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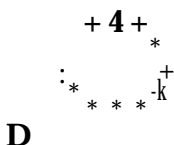
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Title

FLAT OPTICAL ANTENNAE

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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 "cascadhg" is considered : it is shown that the depletion of the pump beam may give rise to optical bistability.

Ex~riments

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 subwave!ength gratings where the phase-matching condition is fulfil[ed 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.

$=on~ harm~n c generation with a subwave! enath mat u

A new device for high efficient frequency doubling is designed, taking in account the results concerning the first experimental demonstration of grating assisted phase matching. The &fraction gratings are etched into a high index layer. Two different grating periods are used : cme is optimised 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 $P_{zw}/P_w=2. 3*1 O-a$ 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 beincreased to $P_{z@}\#P_m= 19*1 0-4$ focalizing the beam slightly on the device. Taking the uncoupling losse @ into account ((5%}, we obtain an efficiency of P2W/P@=0.00S8. 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 $A_k=$ 14.~nm with an interaction length of 1 mm ~grating dimensions). In~reasing the grating !ength will increase the efficiency without reduction of the acceptance bandwidth.

Optical Kerr effect and nonlinear direct~onal couula

[t is first necessary to be abie to realize nonlinear channel waveguides. To this aim, the selected nonlinear medium is PMMA-DR 1 which has a noticable x3 value. This material is provided by the sub-contractor LET1-CEA-Saclay (F). The x3 characterization of planar waveguides made with organic polymer PMMA-DR 1 has been achieved. Low loss {<3dBlcm) channel waveguides have been done and good coupling efficiencies have been obtained [>20*A for a monomode waveguide}, This is achieved using the photob[eaching 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.

Pockeis effect and electroo~tic modulation of liaht usina aratina courders

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 &V= 1 C9V. ExperimentaHy 31.3% modulation with AV=S3V is measured. The maximum electrooptic coefficient obtained in the experiment is r3 3=4. 3pmN' using electrode poling. Using transparent electrodes and buffer layers resuits in a very sharp resonance (w@h Af3=t3,023?⁰) 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 addkion to the intensity modulation of the guided optical field, a spatiai 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.

References

R. REINISCH, M. NEVIERE, E. FOP(3V, H. AKHOUAYRI
"Coupled-mode formalism and linear theory of diffraction for a simplified analysis of second harmonic generation at grating couplers"
Optics Communications 112, 339 (1994)

R. REINISCH, J. i-. COLITAZ, J. F. ROUX, E. POPOV, M. NEVIERE
"Nonlinear zeros in second harmonic generation at grating couplers"
Optics Letters 20, 347 {1995)

R. REINISCH, E. POPOV, M. NEVIERE
"Second harmonic generation induced optical bistability in prism or grating couplers"
Optics Letters 20,854 (1995)

G. BLAU, E. POPOV, F. KAJZAR, A. RAIMOND, J. F. ROUX, J. L. COUTAZ
"Grating assisted phase matched second harmonic generation from a polymer waveguide"Optics Letters 20, 1101 (1995}

M, NEWERE, E. POPOV, R. REINISCH
"Electromagnetic resonances in linear and nonlinear optics : phenomenological study of grating behavior through the poles ans zeros of the scattering operator"
J. Opt. Sot. Am. AI 2, 513 (1 995)

E. POPOV, M. NEVIERE, R. REINISCH, J. L. COUTAZ, J. F. ROUX
"Grating-enhanced second harmonic generation in polymer waveguides : role of losses"
App/. opt. 34, 3398 (1 995)

E. POPOV, M. NEVIERE, G. BIJ4U, R. REINISCH
"Numerical optimization of grating enhanced second harmonic generation in optical waveguides"
J. Opt. Soc. Am. 1312, 2390 (1995)

R. REINISCti, M. NEVIERE, E. POPOV
"Phase-matched guided wave optical bistability in c(2) optical resonators"
Optics Letters 20, 2472 (1995]

R. REINISCH
"Bistabilite optique induite par generation de second harmonique sur des coupleurs ~ prisme ou a reseau"
JNOG'94, Besan$on, 25-26 Octobre 1994

E. POPOV, R. REINISCH, M. NEVIERE
Electromagnetic resonance mediated second harmonic generation : peaks or dips ?
Topical Meeting on Nonlinear Guided Waves and their Applications, 23-25/2/1995, Dana Point (USA)

R. REKWSCH, E. POPW, hi NEWERE
Optical bistabiiity by cascading C(2) in prism or grating coupiers
Topical Meeting on Ncmlirwar Guided Waves arid their Applications, 23-25~2/ 1995,
Dana Point (USA)

M. NEWERE, E. POPUV, R. REINKW4
Bistabi[ity of second harmonic generation in optical waveguides with depletion of the pump field
in Application and Theoty of Periodic Structures, " eds. T. Janrwon, N. C. Gallagher,
WE 2532 (1 995), San-Diego-USA, 7-12 July 1995

M. NEVIERE, E. POPOV, R. REIIWX1-i
Electromagnetic study of second harmonic generation by corrugated waveguides
in Application and Theory of Periodic Structures, " eds. T, Jannson, N. C. Gallagher,
SPIE2532 (1 995), San-Diego-USA, 7-1 Z July 1995

M. NEVIEI?E, E. POPOV, 1?. REINESCH
Enhanced and reduced second harmonic generation in nonlinear corrugated waveguides
bWI meeting, St Petersburg {Russie), 22-29 Mai 199S

G. BLAU, M. CAIRC?NE, i-. RUIZ, G. ViTRANT, P. A. CHOLLET, F. KAJZAR
Light modulation through grating induced resonant excitation of a guided mode
Topical Meeting on "Materials for Nonlinear Optics", Val-Thorens [F] 14-
181111996

E. POPOV, M. NEWERE, I?. REINISCti
Polymeric gratings for frequency conversion second and half harmonic generation
hnvite au NATO Advanced Research Workshop "Photoactive Organic Materials", 2'5-30 Juin
1995, Avignon.

