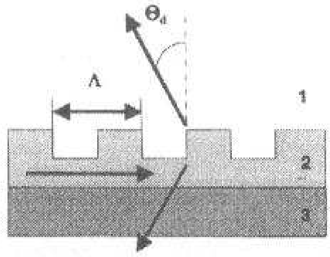

Fig.1 Waveguide with a grating coupler [1].
1 – refractive index of surrounding n_a,
2 – refractive index of waveguide n_f,
3 – refractive index of glass substrate n_s,

In the Fig. 1 the idea of a waveguide with a grating coupler is showed. Light in this structure enters the waveguide with a grating period of Λ. A wave, propagating in this structure at each single perturbation is diffracted. This diffracting waves interference each other. As a result of interference one may observed diffraction maximums [6,7,8], which fulfill conditions as follow:

$$\beta_d - \beta_i = \frac{2m\pi}{\Lambda} \qquad 1)$$

where;

- β_d, β_I - mode propagation constants,
- m - the diffraction order ±1, ± 2,

$$\beta_i = 2\pi n_{eff} / \lambda \qquad 2)$$

and

$$\beta_d = 2\pi n_c \sin\theta_d \, / \, \lambda \qquad 3)$$

The θ_d diffraction angle is obtained from the following relation [1]:

$$\sin\theta_d = n_{eff} \, / \, n_c + m\lambda \, / \, n_c \Lambda \qquad 4)$$

where; n_{eff} - effective refractive index of waveguide,
n_c - refractive index of surroundings.

The main goal of the Bragg reflector is achieved the selective wavelength reflection. This effect is observed only for strict choosing wavelength λ, if the Bragg condition is satisfied [1]:

$$\Lambda = \frac{m\lambda}{2n_{eff}} \qquad 5)$$

where Λ is a period of the grating.

The coupled modes theory [6] is used to find the dependence between grating pitch, depth and coupling waveguide grating couplers or between grating period and reflectivity of Bragg reflectors [1,6,9].

3. Gratings fabrication

Diffraction gratings, as it was mention before, are widely used in integrated optic devices as reflecting filters, grating couplers, laser cavities, wavelength-division multiplexers and sensing devices. Two fabrication methods are mainly applied to make such structures:

- mechanical stamping of grating matrix,
- optical projection on photosensitive layer.

The first method is used to obtain input/output couplers on sol-gel planar waveguide. Mechanical stamping of grating matrixes is made when the sol-gel film is deposited on glass substrate by dip-coating. This fabrication steps in Fig. 2. are shown. The silicon or steel matrix by ionic etching is performed. By this method it's obtained surface perturbation on the waveguide layer.

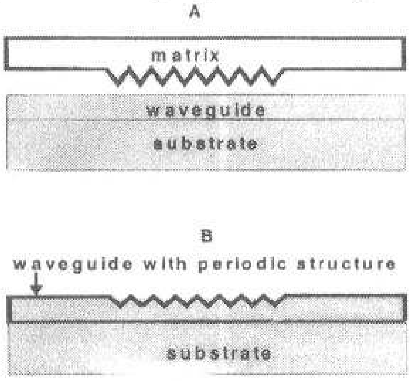

Fig. 2 Fabrication steps of mechanical stamping of grating matrix.

The optical method of diffraction grating fabrication needs photosensitive waveguides or covering films. The gratings are formed by exposing waveguide to UV light. The UV light is used to increase periodically the waveguide refractive index. The optical methods are divided as:

- point-by-point method [3]
- interferometric techniques [1,3],
- phase mask technique [1,3],
- amplitude mask technique [3].

Fig. 3 shows the idea of point-by-point method. By this method each grating element is written individually by focusing point by point UV beam on planar waveguide. The diffraction grating is achieved by moving the planar waveguide with periodic grating Λ. This method is useful for writing of short-period structure for the reason of long time-consuming and for its technical difficulties.

