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PROJECT COORDINATOR : R. REINISCH

PARTNERS :
EMO, GRENOBLE, FRANCE
LOE, MARSEILLE, FRANCE
U, JENA, GERMANY
SEM, NEUCHATEL, SWITZERLAND

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SYNTHESIS REPORT - LEMO-GRENOBLE

Title

FLAT OPTICAL ANTENNAE

Authors. name and address :
LEMO
23 rue des Martyrs
BP 257
38016 Grenoble Cedex 1
FRANCE
*Present address :
LIHAC
Université de Savoie
Campus Scientifique
73376 Le Bourget du Lac Cedex
FRANCE

Abstract

The activities of LEMO-Grenoble are related with nonlinear coupling of light beams. The work has been devoted to the theoretical study of second harmonic generation in distributed couplers (prism or gratings). From an experimental point of view, the study of the second harmonic generation, nonlinear directional couplers and electrooptic modulator has been undertaken and first experimental results obtained.

Introduction

Theory

The aim is to show that the study of second harmonic generation (SHG) at distributed couplers such as prism or grating couplers can be simplified taking into account the fact these devices in guided wave nonlinear optics are used under resonant conditions. Such a coupled-mode analysis applies only for "high finesse" electromagnetic resonances. Finally the case of "cascadehg" is considered: it is shown that the depletion of the pump beam may give rise to optical bistability.

Experiments

The experiments concern nonlinear interactions in the guided wave geometry: second harmonic generation with subwavelength gratings, optical Kerr effect and nonlinear directional couplers, Pockels effect and electrooptic modulation of light using a grating coupler. In all these devices the nonlinear guiding layer is made with a polymere.

Technical description, results

A new approach to study second harmonic generation at grating couplers has been developed where we take full advantage of the fact that, in this type of second harmonic generation, there is a resonant excitation of normal modes of the grating coupler (guided wave or surface plasmon). Therefore the analysis is performed in the framework of the coupled-mode formalism. This allows us to show that the associated diffraction phenomenon, which occurs in nonlinear optics, can be handled using the linear theory of diffraction. The resulting simplicity, which arises from the simultaneous use of the coupled-mode and linear diffraction theories, allows an easy physical insight in the process of second harmonic generation at grating couplers. Proceeding along these lines, we derive not only the guided wave amplitude but also that of the radiated diffracted orders at the second harmonic frequency. This
formalism allows the investigation of new geometries for second harmonic generation. A configuration used during this BFNTE contract involves a subwavelength gratings where the phase-matching condition is fulfilled using a counterpropating scheme leading in this way to a dose nonlinear optical resonator. Such an interaction may give rise to high efficient second harmonic efficiencies.

From an experimental point of view, three nonlinear interactions have been considered: second harmonic generation, optical Kerr effect and Pockels effect.

A new device for high efficient frequency doubling is designed, taking into account the results concerning the first experimental demonstration of grating assisted phase matching. The gratings are etched into a high index layer. Two different grating periods are used: the first grating period is optimized for linear uncoupling efficiency of the fundamental beam into the planar waveguide; the very small value of the period (160nm) of the second grating is designed in order to increases the efficiency of grating assisted phase matching. The generated second harmonic light will be out coupled by the first (i.e. long period) grating. An efficiency of $P_{Z2}/P_{W1} = 2.3 \times 10^{-3}$ has been measured with a peak power of the parallel incident fundamental beam of 32.1 kW and a spot size of d=4mm. The efficiency can be increased to $P_{Z2}/P_{W1} = 19 \times 10^{-4}$ by slightly focusing the beam on the device. Taking the uncoupling loss into account (5%), we obtain an efficiency of $P_{Z2}/P_{W1} = 0.0058$. The generated green light can be easily observed with the eyes. It is important to remember, that this kind of second harmonic generation is not critical on the wavelength. The measured acceptance bandwidth is of $\Delta \lambda = 14.5$ nm with an interaction length of 1 mm (grating dimensions). Increasing the grating length will increase the efficiency without reduction of the acceptance bandwidth.