Title

FIAT OPTICAL ANTENNAE

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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 k, diffraction phenomenae strongly affect the reproduction of the mask. Our solution to obtain a faithfull 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 O order have the same intensities. Thus, they interfere under the mask ieading 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 prob~em. 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 validi~ 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 depafiure 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 apatent 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 k not enough, "bumps" are formed with smai[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. h order to extend the capabilities of the theory, two different methods are developed.

The first one is based on the Rayieigh 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 simp[e programming and is useful for comparison of the results.

The second cme 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 th propagation equation. The tensorial formulation of Electromagnetism of Maxweil-Minkowski in the new non-orthogonal coordinate system !ead to a set of first order differential equations with varying coefficients for the tangentia* components of the field. Taking advantage of the pseudoperiodicity of the prob9em, 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 Ray Jeigh method or by the Differential method, when they work.

A phermrnencdogica! approach is then deveioped 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@ presents 3 complex poles with 3 associated cornph?x zeros. Their knowledge, plus the nonlinear reflectivity of the plane device ailows predicting all the possible shapes of the 20 signal as a function of ang[e of incidence. The phenomenoiogical 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. [t means that in that case phase matching can lead to a minimum instead of maximum.

An algorithm is then proposed to maximize the signai intensity; with polyurethane as a guiding material a conversion factor of up to 4(3⁶A 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,

References

F. MONT!EL, M. NNERE
"Ekxtromagnetic study of the diffraction of light by a mask used in photolithography",
C@. Commun., 101, pm t 51-156, 1993.

f+. REINISCH, M. NEViERE, E. PfXCN, 1+. AKHOUAYRI
"Coupled mode formalism and linear theory of diffraction for a simplified analysis of second harmonic generation at grating cxwpiers"
Optics Commun. 112, 33!3-348, 1 !394

E. POPOV AND M. NEVIERE
"Surface enhanced second harmonic generation in nonlinear corrugated dielectric: New theoretical approaches"
 J. O.S.A. A 11, 1555-1564, 1994

M. NEV[ERE, E. POPOV, R. REINISCH
"Electromagnetic resonances in linear and nonlinear optics: phenomenological
study of grating behavior through the poles and zeros of the scattering operator",
J.O.S.A. A 12, 513-523, 1995

R. REINISCH, AL COUTAZ, J.F. ROUX, E. POPOV, M. NEVIERE
"Nonlinear zeros in second-harmonic generation at grating couplers"
Optics Letters 20, 347-349, 1995

E. POPOV, M. NEVIERE, R. REINISCH, J.L. COUTAZ, J.F. ROUX
"Grating enhanced second harmonic generation in polymer waveguides-roles of losses",
Applied Optics 34, 3398-3405, 1995

M. NEVIERE AND F. MONTiEL
"Deep gratings : a combination of the differential theory and the multiple reflection series"
 Opt. Commun. 108, 1-7, 1994

F. MONTIEL, M. NEWERE
"Differential theory of gratings : extension to deep gratings of arbitrary profile and
permittivity via the R matrix propagation algorithm", J. O.S.A, A 11, 324 I -3250,
1994

M. SAILLARD, E. POP(N, L. TSONEV, i-. SCANDELL4, W. KRUSE
"Light diffraction from rough gratings"
 App[. Opt. 34, 4883-4891, 1995

R. REINISCH, M. NEVIERE, t-f. AKHOUAYR!, J. 13 ANCKAERT, G. VITRANT
"Modal theory of diffraction: a powerful tool for the study of grating couplers in nonlinear optics"
J. Phys. III France 4, 2451-2458, 1994

R. REINISCH, E. POPOV, M. NEVIERE
"Second harmonic generation induced optical bistability in prism or grating couplers",
Opt. Lett. 20, 854-855, 1995

M. NEVIERE. E. POP(N. R. REINISCH
"Bistability of second 'harmonic generation in optical waveguides with depletion of the pump field"
in Appl. And Theory of Periodic Structures, eds. T. Jartnson and N. C. Gullgher, SPIE
2532, ch.4, 1995

E. POPOV, M. NEVIERE, G. BIAU, R. REINESCH
"Numerical optimization of grating enhanced second harmonic generation in optical waveguides"
J. O.S.A. B 12, 2390-2397, 1995.

