SCIENTIFIC BULLETIN OF THE LODZ UNIVERSITY OF TECHNOLOGY
No. 1219 Physics, Vol. 38 2017

MAGDALENA MARCINIAK[1,2], MARCIN GĘBSKI[1,2], MACIEJ DEMS[1], TOMASZ CZYSZANOWSKI[1]

[1]Institute of Physics, Lodz University of Technology, ul. Wólczańska 219, 90-924 Łódź, Poland, e-mail: magdalena.marciniak@p.lodz.pl
[2]Institute of Solid State Physics and Center of Nanophotonics, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany

SUBWAVELENGTH HIGH CONTRAST GRATINGS AS OPTICAL SENSING ELEMENTS

Subwavelength high contrast gratings (HCG) can be used as high reflective mirrors and can be used as mirrors of vertical-cavity surface-emitting lasers. HCG mirrors can be designed in such a way that they are extremely sensitive to environmental changes - changes in the refractive index of ambient substance or changes in the absorption coefficient may cause changes in mirror reflectivity. This phenomenon can be used to detect liquids and gases. In this paper we present analysis of HCG properties. We consider the various HCG mirror designs and the possibilities of detecting gases and liquids.

Keywords: Vertical-Cavity Surface-Emitting Lasers (VCSELs), Optical sensors, subwavelength gratings.

1. INTRODUCTION

Subwavelength High Contrast Gratings (HCGs) found many applications in various areas of integrated photonic. They can be used e.g. as focusing lenses and reflectors or high-quality-factor optical resonators [1] but the most promising application for HCG is to use them as the top mirror in Vertical-Cavity Surface-Emitting Lasers (VCSELs) in place of conventionally used Distributed Bragg Reflectors (DBRs) [2-5]. HCGs are diffraction gratings with subwavelength spatial dimensions. They should be made of material with refractive index much higher than surroundings. Properly designed HCGs provide very high (close to unity) power reflectance or transmission in wide range of wavelength. They also provide high discrimination of polarization of incident light. HCGs can be made in different ways: as a grating located on cladding layer (usually made of dielectric) [2], as a membrane suspended in the air [4-7] or as monolithic HCG (MHCG) [8, 9] (see Fig. 1).

HCGs provide very high power reflectance in wide range of wavelength, in general wider than MHCGs. However their construction requires layer of dielectric material or air gap, which is main drawback of HCGs as mirrors in VCSELs. MHCGs can be made of any kind of semiconductor material of refractive index higher than 1.75 [8, 9], but their power reflectance spectrum is narrower, but still comparable with DBR's spectrum. Some constructions of HCGs or MHCGs can be very sensitive to properties of surrounding medium, especially to absorption or refractive index changes. We can use that property to design new type of detectors with HCGs. In this paper we show how sensitive can be HCGs and MHCGs to changes in surrounding medium. Based on numerical calculations we present constructions of HCGs and MHCGs which can be used as optical sensors. We analyse the influence of absorption and refractive index of surrounding for power reflectance and other optical properties of mirror.

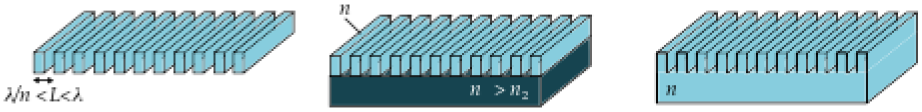

Fig. 1. Different construction of HCG mirrors: membrane suspended in the air (left), grating put on a cladding layer (center) and monolithic HCG (right)

Since now there were proposals to use subwavelenght structures for detection. In [10] authors showed, how to use HCG resonator for liquid sensing. However we propose to employ as a sensor whole VCSEL with HCG mirror, which is new approach.

2. COMPUTER MODEL

For our study we use three dimensional, fully vectorial model. We consider single period with periodic boundary condition. To perform our calculations we employ plane-wave admittance method (PWAM) [11]. PWAM converts the problem of solving the set of differential equations into the problem of finding eigenvalues of a matrix. It solves Maxwell equations with only assumption on planar structure in a frequency domain by using a plane-wave expansion within each layer and computes an analytical solution in the perpendicular direction. Such approach is possible due to transformation of the electromagnetic field to the diagonal coordinates which makes algorithm very time and memory efficient. The boundary conditions can be imposed in the form of the propagating wave in the direction of the analytical solution and as Perfectly Matched Layer (PML) being absorbing condition or periodic boundary condition in the plane of plane-wave expansion.