Optical Kerr effect and nonlinear directional couplers

It is first necessary to be able to realize nonlinear channel waveguides. To this aim, the selected nonlinear medium is PMMA-DR 1 which has a noticable $\chi^3$ value. This material is provided by the sub-contractor LET1-CEA-Saclay (F). The $\chi^3$ characterization of planar waveguides made with organic polymer PMMA-DR 1 has been achieved. Low loss (\leq 3dB/cm) channel waveguides have been done and good coupling efficiencies have been obtained (\geq 20% for a monomode waveguide), This is achieved using the photobeaching technique which gives the best possibility to fabricate some well confined channel waveguides. We finally present the first results concerning a nonlinear directional coupler made with an organic polymer: PMMA-DR 1.

Pockels effect and electro-optic modulation of light using aratina couplers

This is an original device which works as follows: the electric field giving rise to the Pockels effect changes the index of refraction of the electrooptic guiding layer, which, in turn, modifies the effective index of the guided mode. As a result, for a given angle of incidence, the amplitude of the reflected, transmitted or guided electromagnetic field is changed. Hence the amplitude modulation of the reflected, transmitted or guided electromagnetic fields. Electro-optic modulation using grating couplers allows a theoretical 81 % intensity modulation with a voltage change $\Delta V = 1$ C9V. Experimentally 31.3% modulation with $\Delta V = 53$ V is measured. The maximum electrooptic coefficient obtained in the experiment is $r_3 = 3 = 4.3 \times 10^{-3}$ using electrode poling. Using transparent electrodes and buffer layers results in a very sharp resonance $\omega_{th} = 3.023}$ and, as a result, in a high sensitivity. The response in frequency is related to the dimensions of the electrodes. The experiments show that a reduction of the dimensions of the electrodes results in lower signal losses at higher frequencies. We obtain in addition to the intensity modulation of the guided optical field, a spatial modulation of the free propagating light in the reflected zero carder.
Conclusion

A new coupled-mode theory of nonlinear interactions at grating couplers has been developed and applied to second harmonic generation using sub-wavelength gratings. Basic experiments have been performed concerning i) second harmonic generation using sub-wavelength gratings, ii) nonlinear directional couplers using polymers and iii) electrooptic modulation of light with grating couplers. Concerning these three experiments, early experimental results show the interest of associating guided wave nonlinear optics, gratings and polymers.

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Title
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Authors, name and address:
M. Neviere, E. Popov
Case 262
Faculte des Sciences et Techniques de St Jerome
13397 Marseille Cedex 13
FRANCE

Technical description

Grating mask transfer

The aim is to define the range of application of the technique of photolithography of periodic patterns without contact. When the period (d) of the patterns becomes of the same order of magnitude as the wavelength λ, diffraction phenomena strongly affect the reproduction of the mask. Our solution to obtain a faithful reproduction starts from a patent by Roumiguieres and Neviere (US patent n 4,389,094, 1983). It states that the periodic mask must be lighted in TE polarization under Littrow incidence and the wavelength-to-groove spacing ratio must be chosen in such a way that only two diffracted orders propagate above and below the mask, which implies 2/3 < k/d < 2. Then the -1 and 0 order have the same intensities. Thus, they interfere under the mask leading to an interference field with 100 % contrast - if we assume infinite conductivity of the mask - and same period as the mask. Our work consisted in including finite conductivity of the metal, finite thickness, and oxide coating on a mask lying itself on a stratified media (air gap photoresist, high index film, waveguide). Since all commercial existing masks have a square wave (lame[lar) geometry, the classical differential and integral grating formalisms are not the best suitable for the problem. A modal theory has been developed and implemented numerically for both TE and TM polarizations. k not only allows computing grating efficiencies, but gives the field map below the mask, inside the photo resist.

Starting from the lighting conditions described in the Roumiguieres - Neviere patent, the first attempt was to extend the range of validity to larger groove spacings for which more than two orders propagate inside the mask material. The attempt was successful and it was established that the only necessary condition is to have two diffracted propagating orders into air. Four orders inside the glass layer supporting the mask still lead to a good replication process. The second point was to verify that, even in the case of a finite conductivity of the mask, the process allows avoiding contact between the mask and photoresist. We found that the mask pattern is preserved even at several micrometers from the mask, allowing photolithographic transfer without contact. The third attempt was to test the tolerance of the Littrow condition of incidence. It was found that a depaupiare as high as 1/1 deg from the Littrow condition can occur without introducing more than 15 % difference into the -1 and 0 diffracted orders, which still lead to a good contrast. This is an important result in the sense that it allows transferring non-periodic masks, which considerably widens the domain of applicability of the initial patent. The interest of transferring dual-frequency phase coded gratings, low curvature focusing gratings, and other non periodic devices is so high in Integrated Optics that this idea has been protected by a patent taken by CSEM, which has made experiments which confirmed the theoretical predictions.

