Diffraction Properties and Application of 3D Polymer Woodpile Photonic Crystal Structure

Petra URBANCOVA[1], *Dusan PUDIS*[1], *Matej GORAUS*[1], *Lubos SUSLIK*[1], *Beata SCIANA*[2], *Wojciech DAWIDOWSKI*[2], *Jaroslav KOVAC*[3], *Jaroslava SKRINIAROVA*[3]

[1]Department of Physics, Faculty of Electrical Engineering and Information Technology, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovak Republic
[2]Department of Microelectronics and Nanotechnology, Faculty of Microsystem Electronics and Photonics, Wroclaw University of Science and Technology, Janiszewskiego Street 11/17, 50-372 Wroclaw, Poland
[3]Institute of Electronics and Photonics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovicova 3, 812 19 Bratislava, Slovak Republic

urbancova@fyzika.uniza.sk, pudis@fyzika.uniza.sk, goraus@fyzika.uniza.sk, suslik@fyzika.uniza.sk, beata.sciana@pwr.edu.pl, wojciech.dawidowski@pwr.edu.pl, jaroslav_kovac@stuba.sk, jaroslava.skriniarova@stuba.sk

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Abstract. *We present a new technique for modification of diffraction and optical properties of photonic devices by surface application of polymer Three-Dimensional (3D) woodpile Photonic Crystal (PhC) structure. Woodpile structure based on IP-Dip polymer was designed and fabricated by Direct Laser Writing (DLW) lithography method based on nonlinear Two-Photon Absorption (TPA). At first, we investigated diffraction properties of woodpile structure with a period of 2 μm. The structure was placed on a glass substrate, and diffraction patterns were measured using laser sources with different wavelengths. After diffraction properties investigation, the fabricated structures were used in optoelectronic devices by their surface application. Our polymer 3D PhC woodpile structures were used for radiation properties modification of light emitting devices - optical fiber and Light Emitting Diode (LED) and for angular photoresponse modification of InGaAsN-based photodiode. The modification of the far-field radiation patterns of optical fiber and LED and spatial modulation of light coupling into photodiode chip with applied structures were measured by goniophotometer. Quality of fabricated structures was analyzed by a Scanning Electron Microscope (SEM).*

Keywords

Diffraction, Photonic Crystal, woodpile structure.

1. Introduction

Photonic Crystals (PhCs) became important structures for light manipulation. These structures have unique optical properties and application possibilities in many photonic devices [1]. PhCs have been intensively studied for use in a wide range of technologies, such as semiconductors lasers, optical integrated circuits, solar cells, sensors, Light Emitting Diodes (LEDs), optical fibers and telecommunication [2] and [3]. Ultimate control of light is possible by creating Three-Dimensional (3D) PhC structures, which were successfully used in active and passive optic and optoelectronic devices [4]. 3D PhCs could find application as diffractive optical elements for light emission enhancement and radiation pattern modification. Similar to x-ray scattering on solid-state crystals, the PhCs will lead to displaying distinct Bragg peaks upon illumination with light appearing at definite angular positions with respect to the incident beam. Under these conditions, diffraction angles and peak intensities are simple functions of the crystallographic structure of the PhC [5].

For our 3D diffractive photonic element, we chose the woodpile PhC structure, which was in detail described and successfully used for controlling of light emission of LEDs, for particle accelerator applications and for 3D guiding of light in waveguides [6] and [7].

Recently we published results about modification of the far-field radiation pattern of the optical fiber by 3D IP-Dip polymer-based woodpile PhC structure with a period of 4 μm and radiation properties modification of LED by surface application of siloxane membrane with the same woodpile structures on LED chip [8]. In our next investigation, the goal was to decrease the period of the 3D PhC woodpile structure for enhancement of diffraction effect. We decided to fabricate woodpile structure with a horizontal period of 2 μm considering the resolution limit of used fabrication technology as well as exposure and developing process.