Agreement between experimental data and our computer model for MHCGs mirror is confirmed in [9].

In this paper, we took into consideration mirrors designed for wavelength $\lambda = 1.651$ µm which corresponds to the peak of methane absorption spectrum [12]. However similar devices can be designed for arbitrary wavelength and find application in many of sensing applications. We perform our calculations for MHCG mirror made of InP and for Si HCG implemented on SiO_2 cladding layer. Materials parameters used in our calculations are set in Table 1.

To describe HCGs or MHCGs we can use following parameters (see Fig. 2): period of the structure L, width of the stripe a, height of the stripe h, thickness of cladding layer h_C and fill factor F, which is the ratio of width of the stripe and period of the structure. To find optimal parameters of the mirror

Table 1

Material parameters used for calculations– values of refractive indices n of different materials for $\lambda = 1.651$ µm

material	InP [13]	Si [14]	SiO2 [15]
n	3.15	3.47	1.46

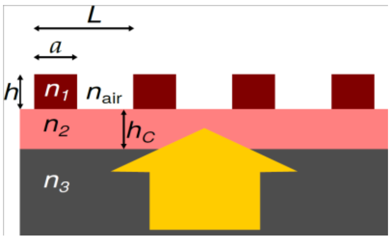

Fig. 2. Schematic structure of HCG mirror; L – period of grating, a – width of stripe, h – high of stripe, h_c – high of cladding layer, n_1, n_2, n_3 – refractive indices of materials, n_{air} – refractive index of surrounding medium. For MHCG mirror $n_1 = n_2 = n_3$

(which provide the highest possible power reflectance) we should consider the power reflectance as a function of spatial parameters of the grating (*L*, *F* and *h*) and perform three dimensional optimization of the power reflectance. In case of sensing elements high power reflectance is not enough. We should find structures for which power reflectance differs significantly for variable external conditions.

3. GAS DETECTION

Presence of gas around the stripes can influence the power reflectance of HCGs and MHCGs. For most of gases refractive index is very close to the unity, which corresponds with refractive index of air. Because of that, it is very hard to detect gases based on refractive index changes. However every gas has very characteristic absorption spectrum, which makes them easy to detect by measurement of absorption coefficient. In this part we would like to show dependence between absorption coefficient of grating surrounding and grating power reflectance.

In Fig. 3 one can see power reflectance maps for MHCGs mirrors for TE and TM polarization. In this figures, we present power reflectance *R* as a function of *L* and *h* for given fill factor *F* for transverse electric (TE) and transverse magnetic (TM) polarization of incident light with wavelength $\lambda = 1.65$ μm. The figures also illustrate difference of power reflectance for absorption coefficient of surroundings equal to $\alpha = 0$ cm^{-1} and $\alpha = 0.05$ cm^{-1}, which is absorption coefficient for 100% methane concentration at $\lambda = 1.65$ μm. We consider MHCGs, based our preliminary studies which shows, that they are much more sensitive to absorption coefficient changes than HCGs. Based on data presented in Fig. 3 we found different structures that provide high power reflectance and high difference of power reflectance for absorption changes at the same time. Parameters of such mirrors are set in Table 2.

Table 2

Parameters of MHCG mirrors which can be used for gas detections

polarization	*L* [nm]	*F*	*h* [nm]	R ($\alpha = 0$)	dR/dα [cm]
TE	977	0.475	2240	$1 - 6\cdot10^{-4}$	$-2.3\cdot10^{-3}$
TM	958	0.693	2441	$1 - 10^{-6}$	$-3.8\cdot10^{-4}$