Characterization of aroove rouahness

Manufacturing of diffraction gratings by interferometric method involves several technological stages, responsible for the quality of the reflective metallic surface. Experimental and theoretical investigations are carried out in order to determine the
influence of some of these theoretical processes on surface roughness and on the influence of the roughness on scattering and absorption. AFM shows that when the baking of the photoresist is not enough, “bumps” are formed with small period during the growth of Al layer. These bumps enhance surface scattering and absorption so that the diffraction efficiency can be reduced even twice, when compared with the correct technological process.

**Nonlinear optical effects**

Study and optimization of grating devices with nonlinear optical properties are practically impossible without numerical methods for their modelling. A method based on the differential formalism has been developed by L(3E, Marseille and LEMO, Grenoble. However, it suffers of some numerical instabilities for deep metallic gratings. In order to extend the capabilities of the theory, two different methods are developed.

The first one is based on the Rayleigh hypothesis that the electromagnetic field inside the grooves can be represented as a sum of plane waves. While valid for shallow grooves, it fails for deeper gratings and profiles with edges, but enables simple programming and is useful for comparison of the results.

The second one is based on a curvilinear non-orthogonal transformation of the coordinate system which maps the corrugated interface onto a plane. This simplifies the boundary conditions but complicates the propagation equation. The tensorial formulation of Electromagnetism of Maxwell-Minkowski in the new non-orthogonal coordinate system lead to a set of first order differential equations with varying coefficients for the tangential components of the field. Taking advantage of the pseudoperiodicity of the problem, the Fourier harmonics of the field are solution of a set of first order differential equations with constant coefficients. The resolution of this system via eigenvalue and eigenvector technique avoids numerical instabilities and leads to accurate results which agree perfectly with those found via the Rayleigh method or by the Differential method, when they work.

A phenomenological approach is then developed to explain the unusual shape of the resonance lines at 201, which is based on the poles and zeros of the scattering operator S at m and 2m [t is shown that 5(2*pi) presents 3 complex poles with 3 associated complex zeros. Their knowledge, plus the nonlinear reflectivity of the plane device allows predicting all the possible shapes of the 20 signal as a function of angle of incidence. The phenomenological study explains an experimental result, found few years ago, that if 2~ lies inside the absorption band of the guiding material instead of the transparent region, the enhanced second harmonic generation is changed into a reduced one. It means that in that case phase matching can lead to a minimum instead of maximum.

An algorithm is then proposed to maximize the signal intensity; with polyurethane as a guiding material a conversion factor of up to 4(33 is found when incident power is equal to 40NV.

Bistability of second harmonic generation in optical waveguides with depletion of the pump field is studied theoretically using the coupled-mode approach and a specially developed computer code based on the rigorous electromagnetic theory. It was found that strong electromagnetic fields can cause half-harmonic generation, i.e. light generation at a frequency twice lower than the pump one.

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INTRODUCTION:

The general purpose of the project was the development of design rules, tools and fabrication technology for the access ports to/frotn integrated optical signal processing modules. In general, this should be achieved by using optical gratings. The objectives of the work performed were:

- Fabrication of short-periodicy grating couplers
- Fabrication of gratings with high COUp(ing efficiency (> so~~)
- Uncoupling focussing gratings in channel waveguides
- Demonstration of non-linear effects

TECHNICAL DESCRIPTION:

The emphasis in the part of FSU Jena and FhG-10F Jena was on the fabrication of samples of waveguide coupling gratings on the one hand, and on the experimental investigation of its optical properties (e.g. coupling efficiencies achieved or demonstration of non-linear effects) on the other hand.