In this paper, we present the design and fabrication of 3D PhC woodpile structures with a period of 2 μm fabricated in IP Dip polymer. For fabrication of woodpile structures, a commercial Direct Laser Writing (DLW) system Photonic Professional GT from Nanoscribe GmbH with polymerization of IP Dip polymer by nonlinear Two-Photon Absorption (TPA) was used. After fabrication process, the diffraction properties of woodpile structures were investigated using a monochromatic laser and LED sources with different wavelength. Woodpile structures were used for radiation properties modification of light emitting devices (optical fiber and LED) and for angular photoresponse modification of photodiode. Modification of the far-field radiation patterns of optical fiber and LED and coupling enhancement of photodiode were measured by goniophotometer.

2. Design and Fabrication of Woodpile Structure

The woodpile structure is a diamond-like structure formed by a stack of alternating layers of parallel dielectric columns with a rectangular profile. It is characterized by the horizontal period a and vertical period c. The woodpile is a four-layer sequence, in which the third and the fourth layers are shifted by $\frac{a}{2}$ relative to the first two layers. Dielectric columns with width w and height $h = \frac{c}{4}$ are generally arranged in body-centered tetragonal (bct) lattice. At two values of the constant c, the symmetry of structure becomes cubical. For $c = a$, it corresponds to a body-centered cubic (bcc) lattice and for $c = a\sqrt{2}$ to a face-centered cubic (fcc) lattice [4] and [9]. The arrangement of woodpile layers in a diamond-like structure is shown in Fig. 1.

We designed woodpile structure of fcc lattice with parameters: $a = 2$ μm, $c = 2.828$ μm, $w = 0.707$ μm and $h = 0.707$ μm. For the application of prepared structures at the output aperture of the optical fiber with a core diameter of 105 μm and on the LED and photodiode chips with a diameter of 100 μm, we designed woodpile structure of a cylinder shape with a circular base of a diameter of 125 μm.

For fabrication of 3D woodpile structure, we used the commercial DLW system Photonic Professional GT from Nanoscribe GmbH. The radiation source of this system is Er-doped femtosecond fiber laser with the central wavelength of 780 nm, pulse duration of 100 fs and pulse frequency of 80 MHz. In the case of our DLW system with objective lens with a high numerical aperture (NA = 1.4) and a magnification 63×, the voxel sizes are of 200 nm horizontally and 500 nm vertically. As a photosensitive material, the IP-Dip polymer with refractive index $n = 1.52$ at wavelength 1550 nm was used [10]. The laser writing process was provided by exposure of the IP-Dip photoresist applied on a glass substrate with scanning speed 10^4 μm·s^{-1} and laser power 25 mW. We worked at Dip in Laser Lithography (DiLL) configuration, where the microscope objective is directly immersed in liquid IP-Dip photoresist. After fabrication process, the sample was developed in PGMEA (Propylene Glycol Monomethyl Ether Acetate) developer and rinsed in isopropyl alcohol. Quality of fabricated structure was analyzed by a Scanning Electron Microscope (SEM). In Fig. 2(a) and Fig. 2(b), there are shown SEM images of prepared low contrast refractive index (1.52/1) 3D PhC woodpile structure.

