Photonic Wavy Structures for Angular Filtering of Light

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ABSTRACT

In this study, we propose and experimentally demonstrate spatial filtering of light by the photonic wavy structures designed to be operated in a Bragg regime. The proposed configuration is designed, optimized and analyzed by 3D finite-difference time-domain (FDTD) method. Both incidence angle variation and wavelength dependency are examined in detail. The multilayered photonic structure with preselected structural parameters is fabricated by physical vapour deposition on the microstructured substrate. The numerical results as well as experimental measurements of the angle/wavelength transmission of the proposed structure indicate the evidence of the angular filtering based on the selective diffraction of light.

Keywords: Spatial filtering; Photonic crystals; Physical vapour deposition; Glancing angle deposition; FDTD; Surface grating.

1. INTRODUCTION

High spatial quality beams are required in many optical applications due to their focusing ability and robustness to destructive nonlinear effects. The spatial characteristic of the beams from different types of lasers (especially micro-lasers) needs to be improved, i.e. the spatial filtering must be applied either in the laser resonator, or outside. Up to now the spatial filtering approaches involve the use of multilayer stacks combined with a prism [1], metallic grids [2], interference patterns [3], graded index photonic crystals (PhCs) [4], one-dimensional (1D), two-dimensional (2D) PhCs [5] and chirped PhCs [6]. The spatial filtering by PhCs is due to the selective diffraction of light spreading through the double-periodic photonic structures. If the angular components of the incident light are in resonance with the transverse and longitudinal periodicities of the structure, they can be removed from the zero-diffraction order of the transmitted beam. On the other hand, the angular components which are out of the resonance can propagate without being affected by the photonic structure. Thus, by adjusting the suitable geometrical parameters of the PhCs, one can implement the effective spatial filtering [7-9].

In this study, we explain the working principle of PhCs filtering in a Bragg configuration. We performed the finite-difference time-domain (FDTD) calculations to select the preferred geometries. Then, we fabricated the obtained filtering PhCs structure by using physical vapour deposition method and collate the numerical results with the experimental ones.

2. DESIGN AND PRINCIPLE OF SPATIAL FILTERING

The PhCs filters can be designed in Laue or in Bragg diffraction regime. In the Laue regime filtered-out components are deflected to forward direction, and the longitudinal period is substantially larger than the incident wavelength. The intracavity PhC filters in Laue regime were proposed [10,11] and are already being used [12,13] for intracavity spatial filtering in microlasers. On the other hand, in the Bragg regime the filtered-out components are back reflected and it requires the longitudinal period of the structure to be less than the wavelength. In this work we focus on the Bragg regime. The principle of PhC spatial filtering in Bragg regime is shown in Fig. 1(a). For an incident wave propagating at the angle θ_i , the condition for Bragg-diffraction branches from the resonant scattering condition as follows [14]:

$$\left|\vec{k}\right|_{mx,mz} = \frac{m_x^2 q_x^2 + m_z^2 q_z^2}{2m_z q_z \cos(\theta_i) - 2m_x q_x \sin(\theta_i)}.$$

In this equation, $m_x = \cdots, -2, -1, 0, 1, 2, \ldots$ denotes the diffraction orders in the transverse direction, and $m_z = 1, 2, \ldots$ corresponds to the harmonics of longitudinal periodicity, and $q_{x,z} = 2\pi/d_{x,z}$ are the reciprocal lattice vectors.

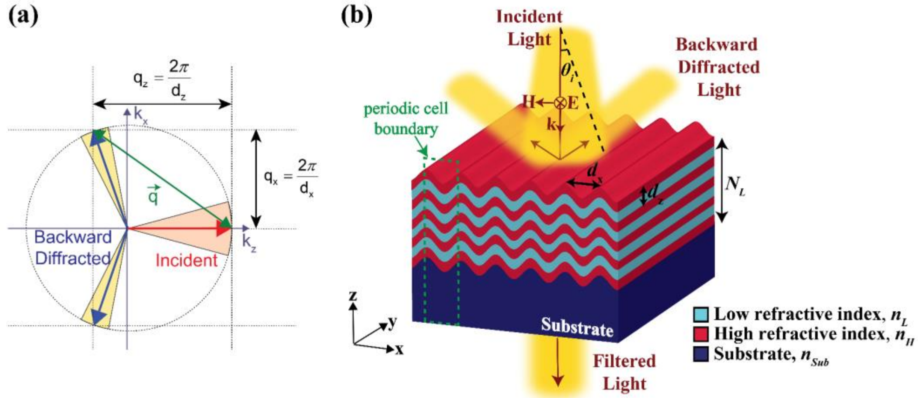

Fig.1. (a) Illustration of the PhC angular filtering in Bragg configurations. (b) Three-dimensional representation of designed PhC spatial filter geometry.

