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Waveguide Bragg Grating Filters Made from Optical Polymers

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Abstract:
We report about the planar optical waveguide with a diffraction Bragg grating made in an optical polymer, which exhibits filter function useable for Passive Optical Network Fiber to the Home (PON FTTH) and sensor components. There were designed two topological and technological variants of an optical waveguide grating structures. The distribution of optical field and topological constants of waveguide grating was calculated and simulated by RSoft's BeamPROP and GratingMode programs. The influence of topological parameters of waveguide grating filters like grating groove depth, waveguide layer thickness, length of the grating, etc. on key characteristic properties of the diffraction grating filter including diffraction efficiency, the central reflected wavelength, the bandwidth at 50% of the maximum transmission for guided modes and insertion losses were mainly investigated. Subsequently, structural parameters were optimized with respect to used fabrication methods.

INTRODUCTION

Fine periodic structures known as gratings, which are made on/in planar waveguide structures are widely used as components for construction of optical integrated circuits (OIC) significantly reducing size and cost. Their implementation in the planar waveguide deliver a series of passive elements (e.g. couplers, deflectors, reflectors, filters), thus they are very suitable for integration [1], [2]. A relief type of grating that is created at the interface of waveguide layer as periodic profiling of surface is most important for applications in planar OIC. OICs based on optical-grade polymers exhibits low optical insertion attenuation, low weight by volume, high packaging densities, high impact resistance, environmental stability, cost efficiency. Additionally some optical-grade polymers provides photoresistivity, thus, simplifying manufacturing process even more using lithography, imprinting and laser-writing techniques.

The paper deals with design and properties of grating waveguide structures usable filtering and physical sensing such as temperature, pressure etc.

BASIC THEORY DESCRIPTION

The grating can be described by the change in the relative dielectric permittivity $\Delta\varepsilon$ caused by the grating in the fundamental waveguide structure. $\Delta\varepsilon$ can be written in Fourier series as (1) [3].

$$\Delta\varepsilon(x,y,z) = \sum\nolimits_q \Delta\varepsilon_q(x)\exp(-jq\mathbf{K}\cdot\mathbf{r}) \quad (1)$$

where $\Delta\varepsilon_q$ denotes the amplitude of the q-th Fourier component, $\boldsymbol{K}$ is grating vector that is normal to the grating plane and the magnitude is correlated with period of the grating Λ is expressed by (2).

$$|\mathbf{K}| = K = \frac{2\pi}{\Lambda} \quad (2)$$

If electromagnetic wave strikes grating perpendicular to grating lines (the grating plane) in form of guided mode with intensity of electric field $\mathbf{E}_i(x,z)$ (3) a perturbation polarization $\mathbf{P}$ (x, z) given by (4) is formed which is the source of diffracted waves in described periodic structure [3].

$$\mathbf{E_i}(x,z) = A_i\mathbf{E_i}(x)\exp(-j\beta_i z) \quad (3)$$

where $\mathbf{E}_i(x)$ is depth distribution of the electric field modes, A_i is amplitude of incident wave, β_i *is* propagation vector of incident wave and q is the order of coupling (diffraction).

$$\mathbf{P}(x,z) = \Delta\varepsilon(x,z)\mathbf{E_i}(x) = \\ = A_i\sum_q \Delta\varepsilon_q(x)\mathbf{E_i}(x)\exp[-j(\beta_i + qK)z] \quad (4)$$

As a result the source polarization contains components having propagation constant β_i + qK along the z axis, where q is any integer. This effectively excite only those modes whose propagation constant along the z-axis is close to some of the values β_i + qK as shown in Fig.1, otherwise, the contributions of individual places cancel each other out in destructive interference.