M. NEVIERE, F. MONTIEL
"Photolithographic set-up for periodic and non-periodic masks",
in Appi. And Theory of Periodic Structures, eds. T. Jannson and N. C. Gullgher, SPIE
2532, ch.2, 1995

M. NEVIERE, E. POPOV

"Electromagnetic study of second harmonic generation by **a corrugated wweguide"**
Appl. And Theory of Periodic Structures, eds, T. **Jarmson and N. C. Gullgher, SPIE**
2532, ch.5, 1 9 9 5

R. REIIWSCH, M. NEVIERE, E. POP(W
"phase-matched guided wave optical bistability in c2 optical resonators"
Opt. Lett. 20, 2472, ? 995

E, POPOV, M. I'JEVIERE, R. REINISCH
"Polymeric gratings for frequency conversion - second and half ham-tonic generation",
in Photoactive organic materials, ed. F. Kajzar, V. Agranovich, and C. Lee, NATO AS
Series, v.9, pp. 263-273, Kluweti, Dordrecht, 1996

E. POP(W, 8. 8CIZKOV, M. NEVIERE
The inverted surface plasrnon resonance: phenomonologicai explanation"
J. Mod. Opt., to be published

F. MONTIEL, M. NEVIERE
"Electromagnetic study of a photolithography set-up for periodic n-tasks and
application to non-periodic ones"
J. O.S.A. A, to be published.

M. NEWERE
"Nonlinear effects in corrugated waveguides: rigorous electromacmetic stuck and
phenomenological approach"
[international Symposium on Modern Problems of Spectroscopy, 1 T-16 October 1993,
Tro!tsk, Moscow, Russia

H. VULLK3MENET, L. FALCO, C). PARRIAIJX, M. NEVIERE
"Transfer of submicron period gratings by conventional chromium mask
photolithography, Proceedings of the International Symposium on integrated Optics,
11-15 April 1994, Lindau, F.R.G.

Q. PARRIAIJX, H. WJILUOMENET, P. SW, M. NEWERE, F. MCNTIEL
"Spatial frequency bandwith in the photolithographic transfer of submicron gratings",
CLEOiEurope 94 conference, 28 August - .2 Septembre 1994, Amsterdam, The
Netherlands.

M. NEVIERE, E. POPOV
"Surface enhanced second harmonic generation using gratings : phase matching
condition",
CLEO/Europe 94 conference, 28 August -2 Septembre 1994, Amsterdam, The
Netherlands.

M. NEVIEI?E, E. POP(IV, R. REINISCH
"Enhanced and reduced second harmonic generation in nordinear corrugated'
waveguides", LW symposium, 23-26 May 1995, StPetersburg, Russia

M. NEV[ERE, E. PCWKW, R. RE1NISC3+
"Bistability of second harmonic generation in optical waveguides with dep[etion
of the pump field"
Appi. And Theory of Periodic Structures, eck T. Jannson and N. C. Wlgher, SPIE
2532, ch.4, 1995, presented at WE meeting in San **!3iego, CA, USA, 10-74 July**
19!35 '

h?. NEWERE, F. MCINTBEL
"Photo6itimgraph~c set-up for periodic and non-periodic masks"

Title   **FLAT OPTICAL ANTENNAE**

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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**

Techical 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. tt 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 polynoms. 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 vety 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 bem 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 transfered into fused silica. The transfer of blazed gratings turned out to be more

complicated. Some etching tests as we[l as model[ing 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 interiayer and converts it into a blazed structure in the substrate by etching with a constant, non-perpendicular ion incidence. in this way several samp[es 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 galvanoforrning. 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 iight 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 coup[ing 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 resdts 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, 80Qnm period, {SONDZEICHEN 108 /f "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 profiJe. For the incoup{ing efficiency the best result achieved by such gratings is about 67% by uncoupling red iight ({ SONDZEICHEN 108 \f "Symbol''] =633nm] with a grating of 260nm period into a PMMA waveguicfe layer,

in the current project, the fabrication technology for binary and blazed gratings was established, and as a result, bina~ 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@tica[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 cm this area.

h addition to the technological and optical research described, we fabricated several samples of **grating structures for speciai 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 outcoupiing efficiency of 74 % by using blazed gratings. The incouling of light in a strip waveguide was demonstrated successfully. For this application focussing gratings were prefered. 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.

Acknowledgements :

References :

R. WALDHAEUSL, P. IIANNBERG, E.-B. KLEY, A. BRAEUER, W. KARTHE,
 '&Asymmetric Triangular (Blazed) Grating Couplers in Planar Polymer Waveguides'~ 6th European Conference on Integrated Optics, Neuchatel, Proceedings, 4-14, 1993

R. WALDt-IAEUSL, P. DANNBERG, E.-B. KLEY, A. BRAEUER, W. KARTI-IE,
 "Highly e%icient blazed grating coupler in p[anar polymer waveguides'~
ht. J. Optoelectronics, 8 (1993) pp.529-536

P. DANNBERG, E.-B. KLEY, R. WALDHAEUSL, A. BRAEUER, W. KARTHE,
 "Passive Polymeric Components Fabricated by Embossing Technique",
ECOC 93, 19thEuropean Conference on Optical Communication, Montreux, September 1993

W. BRUENGER, E.-B. KLEY, B, SCHNABEL, 1. STOLLBERG, M. ZIERBOCK, 1?. PLONTKE
 "Low energy lithography, energy control and variable energy exposure'~
Microelectronic Engineering 27 (1995] ? 35-138

E.-B. KLEY, P. THIEME, B. SCHNABEL, M. BOEIXHER, R. PLONTKE,
 "Eiektronenstrahllithographische Subrnikrometer- und Nanorneterstrukturierung mit Energien zwischen 1 und 20keV,
VD1-Berichte 1172, VD1-Verlag Duesse[dorf 1994, S. 83-94

R. WALDHAEUSL. E.-B. KLEY, P. DANNBERG, A. BFUJEUER, W. KARTHE,
 *'Grating couplek in planar &/ymer wavegffides w"th be~m sha~ina D;owrties'".
Nanofabrication Technologies and Device integration, SPI~ Proceedings 2213, 122-132 (1994)