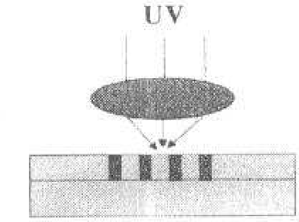

Fig. 3 Optical method point-by-point [3].

Different interferometric techniques of gratings fabrication are showed on Fig. 4 [1]. Fig. 4A shows two-mirror methods. The transmitting and reflecting beams are reflected by mirrors, which are in symmetrical position. The UV interference pattern on planar waveguide is obtain by the two interfering beams. The higher refractive index is generated in the place of the fringe pattern. This method may be modified by using third mirror (Fig. 4B) [3].

Interferometric techniques describing above require the light temporal coherence [3]. The two-mirror and prism methods (Fig. 4A and 4B) not only require temporal coherence but spatially coherence, too [3].

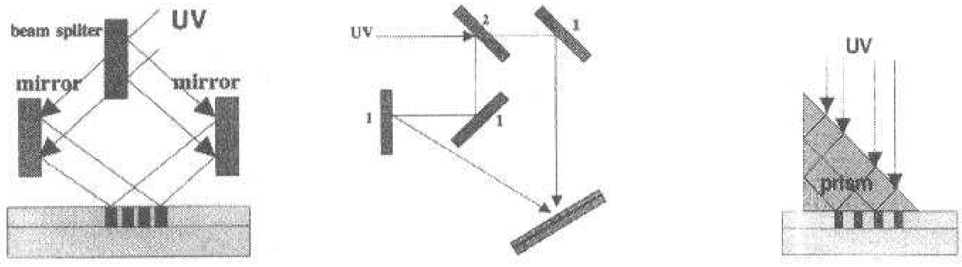

Fig. 4. Various ideas of gratings fabrication by using interferometric methods [3,4];
A) two-mirror method,
B) three-mirror method,
C) prism interferometer method.

The optical techniques used for inscribing diffraction gratings demand a very high degree of mechanical and temporal stability. During the gratings writing the position of the UV interference fringes must be very stable; otherwise is achieved washing out of gratings lines. The sources of instability, which must be eliminated, are the following: fluctuations of laser wavelength, changes of temperature, vibrations, air currents.
Detailed realization of interferometric method shows Fig. 5A and 5B. In [8] K. Kintaka and co-workers has proposed very interesting setup for production of diffraction gratings on sol-gel planar waveguide. This setup (Fig. 5A) permits to produce gratings which perturbation of refractive index can be changed by varying the angle of interference beams. The light from HeCd laser is reflected by mirror M. The half-mirror permits to obtain the same beams, which goes through the optics setup. These beams interfere on the planar waveguide what caused a drastic change in the solubility of the gel films in ethyl alcohol. After etches the relief grating is obtained. The setup shortly described above was used to make the grating at Λ=0,5μm period [8].

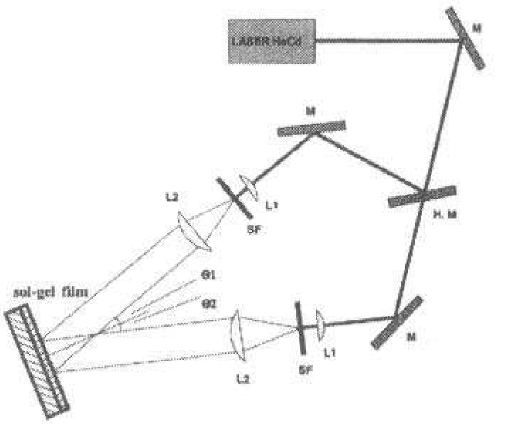

Fig. 5A Setup for fabrication diffraction gratings [8].
M – mirror,
H.M – half mirror,
L1 – lens,
L2 – collimation lens,
SF – spatial filter

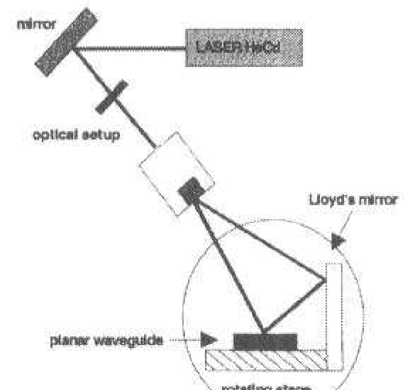

Fig. 5B Setup for fabrication diffraction gratings by using Lloyd's mirror [9].