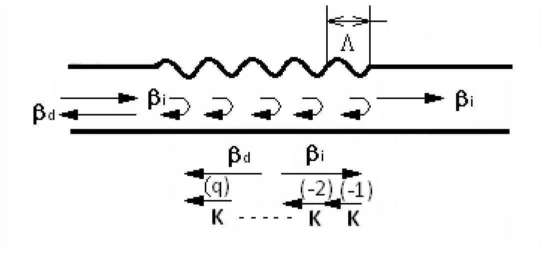

Fig. 1: Constructive interference resulting in diffraction

Hence, from the Coupled-Mode Theory [3]-[5] can be derived that for coupling between two waves, characterized by propagation vectors ***β***, certain relation is required to take place. This relation is known as phase-matching condition (Bragg condition). Phase-matching condition for waveguide Bragg grating is given as (5).

$$\beta_d = \beta_i + qK, \quad q = 0, -1, -2, ... \qquad (5)$$

$$\beta_d = \beta_i = k_0 N \qquad (6)$$

where β_d is propagation vector of diffracted wave, β_i is propagation vector of incident wave, q is the order of coupling (diffraction), k_0 is wavenumber in vacuum, and N is effective index of refraction.

Substituting (2) and (6) into (5), we obtain known formula for the grating period

$$\Lambda = \frac{\lambda}{2N}|q|, \quad q = 0, \pm 1, \pm 2, ... \qquad (7)$$

According to Coupled-Mode Theory, we can obtain the coupled ordinary differential equations. Therefore, we can calculate diffraction efficiency by solving them with boundary conditions for collinear contradirectional coupling. The equations derived via Coupled-Mode Theory are used by utilized simulation engine. The diffraction efficiency for waveguide reflection grating is given under Bragg's condition as (7). The theory is described more complex in [3]-[6].

$$\eta = \tanh^2\left(|\kappa| L\right) \qquad (6)$$

where L is the length of the grating and κ is the coupling coefficient.

DESIGN OF WAVEGUIDE GRATINGS

There were designed two topological and technological variants of an optical waveguide grating. Polymer materials, namely poly (methylmethacrylate) (PMMA) and SU-8 2 Epoxy-Novolak-Resin (ENR) were chosen as base materials of a planar lightwave circuit. Using of polymer materials lead to relatively simple manufacturing process of the waveguide gratings. Furthermore, other advantages of the polymers such as low insertion loss, high packaging densities, environmental stability, simple processing steps and cost efficiency come into play.

The first type of the optical waveguide grating was designed as thin corrugated layer of the PMMA or ENR on a glass substrate with an optical diffused single mode channel waveguide made by ion exchange. Therefore, the optical diffraction grating is part of the "cladding" layer of the diffused waveguide. The designed grating is illustrated in Fig. 2.

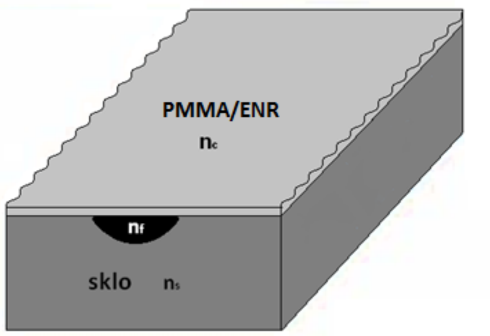

Fig. 2: Polymer grating on the glass diffused waveguide

Properties of a designed single mode optical diffused channel waveguide [7] are presented in Table 1.

Table 1: Parameters of Diffused Channel Waveguide [7]

Parameter	Value
Refractive index of substrate [-]	1.4923
Refractive index change [-]	0.03
Channel width [µm]	4
Diffusion depth [µm]	4

The second designed variant of the waveguide periodic structure uses a spatially profiled optical diffraction grating realized as corrugated ENR ridge single mode waveguide deposit on SiO_2/Si substrate. The designed grating is shown in Fig. 3.

In both cases, the grating profile along the propagation direction was chosen sinusoidal.