A. BRAEUER, R. WALDHAEUSL, W. KARTHE, B. SCHNABEL, E.-B. KLEY,
 "Focusing grating couplers and grating couplers with beam-shaping properties in planar polymer waveguides'~

Proc. DX-95, Hong Kong, 3 (1 !395), p. 44-45

E.-B. KLEY, B. **SCHNABEL,**
"E. -beam Wmg-ap.hy : a witakde technology .%r fabrication d high-accuracy 2D **and** 33
.wrface pfofi~es",
Micromachining and Mkrofabrkation 495, 23-24 October 1995, Austin USA, SPIE
Proceedings VOL 2640

W. KARTHE, R. **GOERH4G, A. BRAEUER, E.-B. KLEY, CM. WAECHTER, P. DANNBERG, T.**
P(3SSNER,
%4cro- and integrated optica~ devices irl glass and polymers fur hybride Megratiun into
micmsystefns ª,
Mkrosystem Technologies 1 (1995) p. 59-67, Springer Verlag 1995

E.-B. KLEY, B. SCHNABEL, U.-D. ZEITNER, 1+. fiUEBNER, W. RCICKSTROH,
 Yabticatioff of eiements for microoptics and integra~ed optics by e-beam direct writing':
EOS topical meetings digest series vol. 9, Engeberg (Switzerland) 1.-3.4.1996

2. Title

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

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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 submicronic 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 A in the range $< A <~, the grating

mask diffracts only one order (-1 st). The diffracted -1st order and the transmitted Oth 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 -1 st and Oth 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 lieCd laser transfer was set up[2]. 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[2].
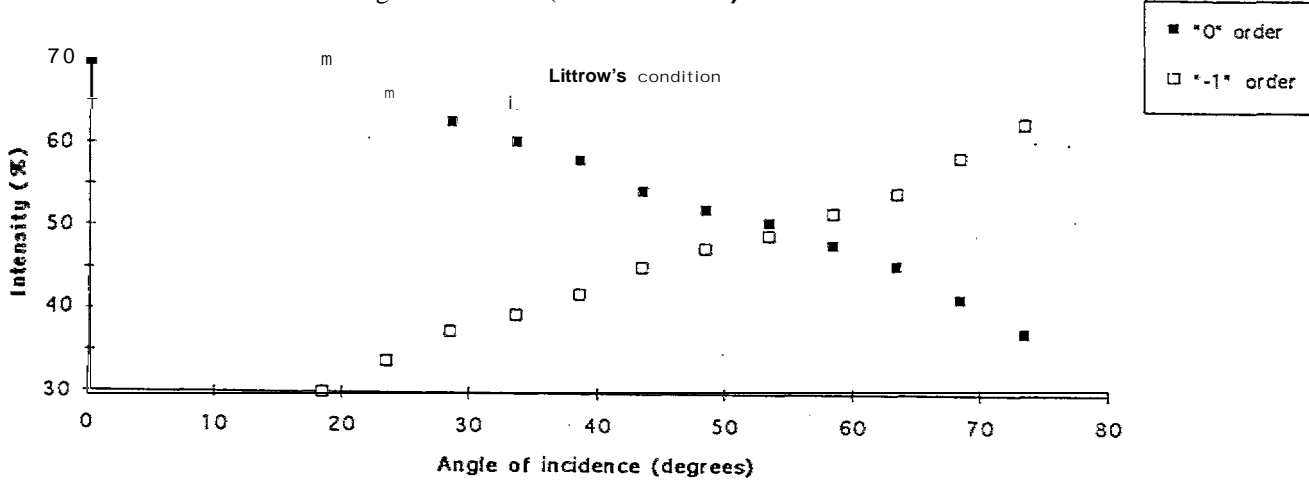
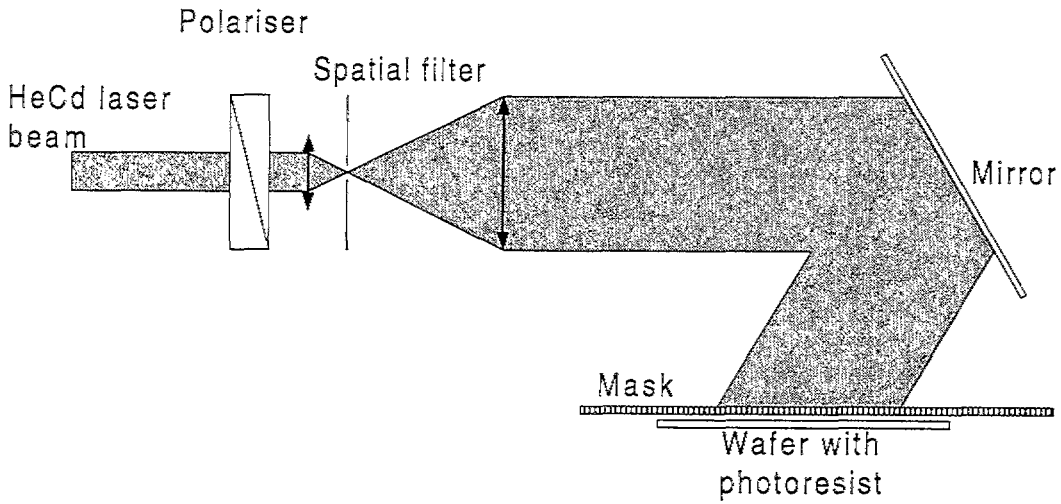**Figure 1: Diffraction properties** of the chromium **mask**