The fabrication of the grating profiles was done by e-beam direct writing. At FSU Jena the e-beam writing technology is established for some years. For the work performed in this project the LION LV1 e-beam writer (Leica Lithography Systems Jena) was used. It offers a special exposure mode “continuous path control” which allows the exposure of linear and arbitrary curved lines by a special data description of such pattern by means of Bezier polynomials. Obviously, this is a very suitable method for the fabrication of linear and focussing optical gratings as required in this project because the amount of data for the pattern description is very low, and the quality of the grating profiles fabricated is very good even in the case of curved lines due to the high resolution of path of 10nm. The realization of binary gratings was done by using the normal gaussian spot of the e-beam (beam diameter below 10nm). For the fabrication of blazed gratings, the variable dose writing technology was used. However, for achieving the sawtooth profile of the grating lines the exposure was not performed with several dose steps, but the e-beam was expanded dynamically by a very fast scanning with a definite asymmetric point distribution which causes the asymmetric electron dose distribution in the resist required. This unique feature of the LION LV 1 e-beam writer is called “dynamic virtual beam profile generation” and makes the fabrication of blazed gratings as easy as for binary ones.

As the result of the e-beam writing, coupling gratings in resist were obtained. Then, such gratings were used in two different ways: either for optical experiments (using the resist layer as a waveguide) or for grating transfer by ion beam etching or replication by embossing. The ion beam etching process was optimized for the transfer of both binary and blazed gratings. The etching of binary gratings was done by ion beam etching (IBE) with argon ions from the resist layer into a metallic interlayer (e.g. chromium). Then, the transfer from this layer into hard materials (e.g. fused silica, tantalpentoxide) was done by special kinds of ion beam etching, e.g. reactive ion beam etching or chemical assisted ion beam etching. Using this technology, high-frequency gratings with periods down to 160nm and aspect ratios up to 2.5 were transferred into fused silica. The transfer of blazed gratings turned out to be more
complicated. Some etching tests as well as modeling calculations showed a considerable change in the grating profile by proportional etching from resist into hard materials. Therefore, instead of proportional etching the "blazing by etching" technology was applied. It uses a binary grating in the metallic interlayer and converts it into a blazed structure in the substrate by etching with a constant, non-perpendicular ion incidence. In this way several samples of blazed gratings with periods down to 200nm have been fabricated. For obtaining several copies of one initial resist grating, the replication by embossing technique was used. As well-known from the compact disc fabrication, a metal master of the surface profile is fabricated by galvanomforming. This master then is used for multiple replication into resin. We used UV-curable adhesive or ormocer which allows the choice of the refractive index by changing the quotas of the different components. Alternatively, in case of only a few copies required the direct replication of the initial resist profile was used. Direct replication of a resist structure turned out to be possible more than 10 times without damaging the initial profile by using a thin metallic interlayer which supports the separation of the master resist profile and the resin copy. The advantage of this method is, that no metal master has to be fabricated, which considerably simplifies the replication process.

Results:

One objective of the project was the realization of high coupling efficiencies and special optical properties like focussing into a channel waveguide or beam shaping. For achieving this, two different kinds of gratings have been investigated: Mazed gratings with periods in the range of the light wavelength, and binary sub-wavelength gratings. In the case of blazed gratings with a period in the range of the light wavelength, the grating causes a diffraction with more than one diffraction orders existing. The purpose of the blazed profile of the grating lines is to shift the light intensity into one diffraction order propagating in the desired direction. That means, the coupling efficiency strongly depends on the quality of the sawtooth profile. The best values for the coupling efficiency are about 46% for uncoupling into a waveguide layer and about 74% for outcoupling from the waveguide layer into one diffraction order desired.

These results have been achieved using focusing gratings fabricated with replication by embossing. The focusing properties are due to the elliptical grating lines which results in a minimum spot diameter of about 10 microns (FWHM, for a 1 mm x 1 mm grating, 800nm period, (SONDZEICHEN 108 /“Symbol”)= 633nm and 4mm focal length). Additionally, beam shaping properties of such gratings were shown to be realizable by a variation of the profile depth versus the grating length. The fit of the measured beam profile of an outcoupled beam to the ideal gaussian profile desired was about 0.9. In the case of high-frequency gratings, the small grating period results in only one propagating diffraction order when illuminated under proper conditions. Therefore, a high coupling efficiency may be realized without a special grating profile. For the incoupling efficiency the best result achieved by such gratings is about 67% by uncoupling red light (SONDZEICHEN 108 /“Symbol”)=633nm] with a grating of 260nm period into a PMMA waveguide layer.