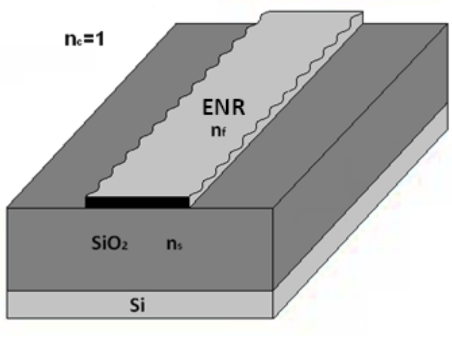

Fig. 3: A corrugated ENR ridge waveguide on SiO_2/Si substrate

MODELLING OF THE DESIGNED WAVEGUIDE GRATINGS

BeamPROP and GratingMOD programs, both part of the RSoft photonic suite, were utilized as simulation engines. Simulations were performed for wavelength λ = 1550 nm. The relative space distribution profiles of the electric intensity field (field distribution profile) in both single mode waveguide with Bragg gratings were calculated. The grating period Λ for the first, and a high order of diffraction (1) were calculated and is presented in Table 2, where n is index of refraction PMMA and ENR polymer for λ = 1550 nm.

Table 2: Calculated grating periods for designed polymer waveguide gratings

Polymer	PMMA	ENR
n	1.477	1.57
N [-]	1.4985	1.5491
$\Lambda_{q=1}$ [μm]	0.517084	0.50033
$\Lambda_{q=2}$ [μm]	1.034168	1.00066
$\Lambda_{q=3}$ [μm]	1.551252	1.50099
$\Lambda_{q=4}$ [μm]	2.068336	2.00132

Design A – ENR

The profile of the transversal fundamental mode for two designed waveguide periodic structures for thickness of ENR "cladding" layer $T = 0.25$ μm, $T = 1$ μm is shown in Fig. 4 and Fig. 5.

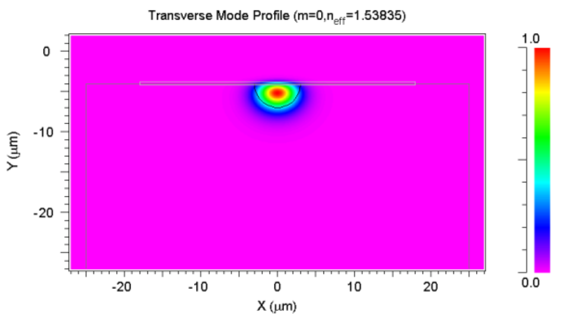

Fig. 4: Simulation of field distribution profile for fundamental mode in designed ENR waveguide grating on the optical diffused channel waveguide

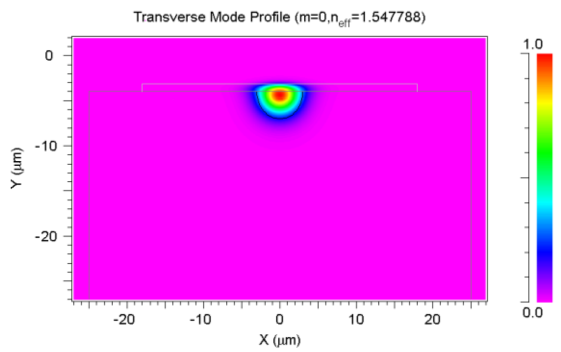

Fig. 5: Simulation of field distribution profile for fundamental mode in designed ENR waveguide grating on the optical diffused channel waveguide

We investigated that very small thickness of the ENR "cladding" layer diminishing diffraction efficiency as depicted in Fig. 6, where thickness is set to 250 nm resulting in diffraction efficiency about 30%.

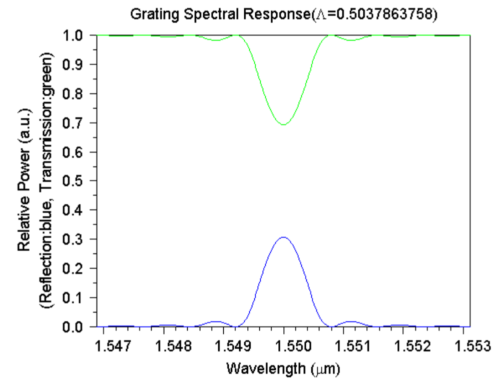

Fig. 6: Simulation of field distribution profile for fundamental mode in designed ENR waveguide grating on the optical diffused channel waveguide

By optimization was recognized that optimal thickness of the ENR "cladding" layer is $T = 1$ μm resulting in 99% relative diffraction efficiency, see Fig. 7. The result of field distribution profile simulations revealed that thickness T of the "cladding" layer covering the optical diffused channel waveguide must not exceed 1 μm to ensure propagation of the radiation in the channel waveguide. The case where thickness was set $T = 3$ μm and radiation is coupling out of the waveguide is shown in Fig. 8.