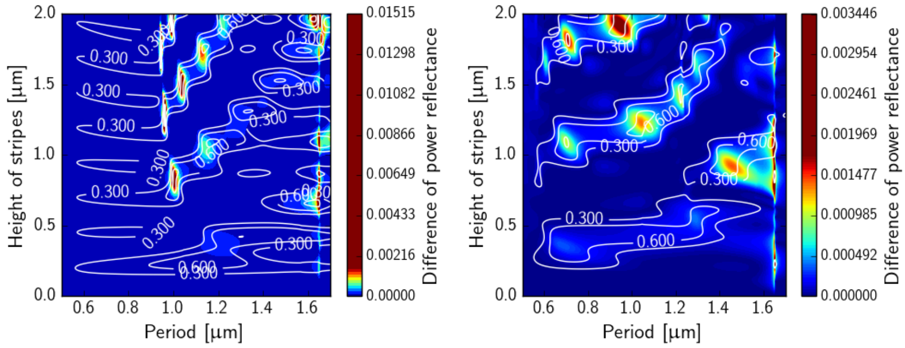

Fig. 3. Difference of power reflectance for absorption coefficient of surroundings equal to $\alpha = 0$ cm^{-1} and $\alpha = 0.05$ cm^{-1} as a function of height of stripes h and period of grating L for fill factor $F = 0.5$ for TE polarization and $F = 0.7$ for TM polarization. The results were obtained for MHCG mirror for TE (left) and TM (right) polarization of incident light with wavelength $\lambda = 1.65$ µm. White solid lines indicate values of power reflectance for $\alpha = 0$ cm^{-1}

4. LIQUID DETECTION

Based on that properties of HCGs and MHCGs, they can be also used for liquid detection. Variable liquids are characterized by different values of refractive index. Refractive index of liquid can strongly depends on external factors, e.g. temperature or chemical composition. Because of that we observe refractive index changes to characterize liquids. Same as the case of gas, presence of liquid between stripes also influences on optical properties of mirror, especially on power reflectance. In Figs. 4 and 5 one can see power reflectance as a function of spatial parameters of HCGs and MHCGs respectively. Figures 4 and 5 illustrate the power reflectance R for TE and TM polarization of incident light with wavelength $\lambda = 1.65$ µm. Figures 4 and 5 also illustrate difference of power reflectance for refractive index of surroundings equal to $n_l = 1.0$ and $n_l = 1.1$, which is hypothetical value not related to any specific liquid. However this range of refractive index changes should be useful for detection.

Based on data presented in Figs. 4 and 5 we found four different structures that provide high power reflectance and high difference of power reflectance for refractive index changes at the same time. Parameters of such mirrors are given in Tables 3 (for HCG mirrors) and 4 (for MHCG mirrors). Changes of the refractive index of surroundings medium influence on the optical field distribution in HCGs and MHCGs, which can be seen in Fig. 6. In this case changes in optical field distribution are more noticeable than in the case of absorption changes.

Table 3

Parameters of HCG mirrors which can be used for liquid detections

polarization	L [nm]	F	h [nm]	R ($\alpha = 0$)	dR/dα [cm]
TE	1616	0.415	1255	$1 - 4 \cdot 10^{-4}$	$-1.55 \cdot 10^{-3}$
TM	1361	0.201	2020	$1 - 10^{-5}$	$-7.48 \cdot 10^{-4}$

Table 4

Parameters of MHCG mirrors which can be used for liquid detections

polarization	L [nm]	F	h [nm]	$\underline{R}$ ($\alpha = 0$)
TE	1515	0.387	2227	$1 - 6 \cdot 10^{-4}$
TM	1114	0.396	838	$1 - 10^{-5}$

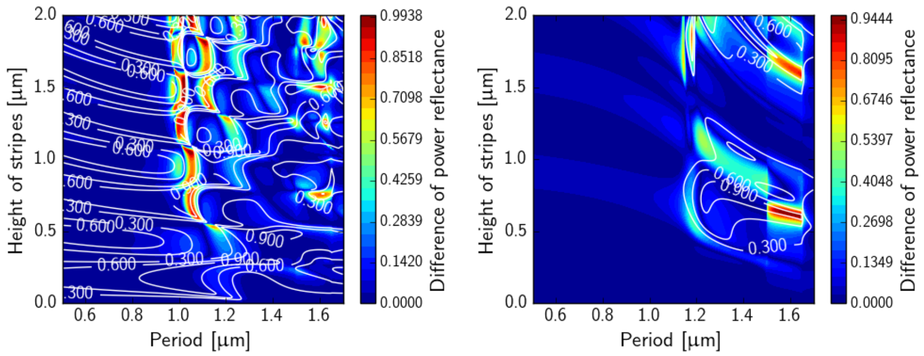

Fig. 4. Difference of power reflectance for refractive index of surroundings equal to $n_l = 1.0$ and $n_l = 1.1$ as a function of height of stripes h and period of grating L for fill factor $F = 0.4$ for TE polarization and $F = 0.2$ for TM polarization. The results were obtained for HCG mirror for TE (left) and TM (right) polarization of incident light with wavelength $\lambda = 1.65$ µm. White solid lines indicate values of power reflectance for $n_l = 1.0$