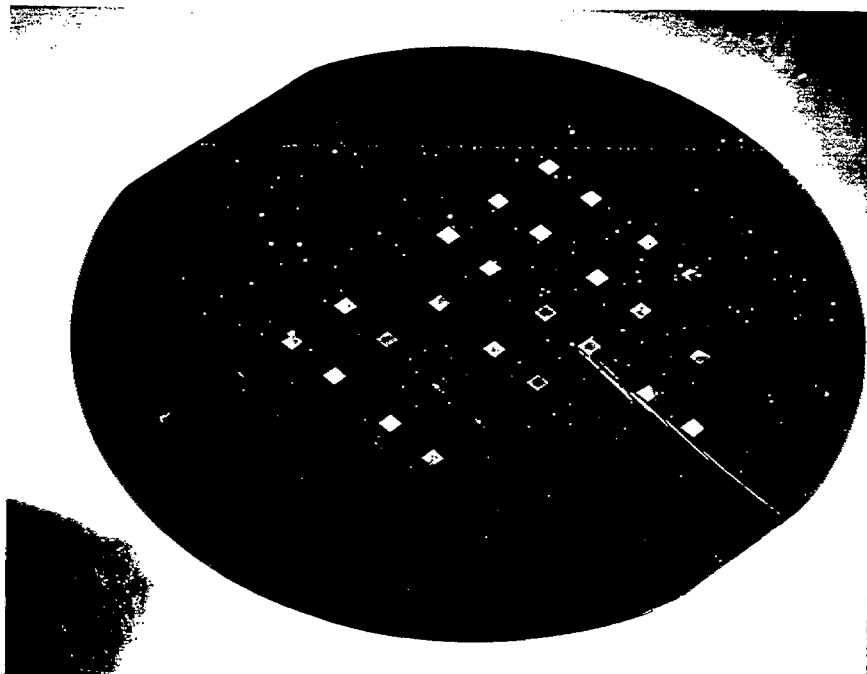**Figure** 2: **Experimental bench for oblique incidence lithography with an HeCd laser**

Figure 3: Photograph d transferred gratings on Si3N₄ Wweguide reaUised cm four i~eh **silicon wafer**

Figure 1: Diffraction properties of the chromium mask

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

[n 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 Si_3N_g waveguicte made on four inch silicon wafers. Figure 3 presents a picture of a transferred wafer and Figure 4 reports the diffraction efficiency measured on twelves gratings couplers after wet chemical etching in BHF 7/1 of the grating in the waveguide layer,

Figure 3: Photograph of transferred gratings *on* **Si~N_q waveguide realised on four inch silicon wafer**
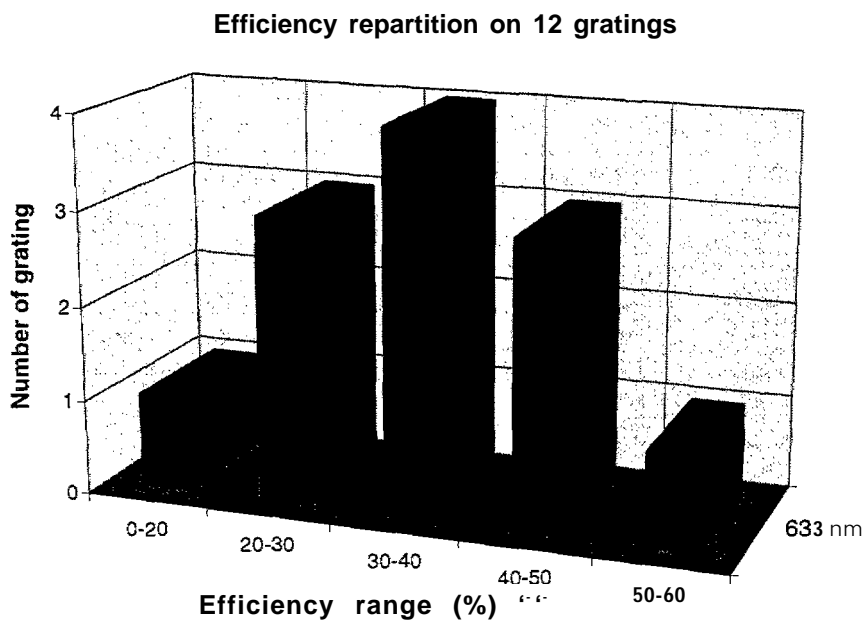
Efficiency repartition on 12 gratings