The setup (Fig. 5B), which was proposed by H. J. Jiang and co-workers [1,10], contains HeCd laser, too. The rotating stage, where the planar waveguide was placed, was applied to obtain different angle between two interference beams. Therefore, the set-up gives chance to produce of gratings with wide values of periods Λ. The next advantage of this setup it's simplicity.

Fig. 6A shows the phase method of gratings inscribing [4]. The phase mask is made of silica. The depth of grooves was chosen to receive maximum intensity of ±1 diffraction order [3] and minimum of zero order. This method is applied in distributed feedback lasers (DFB). Modification of this method in Fig. 6B is shown. The UV light transmits through a cylindrical lens 1 and illuminates a phase mask 2. The diffraction beams of i = ±1 order, after passing through the block of quartz, make interference pattern on a planar waveguide. In typical setups waveguide with photoiniciator is located under the phase mask and illuminated by UV light [3].

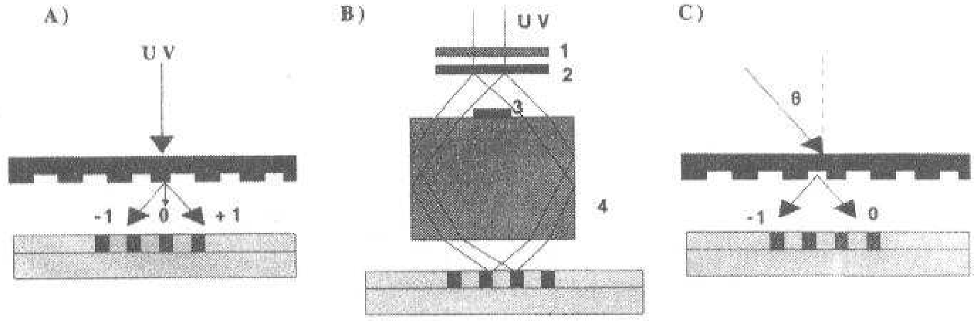

Fig. 6 Different phase mask methods of writing diffraction gratings [1].

The interference pattern is achieved by interference of the light from +1 and −1 diffraction orders. The zero diffraction order must be eliminated [3]. Sometimes 0 and +1 diffraction orders are used (Fig. 6C) but the realization is technically difficult.

The problems may be omitted by using amplitude mask (Fig. 7) [3,17]. The amplitude mask by UV light is exposure. The light, after passing through the lenses, gives interference pattern on the surface of waveguide. All this methods can be used to produce gratings on planar waveguides and optical fibers, too. The disadvantage of the grating fabrication methods presented here, is that they need high coherent, monochromatic light.

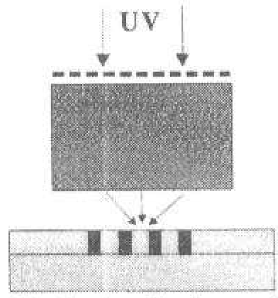

Fig.7 Amplitude mask method [3].

To the group of the electron techniques (not described here) of producing grating patterns belong:

- electrons beam writing method [1,11]
- ions beam etching method [1].

These techniques need very high precision, are expensive, (must be controlled by computer) and time-consuming [1].

4. Application of diffraction gratings

More of the integrated optics devices base on diffraction gratings have fined the practical application as::

- input/output grating couplers [1,9,12,13] in optical sensors,
- filters [1,9]
- DBR – Distributed Bragg Reflectors [14,20],

- DFB – Distributed Feedback Lasers [14],
- WDM/FDM - Wavelength Devision Multiplexing/Frequency Division Multiplexing systems [4].