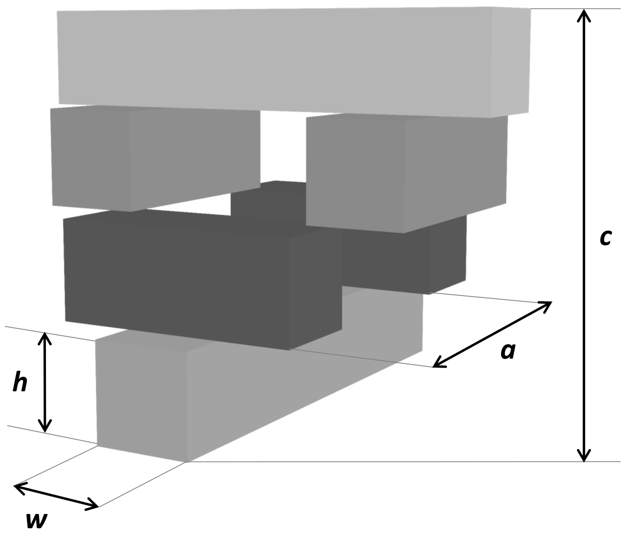
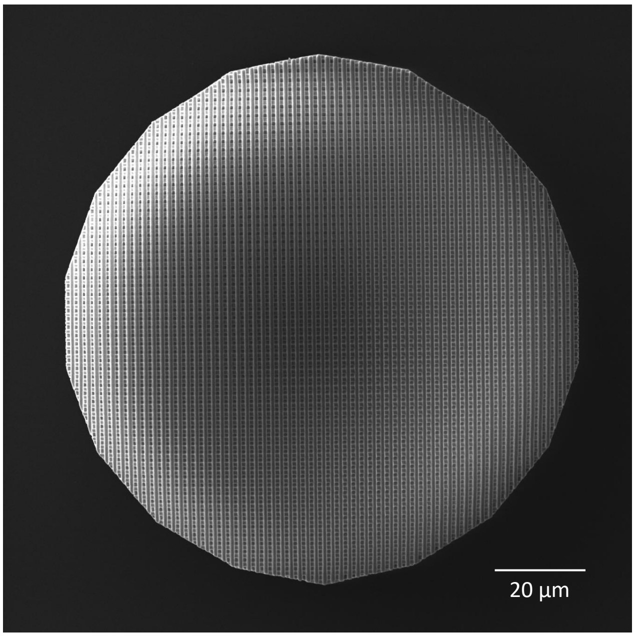


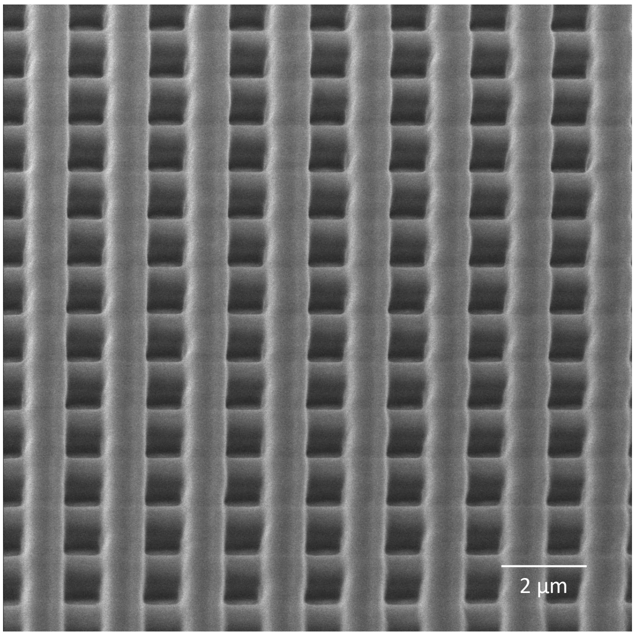
Fig. 1: The four-layer sequence arrangement of diamond-like woodpile structure [4].

3. Diffraction Properties

In this experiment, optical diffraction by woodpile structures was experimentally studied. We measured diffraction pattern of prepared 3D PhC structure using laser sources with different wavelengths. A glass substrate with woodpile structure was placed in a holder in the laser beam. Laser radiation in <001> direction was diffracted on the woodpile structure. We observed Laue diffraction in two dimensions, which is characteristic for low-frequency PhC structures fabricated by 3D laser lithography. The Laue diffraction pattern consists



(a) Fabricated woodpile structure of a cylinder shape.

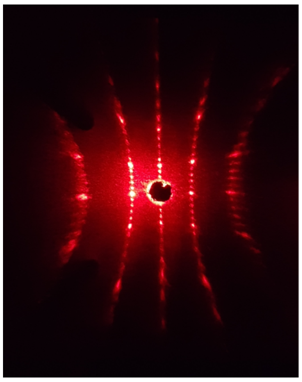


(b) Detail of woodpile structure with well separated dielectric columns by air gaps.

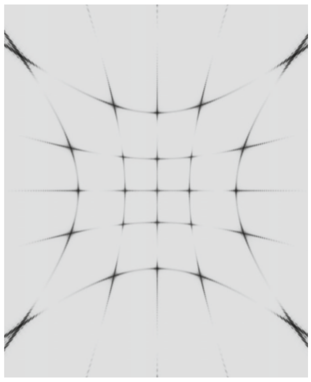
Fig. 2: SEM images of 3D PhC woodpile structure with a horizontal period $a = 2$ µm.

of intersecting straight lines and arcs with bright spots (diffraction maxima) at the points of intersection. Such a pattern gives evidence that the sample thickness is insufficient for the effective Bragg diffraction, in which well-separated diffraction maxima are observed [5] and [11].