In the current project, the fabrication technology for binary and blazed gratings was established, and as a result, binary gratings with periods down to 160nm period and blazed gratings with periods down to 400nm may be realized. The fabrication of the initial profiles in resist is done by e-beam direct writing, the transfer into hard materials is realized by km beam etching. Multiple replication of both binary and blazed gratings is possible by embossing, either by fabricating a metal master copy of the initial grating structure (as known from the compact disc fabrication) or by direct replication using the resist profile as a master. In general, a problem in the whole fabrication process turned out to be the inspection and control of the profiles. C@tical microscopy is near to or beyond the resolution limit, but there is no other easy, fast and cheap technique. Thus, we see a great demand for research in this area.

In addition to the technological and optical research described, we fabricated several samples of grating structures for special purposes by using the fabrication technology established. For the project partner LEMO Grenoble, some gratings for second harmonic generation experiments were realized. The challenge in this structures was the fabrication of gratings.
with strongly different periods (160nm to 1000nm) on one substrate and the transfer of this gratings into tantalpentoxide by special ion beam etching.

Non-linear materials have been investigated, too. We used several poly-phenylviny lene (PPV) polymers, and non-linear properties were demonstrated experimentally. However, the application of such effects appears to be very critical due to the non-stable and non-reproducable material properties.

Conclusions:

The achievement of high coupling efficiencies by means of grating couplers was the main objective in the part of FSU and FhG- IOF. The grating fabrication technologies were optimized. Best results achieved were an uncoupling efficiency of 67 % by means of binary high-frequency gratings and an outcoupling efficiency of 74 % by using blazed gratings. The incouling of light in a strip waveguide was demonstrated successfully. For this application focussing gratings were preferred. The investigation of non-linear materials was performed, too. Due to problems of material stability the results are not as good as expected at the beginning of the project. In summary, all essential tasks were fulfilled.

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2. Title

HIGH EFFICIENCY WAVE FRONT SHAPING INTEGRATED OPTIC FLAT OPTICAL ANTENNAE (FOA)

G. Voirin, H. Vuillomenet, P. Sixt, O. Parriaux, CSEM Centre Suisse d'Electronique et de Microtechnique SA, Jaquet-Droz 1, P.O. Box 41, CH-2007 NEUCHATEL, SWITZERLAND

3. Abstract

CSEIVI has acquired through this project technologies and know how for the fabrication of grating for integrated optics and to make demonstrators of high efficiency gratings that can be used in further industrial applications. The technologies include electron-beam lithography; photolithography with oblique incidence necessary for sub-micron period grating transfer; physical transfer of the gratings in the waveguide material. The demonstrators are: high efficiency waveguide coupler, double spatial frequency grating coupler for applications in displacement measurement and biochemical Microsystems.

4. Introduction

5. Technical description and results

CSEM contributed to the experimental study of the oblique incidence photolithography for the transfer of submicron gratings. The principle is based on diffraction of the exposure light through the grating mask, and interference of the diffracted orders under the mask. Considering the wavelength \( k \) and the grating period \( \lambda \) in the range \( \lambda < \lambda \), the grating mask diffracts only one order (-1st). The diffracted -1st order and the transmitted 0th order interfere and create a fringe pattern with exactly the same period as the grating mask. The interference region extends to a distance corresponding to the coherence length of the light. Experimental study shows that the balance between -1st and 0th orders is tolerant versus the incidence angle around the Littrow angle and versus the grating period for a fixed angle at the Littrow condition for the smallest period. Figure 1 shows the normalised measured intensities of the different orders in function of the incidence angle. The ratio varies less than 10% over 20° angle variation. An experimental bench for HeCd laser transfer was set up. It is represented on Figure 2. The 442 nm wavelength HeCd laser beam is first expanded to an approximately 1 inch cross-section beam. A polariser makes sure that the electric field incident on the grating mask is parallel to the grating slits. The set up allows changing the incidence angle of the laser collimated beam. This bench demonstrated the feasibility of the transfer of submicron grating using standard masks.
Relative intensity of the "0" and "-1" diffracted orders of a 0.4 μm period grating, line-space ratio (3.7S, versus angle of incidence. Incidence from the back side. Wavelength 442 nm (He-Cd Laser).