Figure 4: Histogram presenting the coupling efficiency of twelve 0.5 pm gratings transferred on Si_3N_4 waveguis^d_e(158_0 ~ 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.
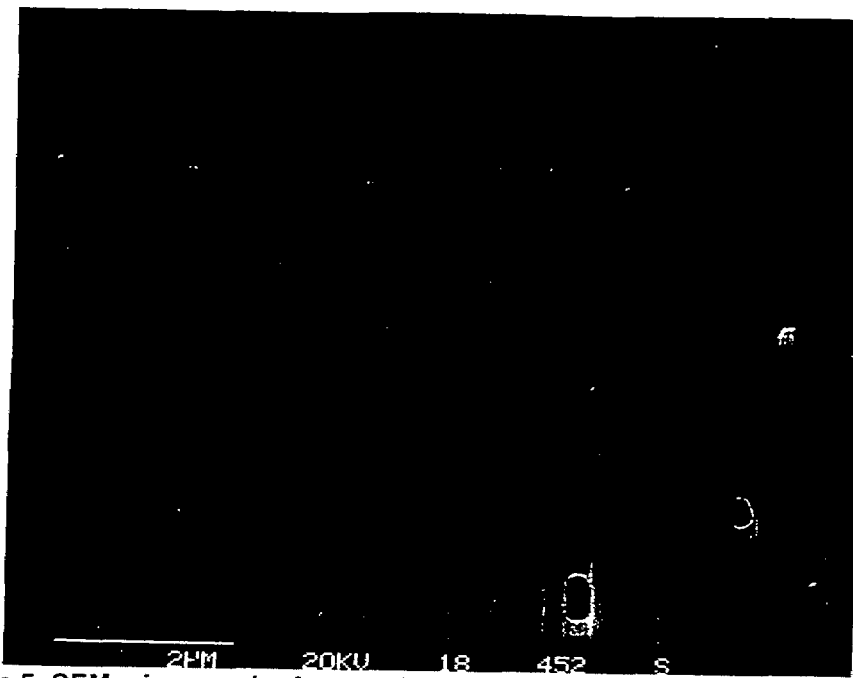
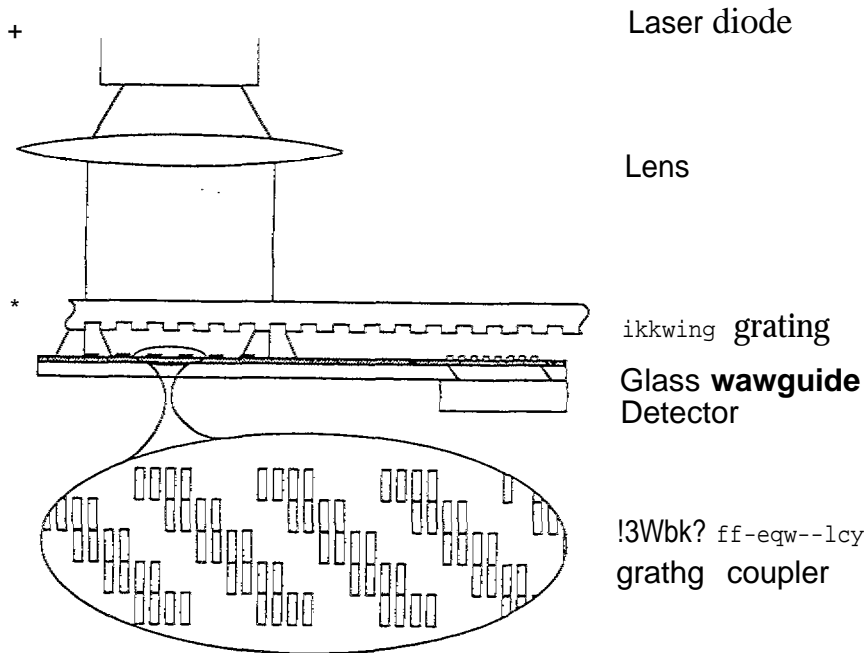Figure 5: SEM micrograph of a transferred double frequency grating

Laser diode

Lens

ikkwing grating

Glass **wawguide**
Detector

!3Wbk? ff-eqw--lcy
grathg coupler

Figure 6: Prhciple of a displacement system using double spatia[frequency grating coupler

Table1 gives theetching rates fordifferent materials obtained with ion beam etching and wet etching in buffered hydrofluoric solution.

Etched material	IBE etching rate @Jmin)	13HF etching rate (A/rein)
BK7	190-210	500 (BHF 7/1)
BK7 with ion exchanged waveguide	190-210	
CSEM LPCVD Si_3Nq		10 (BHF 7/1)
Fused silica	300-340	200 (BHF 39/1)
TiO_z grating 1.5 ym period	120-130	50 (BHF 7/1)
TiO_2 grating 0.5 ~m period	110-120	
Photoresist	-300	

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[3,4]. 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

$\sim_{_=} {}_m\frac{Z}{}$x in the diffracted order m where A is the grating period and equal

4 ~m. In the arrangement of Figure 6, a double frequency coupler is placed

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

close to the moving grating. it has to fulfi! two resonance conditions at once: the coupling of order +1 and -1 in the same propagating mode. Its Fourier spectrum must contain the two spatial frequencies $\sim_{+1}$ andf"l . This is done by the binary coding of the function $\sin(f_o z) \cos(L z)$

where $\sim_{_-} = \frac{\text{'}\text{'}+\text{'}}{2}$ and $\& = \frac{\text{'}\text{'}J+\text{'}}{2} - \frac{2Z}{A}$ A picture of a grating structure is

given on Figure 5. In the waveguide the two coupled beams interfere and the

intensity signal is proportional to $\sin\left[\frac{4?r}{A}x\right)$. The demonstration was made

with a BK7 K^+-Na^+ ion exchanged waveguide (5 hours at 385 *C), the two

periods of the grating were $\frac{2?r}{f_.} = 4jMZ$ and $\frac{2Z}{f_.} = 0.5@$, 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, The reference signal is given by a CSEM integrated laser diode interferometer [5].