For spatial filtering, the structure must have refractive index modulation in both longitudinal and transverse directions. In this study, the utilized PhCs structure consists of alternating multilayers on a substrate where the interfaces of the layers are modified as a periodic array of sinusoidal wavy curves, as shown in Fig. 1(b). Due to the wavy layers, the modulation of the effective refractive index occurs not only in vertical but also in horizontal direction. Hence, the proposed structure can be classified as 2D PhCs structure. Here, the refractive indices of the substrate (Sub), high (H) and low (L) index layers are adjusted as $n_{Sub}=1.50$, $n_H=1.42$ and $n_L=1.33$, respectively. It should be noted that, one longitudinal period consists of two layers and it is equal to d_z=240 nm. The transverse period is d_x =1.67 μm and number of layers is $N_L=33$.

3. NUMERICAL AND EXPERIMENTAL RESULTS

For the numerical analysis the commercial FDTD software was used [15]. Since the proposed structure is periodic in the *x*-direction, numerical analysis is carried out by using the supercell approach where the corresponding boundaries are given in Fig. 1(b) as a dashed green frame. Here, the Maxwell's equations are solved by infinitely repeating the defined periodical supercell in the *x*-direction by employing the FDTD method. Angular filtering property is examined by measuring the zero-order transmissions in the range of the wavelengths between 450 nm and 850 nm under the *P*-polarized and the range of oblique incident plane wave illumination angles ($-40° < \theta_i < 40°$). The obtained zero-order angular transmittance profile is given as a map in Fig. 2(a).

The fabricated structure starts from a blazed surface grating and develops an almost sinusoidal character towards the outer layers. Hence, the final structure results as a combination of both blazed and sinusoidal modulated wavy layers which we denote it as blazed-rounded structure. Considering the fabrication process, a blazed-rounded structure is also analyzed, the transmission map of which is given in Fig. 2(b).

Based upon the given maps, the designed structure was fabricated by physical vapour deposition method (see Ref. [14] for details). Glancing angle deposition (GLAD) technology was used in all evaporation processes to acquire necessary variation of refractive indexes for individual layers [16]. The experimental measurement of zero-order angular transmittance profile is given in Fig. 2(c). When the general trend is compared with the numerical results, we see the similarity to sinusoidal wavy structures transmittance and asymmetry induced by the blazed-rounded profile.

Furthermore, for all cases, cross-sectional profiles are plotted at λ = 582 nm and the results are given for sinusoidal, blazed-rounded and compared with real measurements of fabricated structures in Figs. 2(d), 2(e) and 2(f), respectively. It is evident that the transmission efficiencies at zero incidence angle decreases when the symetry of the structure is broken. However, the filtering bands are presented for angles at θ_i = -10° and 10° in all cases. One should note that, for the blazed-rounded and fabricated structure, there is an asymmetric behavior between positive and negative incident angles, as expected. For the interpretation of the FDTD results, the analytical Bragg-diffraction branches, the Eq. 1, were calculated and superimposed with transmission maps (dashed lines) showing a good agreement with the numerical and experimental results.