Figure 3(a) shows the diffraction pattern of woodpile structure with the period $a = 2$ µm measured using a monochromatic laser with a wavelength of 635 nm,



(a)



(b)

Fig. 3: (a) Laue diffraction pattern of 3D PhC woodpile structure with period $a = 2$ µm, irradiated by a monochromatic laser light with a wavelength $\lambda = 635$ nm. (b) Calculated diffraction pattern of woodpile structure with period $a = 2$ µm, irradiated by a monochromatic laser light with a wavelength $\lambda = 633$ nm [11].

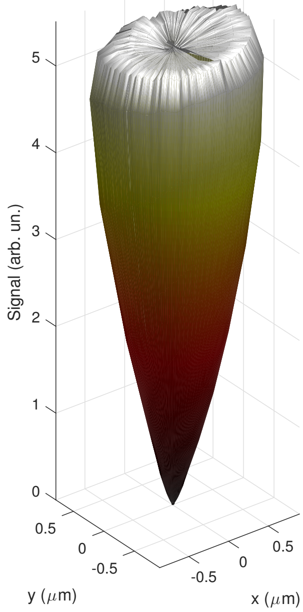
which was compared with the theoretical diffraction pattern in Fig. 3(b) [11]. The position of diffraction maxima shown in Fig. 3(a) indicates the square plane symmetry of the woodpile structure.

4. Application of Woodpile Structure in Photonic Devices

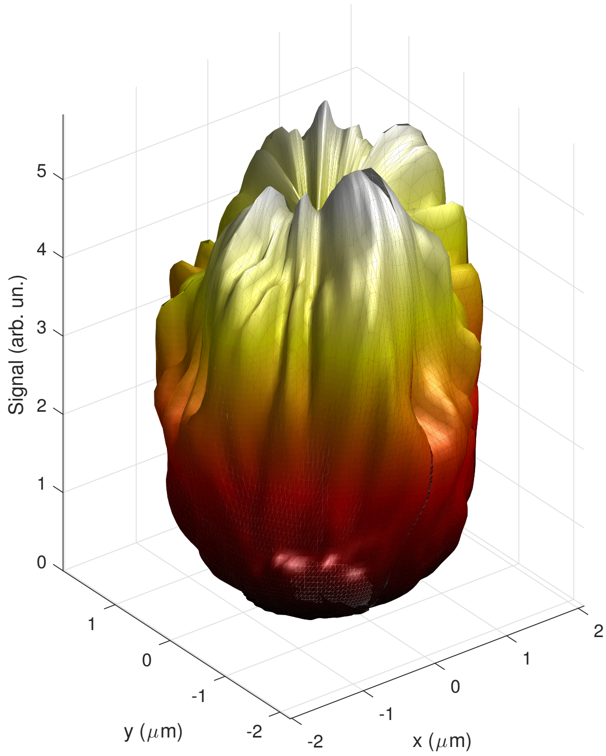
After diffraction analysis, the woodpile structures were applied at different photonic devices. Our goal was to modify radiation properties of light emitting devices (multi-mode optical fiber and LED) and photoresponse of a photodiode.

4.1. Optical Fiber Application

We investigated the radiation pattern modification of multi-mode optical fiber with applied 3D PhC woodpile structure at the output aperture. The angular diffraction was measured by goniophotometer. The woodpile structure was directly applied at the output of optical fiber coupled to the different LED sources, and far-field radiation patterns were measured as spatial angular distribution of optical field with resolution 2°. Figure 4(a) shows reference far-field radiation pattern of the optical fiber with applied smooth reference cylinder IP-Dip structure, which shows typical cone shape caused by a numerical aperture of the multi-mode optical fiber (NA = 0.22). Figure 4(b) shows the far-field radiation pattern of modified optical fiber with applied woodpile structure at the output aperture. Both radiation patterns were obtained using LED with central emission at $\lambda = 625$ nm. The significant diffraction extremes are caused by efficient scattering on 3D PhC woodpile structure.