![Intensity graph](image1)

**Figure 1:** Diffraction properties of the chromium mask

![Experimental setup](image2)

**Figure 2:** Experimental bench for oblique incidence lithography with an HeCd laser

![Photograph of transferred gratings](image3)

**Figure 3:** Photograph of transferred gratings on Si3N4 waveguide realised on four silicon wafers.
in order to have a more industrial tool, a conventional mask aligner using a mercuty lamp, Karl Suss MJB3, was modified so as to allow illumination under an angle. It was necessary to modify the optical system: the system that homogenise the beam was removed and replaced by optical elements which filter the light either at 385 nm or at 436 nm and to polarise the light parallel to the grating line. The transfer of 0.4 ~m and 0.5 pm grating was demonstrated on Si₃N₄ waveguide made on four inch silicon wafers. Figure 3 presents a picture of a transferred wafer and Figure 4 reports the diffraction efficiency measured on twelve gratings couplers after wet chemical etching in BHF 7/1 of the grating in the waveguide layer.

The tolerance of the transfer with respect to incidence angle and periodicity let the transfer of special gratings that are often used in integrated optics like double spatial frequency gratings, focusing gratings or chirp gratings. On Figure 5 can be seen a SEM picture of a transferred double frequency grating etched in a waveguide structure.

CSEM participated also in the fabrication of waveguide grating couplers. The structures were generated either by electron-beam direct writing or by oblique incidence photolithography. Different etching techniques were characterised and selected for their ability to fit the specific needs of the different gratings.

Figure 1: Diffraction properties of the chromium mask

Figure 2: Experimental bench for oblique incidence lithography with an i+eCd laser

Figure 3: Photograph of transferred gratings on Si₃N₄ waveguide realised on four inch silicon wafer

Figure 4: Histogram presenting the coupling efficiency of twelve 0.5 pm gratings transferred on Si₃N₄ waveguide*(158₃~ thick) deposited on oxidised silicon substrate (oxide thickness: 22'740 ®).

The tolerance of the transfer with respect to incidence angle and periodicity let the transfer of special gratings that are often used in integrated optics like double spatial frequency gratings, focusing gratings or chirp gratings. On Figure 5 can be seen a SEM picture of a transferred double frequency grating etched in a waveguide structure.

Figure 5: SEM micrograph of a transferred double frequency grating

CSEM participated also in the fabrication of waveguide grating couplers. The structures were generated either by electron-beam direct writing or by oblique incidence photolithography. Different etching techniques were characterised and selected for their ability to fit the specific needs of the different gratings.
Figure 5: SEM micrograph of a transferred double frequency grating coupler

Figure 6: Principle of a displacement system using double spatial frequency grating coupler
Table 1 gives the etching rates for different materials obtained with ion beam etching and wet etching in buffered hydrofluoric solution.

<table>
<thead>
<tr>
<th>Etched material</th>
<th>IBE etching rate (Å/min)</th>
<th>13HF etching rate (Å/rein)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>190-210</td>
<td>500 (BHF 7/1)</td>
</tr>
<tr>
<td>BK7 with ion exchanged waveguide</td>
<td>190-210</td>
<td>10 (BHF 7/1)</td>
</tr>
<tr>
<td>CSEM LPCVD Si$_3$N$_4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fused silica</td>
<td>300-340</td>
<td>200 (BHF 39/1)</td>
</tr>
<tr>
<td>TiO$_2$ grating 1.5 μm period</td>
<td>120-130</td>
<td>50 (BHF 7/1)</td>
</tr>
<tr>
<td>TiO$_2$ grating 0.5 μm period</td>
<td>110-120</td>
<td></td>
</tr>
<tr>
<td>Photoresist</td>
<td>-300</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Etching rate for different waveguide materials

Different gratings were realised and, in particular, a double frequency grating coupler for a displacement measurement system. The principle is to measure the phase-shift between two orders which are diffracted along and against the displacement direction. A movement of $x$ creates a phase-shift $\Delta \phi = \frac{2\pi}{A} x$ in the diffracted order $m$ where $A$ is the grating period and equal to $4 \mu m$. In the arrangement of Figure 6, a double frequency coupler is placed close to the moving grating.

Figure 6: Principle of a displacement system using double spatial frequency grating coupler.