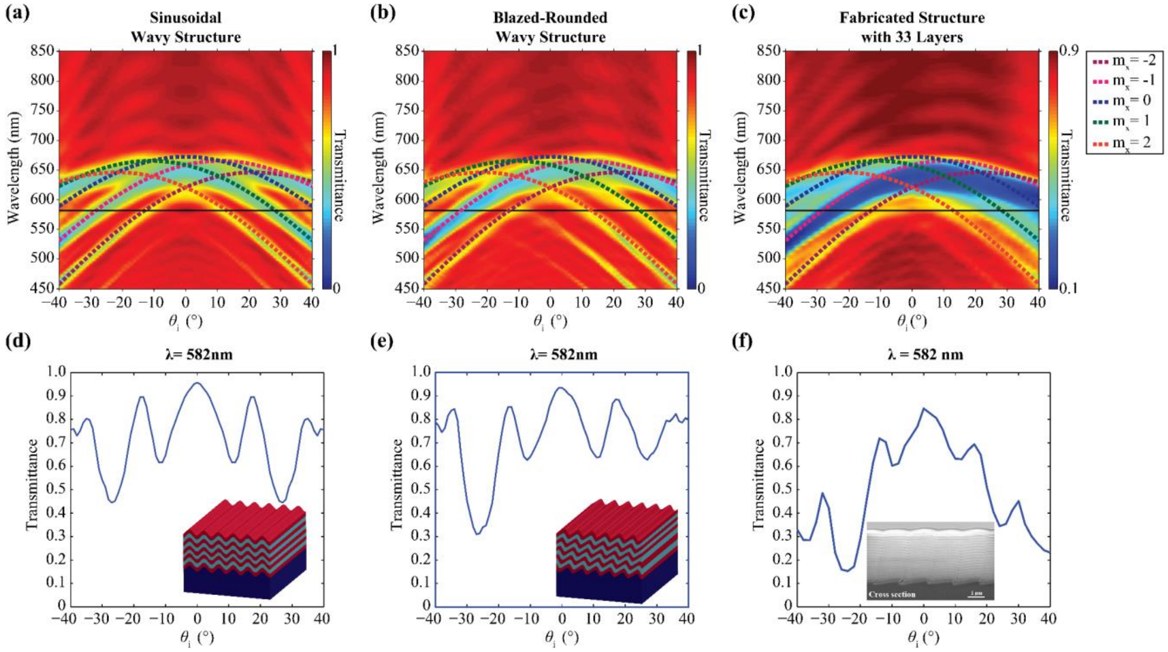

Fig.2. Zero-order transmittance maps for structures with d_z = 240 nm and d_x = 1.67 μm for (a) sinusoidal, (b) blazed-rounded wavy layered structures. (c) Measured zero-order transmittance map for the fabricated structure. Dashed lines indicate the analytically calculated Bragg-diffraction branches. Cross-sectional profiles at the wavelength λ = 582 nm (see black solid lines) for (d) sinusoidal, (e) blazed-rounded wavy layered and (f) fabricated structures. Schematically representations of the sinusoidal and blazed wavy layered structures and the SEM image of fabricated PhC structure are given as insets in the cross-sectional figure plots.

To show the potential of the spatial filtering performance of the multilayered wavy structure, we calculated it using parameters that are more complicated to accomplish with standard technological setups: the smaller periods of the structure, and higher contrast of low and high refractive indices. In this regard, to show the effect of the transverse period d_x, we performed FDTD simulations for wavy structure by adjusting d_x as 835 nm and keeping the other structural parameters same as in Section 2. The zero-order transmittance angular filtering characteristic of the structure is given in Fig. 3(a). Besides, the cross sectional profiles are calculated for selected wavelengths (denoted by black solid lines) and presented in Fig. 3(b). The cross section profiles, as comparied with the profiles in Fig. 2, show that the low-pass transmittance peak becomes sharper and the filtering bands extend beyond the incidence angles $|\theta_i| > 10°$.

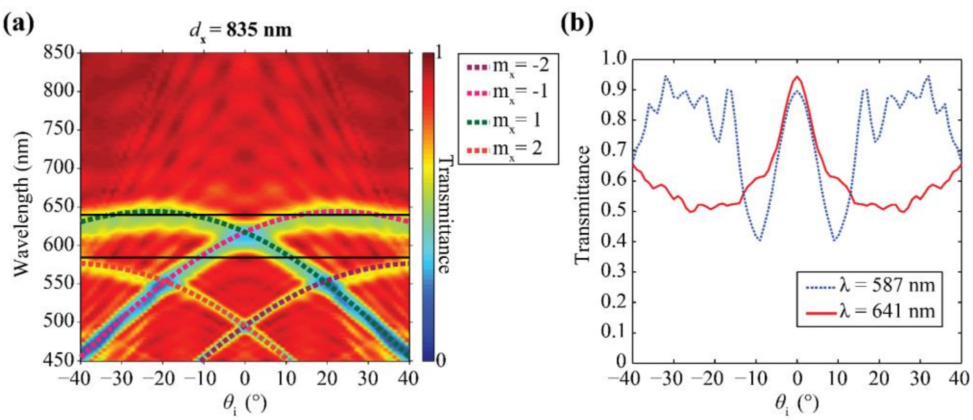

Figure 3. (a) Zero-order angular transmittance map for λ, when d_x = 835 nm.(b) Cross-sectional profiles at the wavelengths λ = 587 nm a λ = 641 nm. Dashed lines indicate the analytical dependences, Eq. (1).

4. CONCLUSION

In this study, we propose photonic multi-layered wavy microstructure for spatial filtering of light in the Bragg regime. The proposed configuration is analyzed by 3D FDTD simulations and fabricated by physical vapour deposition method. Based on the numerical results and the obtained measurements of the fabricated structure, the potential of the proposed structure for angular filtering is obvious. In addition, to show the potential of the proposed structure, we present the calculations using the structures beyond the technological fabrication possibilities currently available by us. In this regard, the obtained results show that the developed idea for spatial filtering has a bright perspective and potential for practical applications in the field of optics and photonics. The presented approach for spatial filtering is highly feasible and practical. Moreover, the proposed design can be implemented as a coating to any surface that demonstrates its high suitability to complex microlaser systems.

ACKNOWLEDGMENT

The study is supported by the EUROSTARS Project E!10524 HIP-Lasers, Spanish Ministerio de Ciencia e Innovación, and European Union FEDER through project FIS2015-65998-C2-1-P, also from "FOKRILAS" (Project No. P-MIP-17-190) from Research Council of Lithuania. Authors are grateful to dr. Algirdas Selskis from State research institute Center for Physical Sciences and Technology for SEM measurements.

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