(a)



(b)

Fig. 4: (a) Reference radiation pattern of multi-mode optical fiber with applied smooth cylinder IP-Dip structure measured using LED with a central wavelength of 625 nm. (b) Modified far-field radiation pattern of multi-mode optical fiber with applied 3D PhC woodpile structure measured at wavelength $\lambda = 625$ nm.

The radiation pattern of modified optical fiber shows strong diffraction efficiency of the woodpile structure. The position of diffraction extremes was more studied at <110> cross-section of radiation patterns.

In Fig. 5, there is shown a cross-sectional view of far-field radiation patterns measured using LEDs with wavelengths 490 nm, 625 nm and 940 nm compared to a far-field radiation pattern of reference cylinder structure. In cross-section of radiation patterns, we can see the different shape of the optical field measured at different wavelengths. It was caused by the position of diffraction extremes at different angles relative to the used wavelength of fiber-coupled LEDs. The significant diffraction extremes are caused by scattering on crystallographic structure of the 3D woodpile PhC. Presented results document well woodpile capability for light coupling to optical fibers at greater angles.

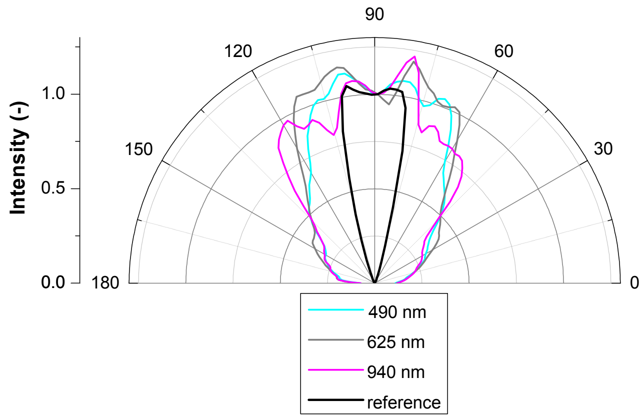


Fig. 5: <110> cross-section of far-field radiation patterns of modified multi-mode optical fiber by a 3D PhC woodpile structure with period of 2 µm measured at stated wavelengths.

4.2. LED Application

The prepared 3D PhC woodpile structure was applied on the surface of GaAs/AlGaAs based LED emitting at 850 nm. The confocal microscope image of LED chip with applied 3D PhC woodpile structure is shown in Fig. 6.

After surface application on the LED chip, we investigated the modification of radiation properties. Far-field radiation pattern of woodpile structure applied on the LED chip was measured by 3D distribution of optical field at full range of azimuthal and elevation angles. The far-field radiation pattern with resolution 5° was measured using goniophotometer with Si detector placed above the LED chip surface. We compared reference radiation pattern of reference clear LED chip with modified LED chip. The comparison of far-field radiation patterns is shown in Fig. 7. The red dashed line document reference radiation pattern of clear LED

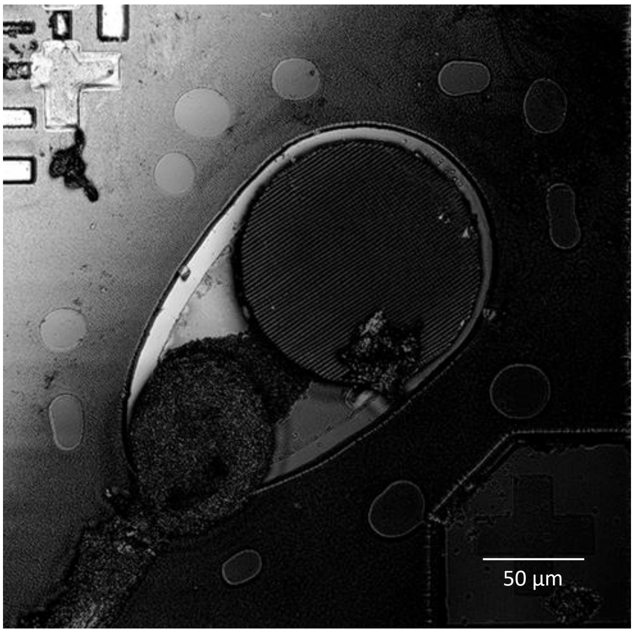


Fig. 6: Confocal image of GaAs/AlGaAs based LED with applied 3D PhC woodpile structure at surface.