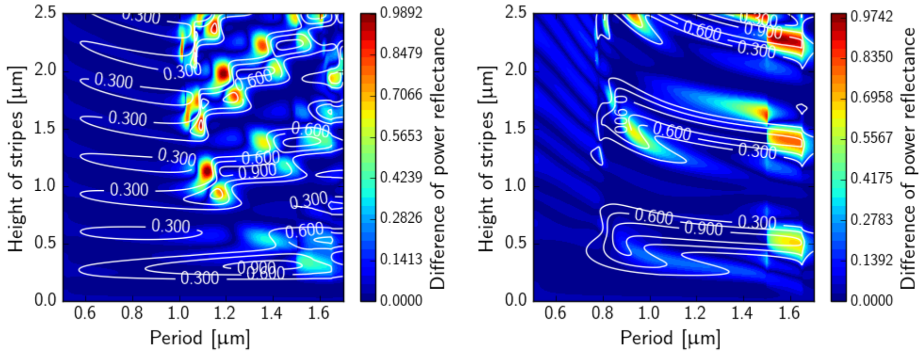

Fig. 5. Difference of power reflectance for refractive index of surroundings equal to $n_l = 1.0$ and $n_l = 1.1$ as a function of height of stripes h and period of grating L for fill factor $F = 0.4$. The results were obtained for MHCG mirror for TE (left) and TM (right) polarization of incident light with wavelength $\lambda = 1.65$ μm. White solid lines indicate values of power reflectance for $n_l = 1.0$

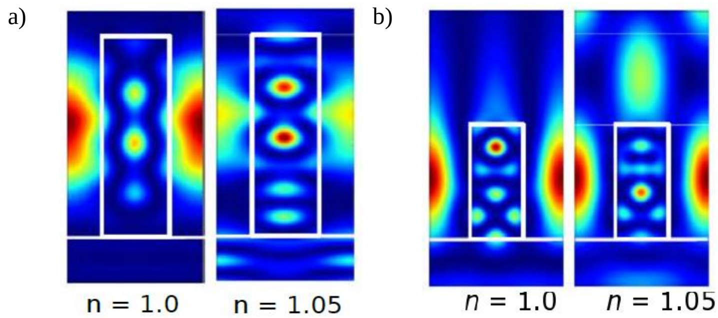

Fig. 6. Optical field distribution in stripes of HCG (a) and MHCG (b) mirrors for TE polarization

5. APPLICATION IN VCSELs

Based on presented results one can notice that HCGs and MHCGs can be very sensitive to changes of surrounding medium. Even small change of absorption or refractive index influence on power reflectance. This phenomena can be used to detect gases or liquids. For that we can employ VCSELs designed for specific wavelength *e.g.* for methane detection we design 1651 nm InP-based VCSEL. The idea of such detectors is following: presence of gas or liquid between stripes influences power reflectance of top mirror and, consequently, the electric properties of VCSELs. By this the voltage-current characteristic is changed. Hence one can deduce information on surrounding of grating by observation of voltage-current characteristic.

One can notice that such devices would be more sensitive for refractive index changes than for absorption coefficient changes, which makes such detectors better for liquid sensing. Such devices can be used not only for liquid detection, but also for studying optical properties of liquids.

The most important advantage of that solution is that one can be able to design detector which requires only one element, which is laser. Usually optical sensing systems employ light source and external detector. In proposed design only the light-emitting device is required.

6. SUMMARY

In conclusion, we presented analysis of properties of HCGs and MHCGs mirrors as sensing elements. We showed that HCGs and MHCGs can be very sensitive to changes of refractive index or absorption of surrounding medium. We performed our analysis based on mirrors designed for 1651 nm wavelength, which corresponds to the maximum of the methane absorption. However HCGs or MHCGs can be designed for another wavelength of incident light [9], which can enable to detect another substances.

REFERENCES

[1] Chang-Hasnain C.J., Yang W. 2012. High-contrast gratings for integrated optoelectronics. Adv. Opt. Photonics 4: 379-440.