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 sutiace, coated with a thin high index film (here $Ta@_5$) as illustrated in Figure 8. The upper undulation of the Ta_2O_5 layer is phase-shifted relatively to the lower

Figure 7: Interference signal obtained with the double frequency grating coupler measurement system
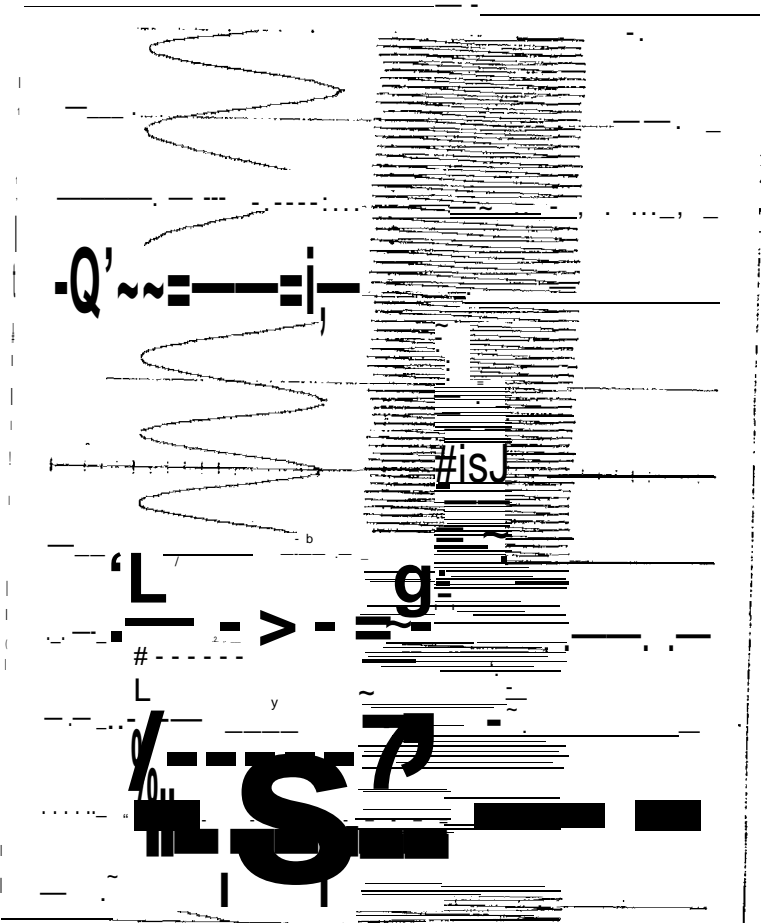
CSEM interferometer sig
(pitch 0.39 μm)

Reading signal obtained w
the grating waveguide opt
head (pitch 4 μm)