Diffraction gratings in planar optical sensor systems are used as;
- input/output couplers [21],
- sensing element.

From equation (4) it is seen that a coupled angle of incident beam dependants on a value of a refractive index of a surrounding medium. The surrounding medium may be a sensor layer. The propagated mode in waveguide "see" an effective refractive index of surrounding, modifying by optical properties of waveguide medium. The evanescent field of a mode penetrates sensor layer. When the thickness of liquid cladding is greater than wavelength the effective refractive index of cladding is near the same as a refractive index of liquid. In the other hand, when the thickness of a cladding is penetrated by evanescent field, then the effective refractive index of cladding is near average value of refractive indexes of each layers.

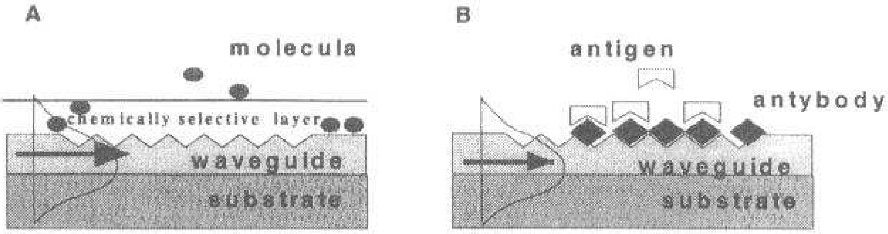

Fig. 8 Principle of working A) chemical sensor, B) biochemical sensor [5,12].

Planar sensors generally on two physical effects are based [12];
- modification of a refractive index of a sensor layer,
- modification of a thickness of a sensor layer.

These effects in biosensors and chemical sensors are used. Fig. 8A shows chemical sensor [5,12] with chemoresponsive coating binds analyt molecules. It gives a changing of a refractive index of layer which coating the grating. It influences on θ_d angle (eq. 4), which is the angle of a coupling beam into a structure. In the Fig. 8B the idea of a biosensor is presented. The coating, which consists of antibody molecules, binds the corresponding antigen molecules. The result of absorption is higher thickness of sensor layer and increase of effective refractive index, which is "seen" by propagated mode. It's very useful effect for modulators and physical sensors (Fig. 9). The dielectric element, near grating (1μm), may change the distance between dielectric and grating under the pressure or force. The effective input beam coupling in the structure depends on changing the distance d. The light beam is next detects by detector in front of waveguide.

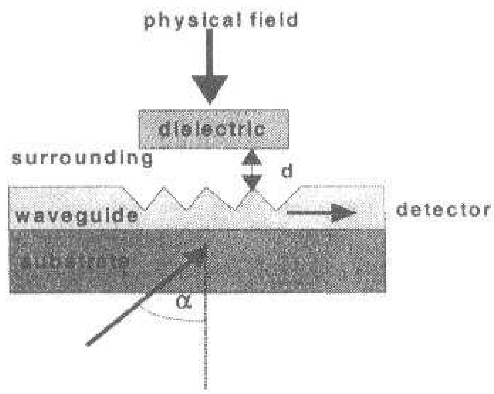

Fig. 9 Input grating coupler working as modulator [16].

Periodic structures were proposed by W. Lukosz [5] as couplers in various biosensors. The out coupled beam passes through the spherical lens and it's detected on PSD, which permits to define the outcoupling angle $\Delta\alpha$. By changing propagations constant of a mode TE_0 (orTM_0) as a result of external action which is taken place in the grating region, there gives a change of the outcoupling angle $\Delta\alpha$. This is registers in the setup as displacement of the outcoupled beam.

R. Dangel and W. Lukosz [13] used the periodic structure to couple laser beam to rib waveguide. The input grating coupler was produced on sol-gel waveguide. It may be applied in Y -type branch, which is used in Mach – Zehnder interferometer.