The demonstration was made with a BK7 K$^+$-Na$^+$ ion exchanged waveguide (5 hours at $385^\circ$C), the two periods of the grating were $2\frac{\pi}{f} = 4j\lambda z$ and $2\frac{\pi}{f} = 0.5@$, the source was a collimated laser diode at 780 nm wavelength. The interference signal was recorded versus the grating ruler displacement and is presented on Figure 7.

Figure 7: Interference signal obtained with the double frequency grating coupler measurement system.

With the active collaboration of 10FAN, CSEM partipated to the realisation of high efficiency grating using phase-shifted corrugations. The basic structure is a glass ion exchange waveguide having a first corrugation at its suface, coated with a thin high index film (here Ta$_2$O$_5$) as illustrated in Figure 8. The upper undulation of the Ta$_2$O$_5$ layer is phase-shifted relatively to the lower
Figure 2: Interference signal detected with the double frequency grating coupler.

Measurement system.
Figure 9: SEM micrograph of the phase-shifted grating cross-section
one which modifies the interference conditions between the two diffractkm spectra into either medium [substrate and air]

**Figure & High efficiency** phase-shifted grating coupler

A suitable phase-shift will privilege radiation (therefore the uncoupling also) into the air or into the substrate. The phase-shift was created by the deposition of non conformal Ta@layer under a 45° angle. For a layer thickness of 70 nm a ratio between power radiated into the substrate and into the air as high as 22 were measured. Figure 9 shows an SEM picture of a cross-section of this grating where the phase-shift between the two corrugation is evident.

**Figure 9: SEWI micrograph of the phase-shifted grating cross-section**

6. **(incluicsims**

The oblique incidence lithography was demonstrated on a modified standard mask aligner: 0.4 pm period, two millimetre square gratings were easily transferred on four inch waveguide wafers. Special gratings like focusing grating and double frequency grating are also transferred in the same condition due to the large tolerance in angle and in period that were demonstrated. The fabrication of high diffraction efficiency grating and demonstrators for industrial application in metrology and biochemical Microsystems were achieved.

7. **Acknowledgments**

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**& References**

Title
FLAT OPTICAL ANTENNAE

Authors, name and address :
V. A. Sychugov, N. N. Lyndin, A. V. Tishchenko, U. B. Alexandrovich
Institute of General Physics of the Russian Academy of Sciences (Vavilov Street 38, Moscow 117942, RUSSIA

Technical description

Rayleigh-Fourier method is the simplest and it is widely used one for calculation of light diffraction cm a corrugated interface between two optical media. However, the application field of this method is restricted due to unpredictable inaccuracy of its results for deep gratings. Therefore in the frame of the BRITE project we compared calculation results of light diffraction analysis in corrugated guiding and non-guiding structures, obtained by rigorous (LOE, Marseilles) and Rayleigh-Fourier methods. The comparison shows that the Rayleigh-Fourier method can be used for analysis of typical waveguide structures with a grating, when the groove depth does not exceed 50 nm.

The problem of balanced coupling of two waveguide modes arose due to the use of two-mode waveguides in sensor applications. We analyzed this problem using the Rayleigh-Fourier method and compared the results with the rigorous theory (LOE, Marseilles). Two cases of two-mode excitation under the same angle of incidence were considered: 1) TEO - TMO mode excitation and 2) TE~ - TE 1 (TMO - TM 1) mode excitation. In the first case both modes can be excited independently while in the second case some conditions should be satisfied. Large part of our theoretical investigations was dedicated to search for these conditions. It was found that for even integer value of long-t~short period ratio N and duty ratio F of large period equal to 0,5, it is possible to excite practically independently two modes of the same polarization on the two-period grating. From physical point of view this is due to intermode coupling coefficient is very close to 0. In other cases (odd integer N, F not equal 0.5 for even N) it is rather difficult to achieve the balanced excitation of two modes. When N=6 and F=0.5 the balanced excitation can be accomplished by moving the position of the Gaussian beam center relative to the grating boundary. When two modes are of different polarization, their intensities can be easily balanced by rotating the polarization plane of the incident Gaussian beam. We calculated excitation efficiency for waveguide modes using the coupled modes equations.