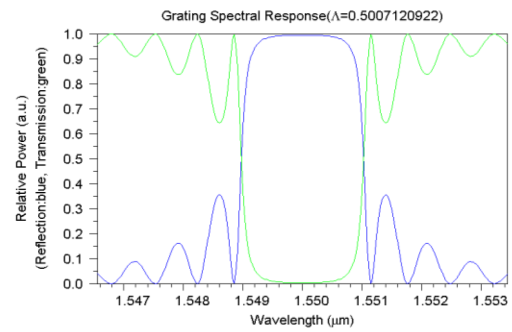

Fig. 7: Simulation of field distribution profile for fundamental mode in designed ENR waveguide grating on the optical diffused channel waveguide

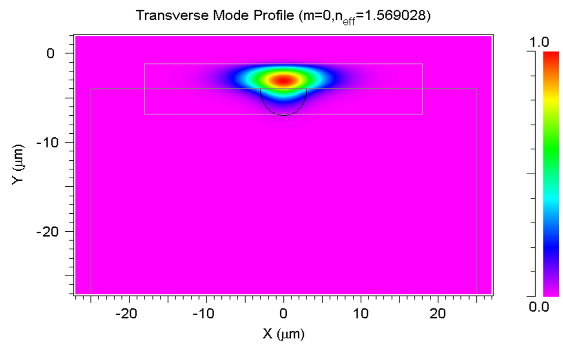

Fig. 8: Simulation of field distribution profile for fundamental mode in designed ENR waveguide grating on the optical diffused channel waveguide – radiation is coupled out from a channel

Design A – PMMA

Using PMMA instead of ENR as the "cladding" layer leads to thickness of about 500 nm to achieve relative diffraction efficiency highest as possible. The lengths of the gratings L were set 1000 µm. The grating periods for the first order of diffraction calculated by (5) are in agreement with values given by the simulation and optimization for pre-set wavelength of 1550 nm. In the both simulated cases relative diffraction efficiency exceeds 90%, which correspond with insertion loss greater than 10dB at the Bragg wavelength.

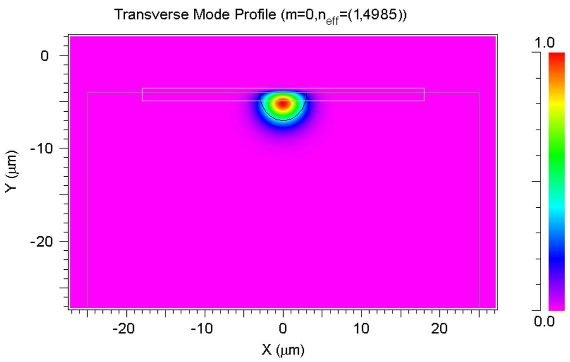

Fig. 9: Simulation of field distribution profile for fundamental mode in designed PMMA waveguide grating on the optical diffused channel waveguide

The maximum of diffraction 0.18 (18%) is reached for the thickness T = 500 nm and modulation depth h = 180 nm (36%). For achieving of the highest diffraction efficiency is necessary to prolong the grating length up to 5000 µm, when relative efficiency reaches 96%. The dependence of diffraction efficiency and Full Width at Half Maximum (FWHM) on the length (L) is showed in Table 3.

Table 2: Calculated diffraction efficiency, L= 1000 µm

T [nm]	h [nm]	η [-]
730	270	0.144
500	180	0.18
400	130	0.15
220	30	0.015

Table 3: Calculated η and FWHM for different lengths of PMMA grating

L [µm]	η [-]	FWHM [pm]
1000	0.18	760
2000	0.52	450
3000	0.66	370
4000	0.77	340
5000	0.96	310

Design B – ENR

The influence of topological parameters of ENR ridge waveguide grating, such as ratio of grating groove depth h to waveguide layer thickness T, length of the grating L, and period of the grating Λ on the key characteristic properties of the diffraction grating filter including diffraction efficiency, central reflected wavelength, full width at half maximum transmission (FWHM) for guided modes and insertion losses were analyzed. The sinusoidal grating profile along the propagation direction was chosen.