Periodic structure was used in electro-nanomechanically wavelength–tenable Bragg reflectors [16] proposed by W. Gabathuler and W. Lukosz. The periodic structure on planar SiO_2-TiO_2 waveguid was made. The membrane above grating was placed. Distance between the membrane and grating by electrostatic forces was reduced, which by transversal voltage were changed. Changing the d distance one leads to vary the effective refractive index and gives shift of Bragg wavelength. The electro-nanomechanically wavelength tenable Bragg reflectors is used as filters and in the WDM systems.

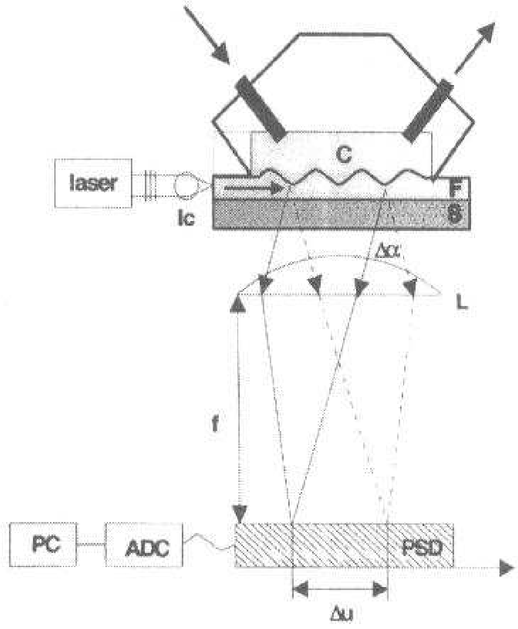

Fig. 10 Schematic of output grating coupler in chemo – and biosensors [5];
C – cuvette, I_c – cylindrical lens, L – spherical lens, S – substrate, F – waveguide, PDS – position – sensitive detector, ADC – analog – to – digital converter, PC – computer.

L. U. Kempen and R. E. Kuntz [15] have proposed new idea of coupling and outcoupling light for Mach – Zehnder interferometer by using a grating coupler. The device has one very important domain – no needs external optics setup (for focusing beam) what permits to make smaller devices which may be used as sensors.

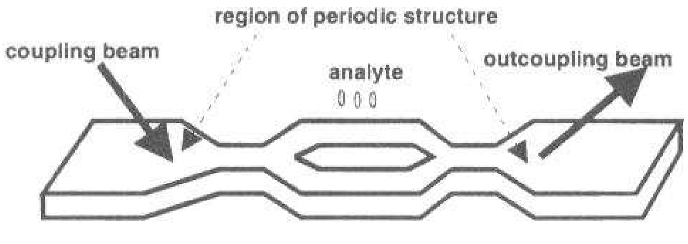

Fig. 11 Mach – Zehnder interferometer with periodic structure [15].

The most important for the WDM systems is wavelength multi/demultiplexing signals [1,18,19]H. It is made by using planar waveguide with grating structures (Fig. 12). In Fig. 12 is shown the structure with three different grating period permits outcoupling three different wavelengths.

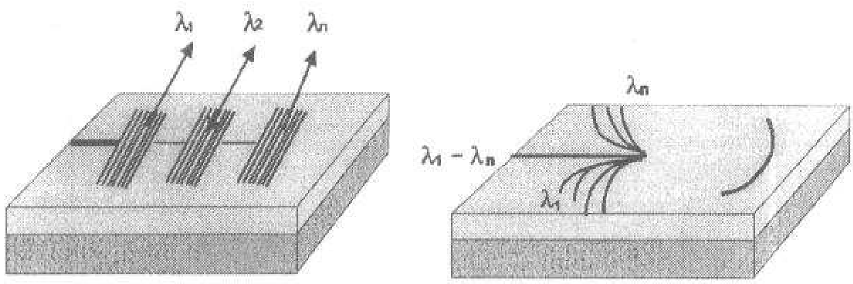

Fig. 12 WDM system [1].