[2] Chung I-S. Mork J., Gilet P., Cheikonov A. 2008. Subwavelength grating-mirror VCSEL with a thin oxide gap. IEEE Photon. Technol. Lett. 20: 105-107.

[3] Sciancelepore C., Ben Bakir B., Letartre X., Fedeli J.-M., Olivier N., Bordel D., Seassal C., Rojo-Romeo P., Regreny P., Viktorovitch P. 2011. Quasi-3D light confinement in double photonic crystal reflectors VCSELs for CMOS-compatible integration. IEEE J. Lightwave Technology 29: 2015-2024.

[4] Huang M.C.Y., Zhou Y., Chang-Hasnain C.J. 2007. Surface emitting laser incorporating a high-index-contrast subwavelength grating. Nat. Photonics 1: 119-122.

[5] Chase C., Rao Y., Hoffmann W., Chang-Hasnain C.J. 2010. 1550 nm high contrast grating VCSEL. Opt. Express 18: 15461-15466.

[6] Hashemi E., Bengtsson J., Gustavsson J.S., Carlsson S. 2015. TiO_2 membrane high-contrast grating reflectors for vertical-cavity light-emitters in the visible wavelength regime. J. Vac. Sci. Technol. B33: 050603.

[7] Wu T.S. Wu T.T., Syu Y.C., Wu S.H., Chen W.T., Lu T.C., Wang S.C., Chiang H.P., Tsai D.P. 2012. Sub-wavelength GaN-based membrane high contrast grating reflectors. Opt. Express 20: 20551-20557.
[8] Gębski M., Dems M., Szerling A., Motyka M., Marona L., Kruszka R., Urbańczyk D., Walczakowski M., Pałka N., Wójcik-Jedlińska A., Wang Q.J., Zhang D.H., Bugajski M., Wasiak M., Czyszanowski T. 2015. Monolithic high-index contrast grating: a material independent high-reflectance VCSEL mirror. Opt. Express 23: 11674-11686.
[9] Marciniak M., Gębski M., Dems M., Haglund E., Larsson A., Riaziat M., Lott J.A., Czyszanowski T. 2016. Optimal parameters of monolithic high-contrast grating mirrors. Optics letters. 41: 3495-3498.
[10] Karagodsky V., Tran T., Wu M., Chanh-Hasnain C. 2011. Double-Resonant Enhancement of Surface Enhanced Raman Scattering Using High Contrast Grating Resonators. CLEO: 2011 – Laser Applications to Photonic Applications.
[11] Dems M., Kotyński R., Panajotov K. 2005. Plane Wave Admittance Method – a novel approach for determining the electromagnetic modes in photonic structures. Opt. Express 13: 3196-3207.
[12] Hodgkinson J., Tatam R.P. 2013. Meas. Sci. Technol. Optical gas sensing: a review. 24: 012004.
[13] Pettit G.D., Turner W.J. 1965. Refractive Index of InP. J. App. Phys. 36: 2081.
[14] Li H.H. 1980. Refractive index of silicon and germanium and its wavelength and temperature derivatives. J.Phys. and Chem. Reference data 9: 561.
[15] Gao L., Lemarchand F., Lequime M. 2012. Exploitation of multiple incidences spectrometric measurements for thin film reverse engineering. Opt. Express 20: 15734.

PODFALOWE SIATKI DYFRAKCYJNE O WYSOKIM KONTRAŚCIE WSPÓŁCZYNNIKA ZAŁAMANIA ŚWIATŁA JAKO SENSORY OPTYCZNE

Streszczenie

Zwierciadła HCG to podfalowe siatki dyfrakcyjne wykonane z materiału o wysokim współczynniku załamania światła. Mogą one zostać wykorzystane jako zwierciadła o wysokiej odbijalności w laserach typu VCSEL. Zwierciadła HCG można zaprojektować w taki sposób, że będą wyjątkowo czułe na zmiany współczynnika załamania światła lub współczynnika absorpcji w otoczeniu zwierciadła. Zmiana tych parametrów powoduje zmianę odbijalności zwierciadła HCG. Zjawisko to może być wykorzystane w sensorach optycznych. W niniejszej pracy prezentujemy analizę właściwości zwierciadeł HCG. Rozważamy różne struktury zwierciadeł HCG i pokazujemy, że mogą być one wykorzystane do detekcji gazów i cieczy.