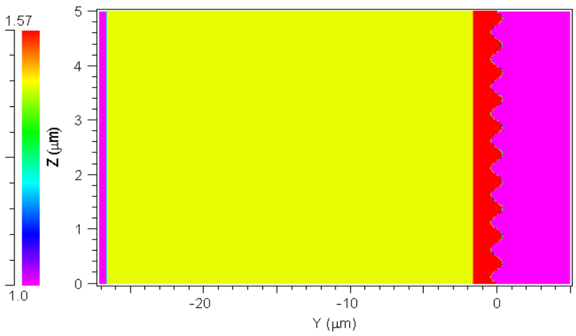

Fig. 10: Cross-section of corrugated ENR ridge waveguide on SiO_2/Si substrate

The default simulation parameters were L = 100 µm, h = 0.4 µm, and T = 2 µm. Effective index of refraction were calculated as $N_{2\mu m}$ = 1.546.

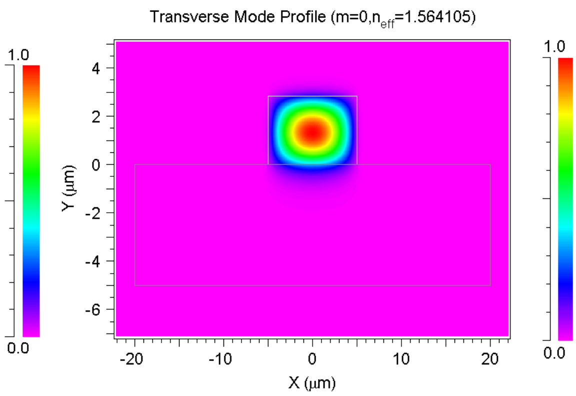

Fig. 11: Simulation of field distribution profile for fundamental mode in corrugated ENR ridge waveguide on SiO_2/Si substrate

The influence of the ratio h/T on the spectral characteristic of the relative diffraction efficiency of the diffraction grating made on ENR ridge waveguide is shown in Fig. 11. The grating period is optimized by simulation software with regard to the set Bragg wavelength. The performed simulations have revealed that the increase of the modulation depth (ratio h/T) causes the increase of diffraction efficiency and FWHM. The ratio h/T should be at least 30% when relative diffraction power reaches 99%.

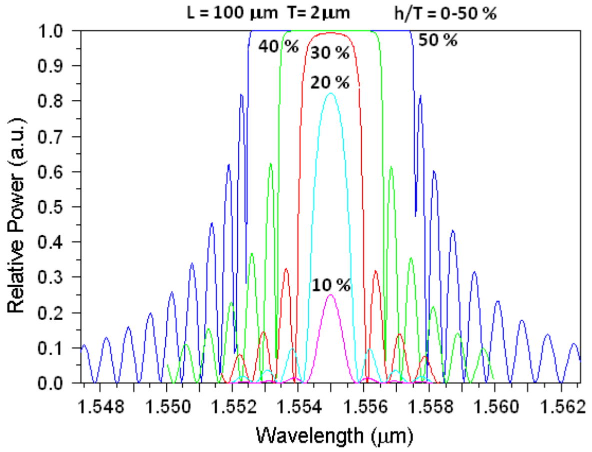

Fig. 12: Simulated spectral dependence of the relative optical power with parameter h/T

The relationship between relative diffraction efficiency and the length of the grating *L* on the ENR ridge waveguide is shown in Fig. 12. The diffraction efficiency increases with increasing length of the grating. The FWHM, however, slightly decreases with the length of the grating.