Typical excitation efficiency for two-period grating is 10-15% when the Gaussian light beam goes from the air. These values can be improved by fabrication of special gratings, i.e. with the changing duty ratio. This method was applied to the thin-film waveguide with ordinary, one-period grating with the period close to 0,5 mkm. Our estimations show that varying duty ratio along the grating increase the excitation efficiency from 18% to 22% if the excitation is from the air and from 62% to 74% if the excitation is from the substrate.

However, changes in duty ratio result in variation of the effective refractive index of the waveguide along the grating. This variation can be substantial and requires the corresponding change of grating period in order to ensure phase matching along the grating. Hence, we investigate several other possible methods for increasing the efficiency of waveguide excitation by Gaussian beam:
1. phaseshifted gratings [1]
2. parallelogramic gratings
3. waveguide structure with 3 corrugated boundaries.

Common drawback of methods 1 and 3 is the dependence on the polarization. Parallelogramic gratings made on the waveguide exhibit much weaker dependence on the polarization. Parallelogramic grating were first proposed in [2]. However, the authors of the paper restricted their consideration by the case of TE ~olarization and weakly-cmidina waveguides.
In practice, both TE and TM polarization and strongly-guiding waveguide are often used. Hence we considered the glass-Ta$_2$O$_5$-Si(3-α-water/air) waveguide structure, Parallelogramic grating was formed in the SiO$_2$ layer. We investigated the dependence of the excitation efficiency for both TE and TM polarization on the grating depth and on the tilt angle of the grating teeth. It was found that radiation loss coefficient begin to saturate at grating depth about 13, 15nm and weakly depends on the tilt angle. Well-defined “blazing” effect appears at grating depth greater than 0.15nm. Our calculations shows that with optimum tilt angle it is possible to achieve 78% and 72% excitation efficiency for light falling from the substrate and from the cover respectively. optimum tilt angle is determined from grating period, effective refractive index etc. by simple geometrical consideration and not by Bragg condition. In order to test parallelogramic grating, we fabricated the waveguide structure: glass substrate (n= 1.51), Ta$_2$O$_5$ waveguide layer (n=2.07, h=200(3A), SiO$_2$ grating layer (n= 1.46, h=2fNOA). Then we deposited photoresist on the top of the structure (h= 2 500A) and recorded a grating with 0.36 mkm period using holographic technique. After that we deposited tantalum under the sliding angle (-80°). As a result a thin tantalum film appeared on the top of the photoresist grating teeth and on one of its slopes. Then the sample was etched under 47° angle with CF$_4$ ions. The remaining of the resist and metal were cleaned. In order to excite the waveguide mode by means of prism, SiO$_2$ layer was chemically thinned close to the grating region. We measured the ratio between the radiation from the waveguide into the air and into the substrate. Experimental result 4.5 differed from the theoretically predicted value 5.7. The above mentioned technology of parallelogramic grating fabrication is based on the model of RIBE process of the plane substrate through the photoresist or metallic mask. This model describes the evolution of the grating profile as movement of planes constituting the grating. We used the computer code to elaborate technology for parallelogramic grating production in SiO$_2$ layer on top of Ta$_2$O$_5$ guiding layer.

The task of high-quality gratings fabrication requires to develop the methods for assessment of various grating’s parameters. Most important of them are radiation, scattering and dissipation loss coefficients. Applying the different methods for both TE and TM modes, we studied more than 30 samples. Analysis of the results shows that formation of gratings is usually accompanied by increase in scattering losses, which are comparable with diffractive radiation losses. The main obstacle is the way of a broad utilizing of diffraction gratings in integrated optics is a substantial losses of light owing to its scattering on grating. Grating imperfections can be divided into two classes. small imperfections with the size less then grating period (0.5 mkm) and a large imperfections with the size more then grating period. We developed a technology for removing of grating imperfection for sodalime glass and quartz substrates. Glass samples were annealed in furnace at temperature 5 15°C (corresponding to the initial stage of glass softening. To clean gratings on quartz substrate we used heating of corrugated quartz surface under irradiation of cw 032 laser.

Conclusions:

1. Two-period grating with even period ratio N can provide balanced excitation of two waveguide modes.
2. Effective excitation of the waveguide mode by the light beam incident from the air can be achieved with the help of parallelogramic grating.
3. For effective operation of the waveguide grating it is necessary to ensure that dissipative and scattering losses are srrd.

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