DATE: 00_000.00

CH1: 0.50V : 5ms

CH2: 1.00V : 5ms

8: High efficiency phase-shifted   coupler

n

Ta₂O₅ layer

Ion exchanged
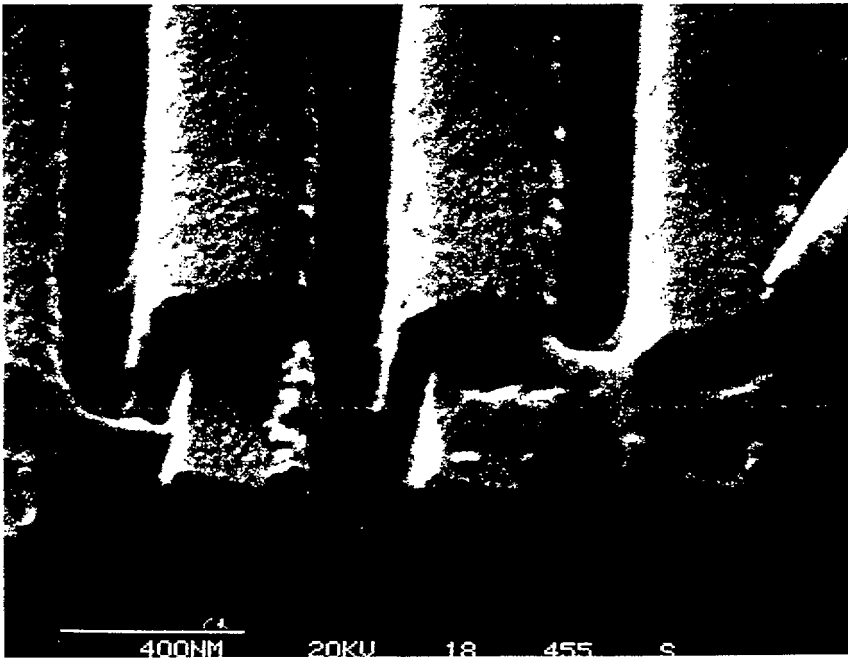waveguide

Glass

Refractive index
profile
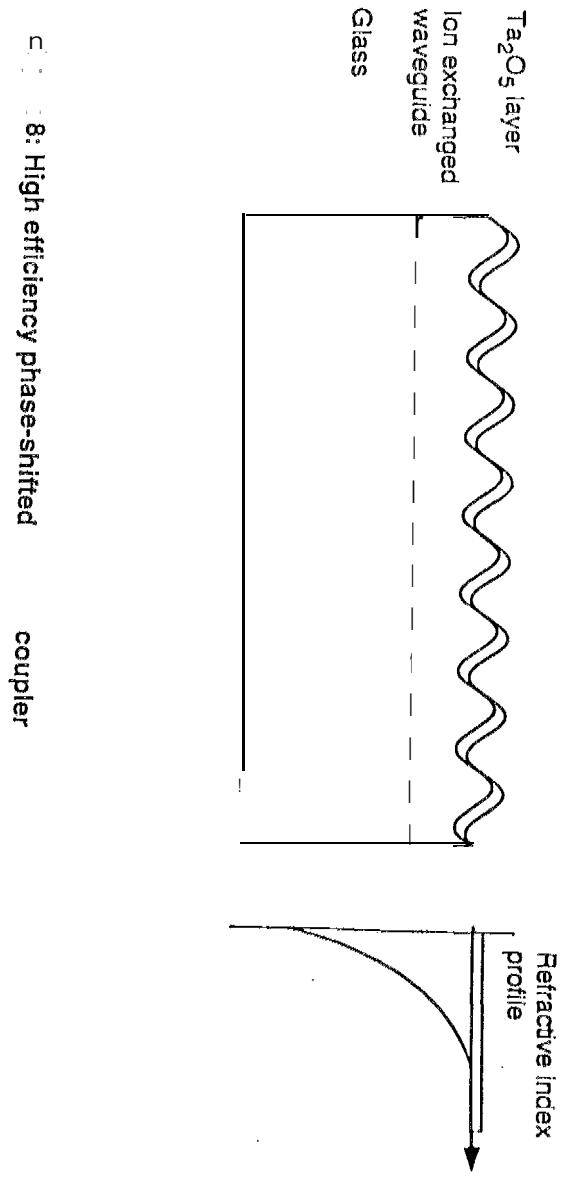
Figure 9: SEM micrograph of the phase-shifted grating cross-section

one which modifies the interference conditions between the two diffractkm spectra into either medium [substrate and air)ᴳ,

Figure & High efficiency phase-shifted grating coupler

A suitable phase-shift will privilege radiation (therefare the uncoupling also) into the air or into the substrate. The phase-shift was created by the deposition of non conformal Ta@$_5$ layer under a 45° angle, For a layer thickness of 70 nrn 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. (hnclusicms

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

& References

ᵀ J.-L. A. Roum:guieres, J. M. Nevi&e, US Patent N" 4.389.094, 1983

ᶻ I+. 'duilliomenet, L. Faico, 0. Pawiaux, M. Nevi&re. *Transfer of submkron period gratings by conventional chromium mask* photollfhography. International Symposium on Integrated Gplics, Lindau, Germany, 1994

³ G. Voirin, P, Sixt, O. Parriaux. Digitized *dua{ frequency .coup/iffg grsting for waveguide displacement Metierm?ehy.* Proceedings CLEO-Europe, Amsterdam 1994, p 339.

⁴ G, Voirin, P. Sixt, 0. Parriaux. *Digitized Dt.#Ffequency W% veguide Coupling giathg iof Sthmkmn Fkscdufh DkplacernenF Encoder.* CSEM scientific and technical reporl 1994

⁵ G. Vokin, L. Fakm, Cl. Boiltat, 0. .Zogmal, P. Regnault, 0. Parriaux. *Monolithic double* interfe,mmeter dispkcemer?f sensor with *wavelength stabikzathx?.* Proceedings ECXO'93, 12-28, European Conference on Integrated Optics, Neuchatel, Switzerland, April 18-22, 1993

⁶ 1. A. A.vrutsky, A. S. Svakhin, 'd. A. Sychqov, Kigh-eti~ciency *single-order waveguide grating coupler. Optics* Letters, Vol. 15, No 24, December 15, 1990

Title

FLAT OPTICAL ANTENNAE

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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 nonguiding 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 anaiyzed 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 physicai point of view this is due to intermode coupling coefficient is very close to O. 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=O. 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 el%cieney 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 resuit 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. paralJelogramic 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 weaklv-cmidina waveauides.

In practice, both TE and TM polarization and strongly-guiding waveguide are often used. Hence we considered gUass-Ta20~-Si(3 ~-water[air) waveguide structure, Parallelogramic grating was formed in the SiU2 layer. V#e 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 coeti~cient begin to saturate at grating depth about !3, 15mkm and weakly depends on the tilt angle. Well-defined "blazing" effect appears at grating depth greater than 0. 1.5mkrm Our caiculatiems shows that with optimum tilt angle it is possible to achieve 78% and 7 Z% 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. [n order to test parallelogramic grating, we fabricate the waveguide structure: glass substrate (n= 1.51), Ta205 waveguide layer (n=2.07, h=200(3A], Si02 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 f ih-n {h=600?t) appeared on the top of the photoresist grating teeth and on one of its slopes. Then the sample was etched under 47° angle with CF4 ions. After etching the remains of the resist and metal were cleaned. in order to excite the waveguide mode by means of prism, SiQ2 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 pianes constituting the grating. We used the computer code to elaborate technology for paralleiogramic grating production in Si02 layer on top of Ta205 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 iosses, which are comparable with diffractive radiation losses. The main obstacle cm 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. 5mkm} 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.

Acknowledgments:

References :

L4.AVRUTSKY, A. S. SVAKHN,V. A. SYCHUGOV,
"interference phenomena in wavecyide with two *mfrifgsted boufdiwies'~

J. of Modern Optics, v.36, N. 10, pp.1 303-1320 (1 989)

MING U, S. J. SHEARD,
 "Waveguide couplers using paralleiogramic-shaped biazed gratings':
Opt. Commun., v. 109, PP.239-245 (1 994)