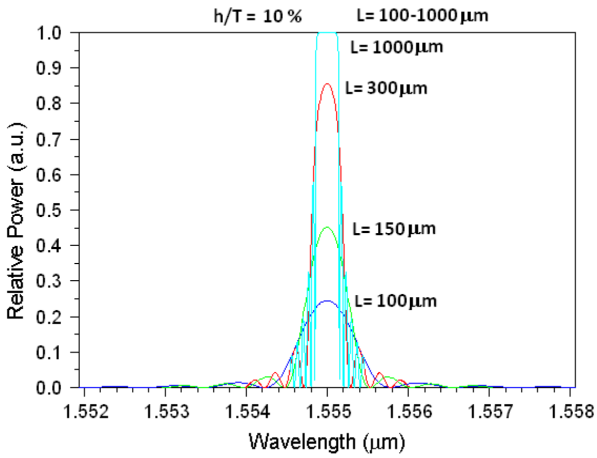

Fig. 13: Simulated spectral dependence of the relative optical power with parameter L

From Fig. 13 is clear that from certain value of length of the grating the efficiency is maximal and further prolongation is not practical and feasible since optical attenuation caused by radiation out of the waveguide grating is directly proportional to it. The grating is directly part of the waveguide, thus, the coupling between guided and reflected mode is much higher than in cladding variant. Consequently, the ten times shorter length and four times smaller groove depth of ENR core grating is required for reaching the same value of relative diffraction efficiency.

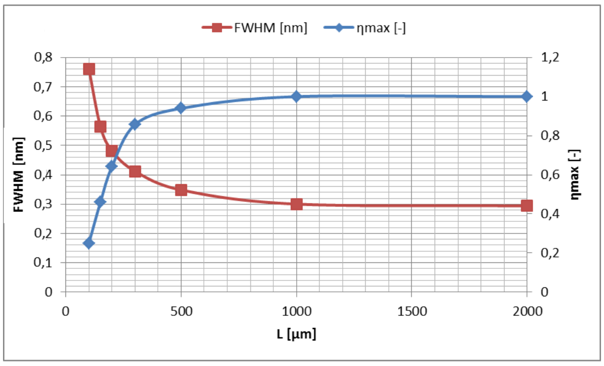

Fig. 14: Simulated spectral dependence of the relative optical power with parameter L

CONCLUSION

The two designed variants of the optical waveguide grating were investigated. Optimal cladding layer thickness, groove depth and minimal grating length were found by performed simulations.

The simulations of spectral dependence of optical power revealed the significant effect of the topological parameters of spatially profiled ridge waveguide on the waveguide filter. The increase of modulation depth caused significant increase of the diffraction efficiency and FWHM. The diffraction efficiency is increased with increasing length of the grating. The FWHM, however, decreases with length of the grating. Thus, suitable ratio of the groove depth to the waveguide layer thickness has been set to archive optimum between the desired selectivity and maximum diffraction efficiency. Grating periods for diffraction at 1550 nm have been calculated.

Current work is focused on fabrication of lattices with optimized parameters given by modeling.

The lattice structures in planar form could be also used in coupling, sensing and plasmonic applications, or function as a base structure for material with meta-material properties.

REFERENCES

[1] Nishihara H., Haruna M, Suhara T.; *Optical integrated circuits*. 1989, pp.46–95 [Chapters 3–4]. ISBN 0-07-046092-2.

[2] Čtyroký, J., Hüttel, I., Schröfel, J., ŠIMÁNKOVÁ L. Integrovaná optika, SNTL, Praha 1986

[3] Kogelnik, H.; Introduction to Integrated Optics, IEEE Transactions on Microwave Theory and Techniques, vol. MT23, issue 1, 1973, pp. 2-16. ISSN: 0018-9480.

[4] Yariv A.; *Coupled-mode theory for guided-wave optics*, IEEE Journal of Quantum Electronics, vol. 9, issue 9, September 1973, pp. 919–933.ISSN: 0018-9197.

[5] Yariv, A., Nakamura, M.; *Periodic structures for integrated optics*, IEEE J. Quantum Electron., QE-13(4):233, April 1977.

[6] Zhang, et al.; *Long Period Grating in/on Planar and Channel Waveguides: A Theory Description*, Optics & Laser Technology, vol. 39, issue 6, September 2007, pp. 1204–1213.

[7] Barkman, O., Jeřábek, V., Prajzler, V.; Optical splitters based on self-imaging effect in multi-mode waveguide made by ion exchange in glass, Radioengineering, vol. 22, issue 1, April 2013