Nowadays every communication system needs the single-mode laser-light source because of dispersion effects in optical fibers. These problems are solved by using in semiconductor lasers distributed Bragg reflector (DBR) and distributed feedback (DFB) systems.

The periodic structure in the distributed feedback laser DFB under an active layer is placed (Fig.13a) [14]. Using this structure, the feedback effect by periodically changes of refractive index is obtained. The wavelength of singlemode laser beam is determined by the period Λ of the periodic structure. The antireflection layer, which is on the one side of the structure, permits to lead the laser beam out.

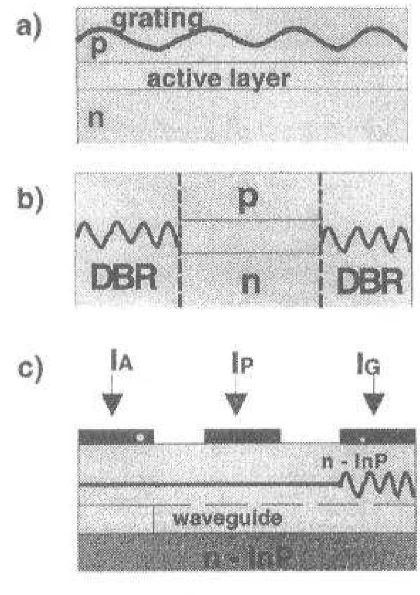

Fig.13 Structure of semiconductor lasers with feedback[14];
a) DFB,
b) DBR,
c) multielectrode DBR.

In lasers with a distributed Bragg reflector (DBR) mirrors by diffraction gratings are realized, which enable to get a singlemode laser beam.

Telecommunication transmission systems as well as single research systems often need lasers with tunable wavelengths and very narrow linewidth. The realization of these conditions is practically possible by using in laser the multisections of DFB and DBR structures [14] as: active region, laser cavity, diffraction grating.

The DBR laser generates mode,which wavelength is the same as Bragg's wavelength [14].

Fig. 14 shows periodic structure, which are used in lasers for enlarge surface emission [1]. These solutions seem to be very promising but actually need solving of some technical problems, first of all – the problem of the connection the DBR structure with the optical pump of a laser.

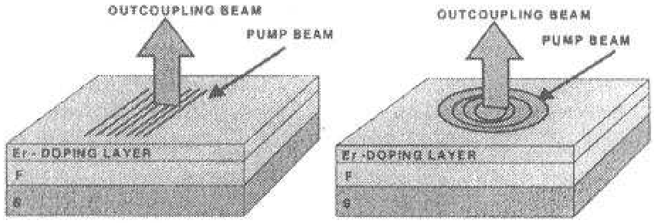

Fig. 14 Semiconductor lasers with surface emission [1].

5. Summary

In the paper, the principle of the gratings formation, the fabrication techniques and some their applications are described. Two fabrications methods mainly applied for making periodic structure are;

- mechanical stamping of grating matrix,
- interferometric techniques.

The first method is only used to obtein diffraction gratings on sol-gel planar waveguide. The second one permits to fabricated this structure on sol-gel planar waveguides and ion-exchange waveguides.

Devices with periodic structure, in this paper, are limited to the most useful applications in integrated optics like: lasers, optical sensors,WDM/FDM systems.

In Optoelectronics Department of Silesian University of Technology for years various technology for acustic, acustooptics, optics and optoelectronics are solved. Recently one puts strong emphasis on the development of sol-gel technology. The sol-gel technology is an attractive alternative for the fabrication of integrated optics waveguides with diffraction gratings. The sol-gel process is simple, flexible, reproducible, low-loss and low cost.

In Optoelectronics Department is realized mechanical stamping method of fabrication gratings and is prepared setup for making diffraction grating by using interferometric technique. The results of experimental investigation of optoelectronics devices with periodic structure will be publish.

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