chip, which corresponds to a typical Lambertian pattern of the LED. Black line shows the radiation pattern of modified LED chip with applied 3D PhC woodpile structure. In the diagram of modified LED chip, we can see significant local diffraction extremes, which are caused by high diffraction efficiency of 3D PhC woodpile structure corresponding to the diffraction orders at defined direction. Extremes at large angles over 75 degrees correspond to the diffraction caused by an edge emission on MESA contacts.

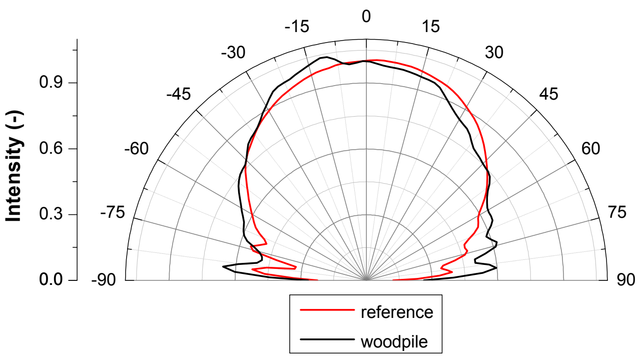


Fig. 7: The comparison of reference radiation pattern of clear LED chip and modified LED chip with applied 3D PhC woodpile structure.

4.3. Photodiode Application

For the application of 3D PhC woodpile structure on the photodiode chip, the GaAs-based photodiode with InGaAsN active region was used. The woodpile structure was applied on the photodiode surface, and effect on light coupling in photodiode was investigated. In Fig. 8, there is shown a confocal microscope image of a photodiode chip with applied 3D PhC woodpile structure.

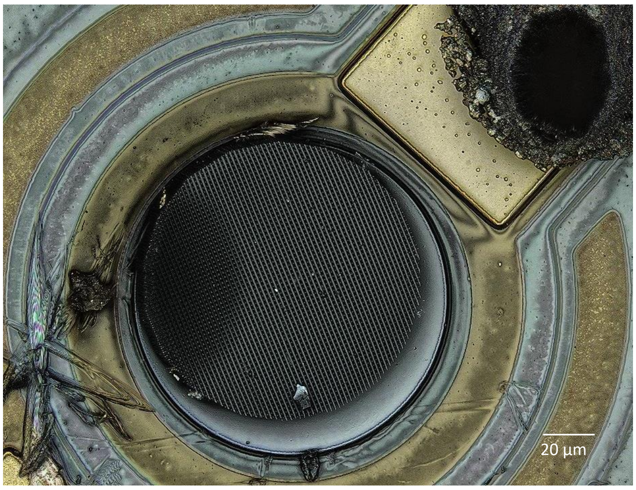


Fig. 8: Confocal image of InGaAsN-based photodiode with applied 3D PhC woodpile structure at surface.

Photoresponse angular diagrams of photodiode with applied 3D woodpile structure was measured by goniophotometer using the irradiating the photodiode chip by multi-mode optical fiber from 6 cm distance at different angles. Measurement was performed by irradiation photodiode chip in vertical plane by rotation of optical fiber around the photodiode chip with 5° resolution. Two different directions with respect to the woodpile structure were measured: i) in normal direction to the surface dielectric columns and ii) in diagonal direction. As a light source, the LED with a wavelength of 530 nm coupled to the optical fiber was used. In measured angular photoresponse, the diagrams show evident angularly distributed maxima given by light diffraction on woodpile structure. Comparison of photocurrent distribution of modified photodiode with reference clear photodiode is shown in Fig. 9. There are shown two important directions with respect to the woodpile structure orientation. The character of photoresponse angular pattern of photodiode is caused by diffraction effect of the woodpile structure.

5. Conclusion

In this paper, we presented the modification of optical properties of multi-mode optical fiber and InGaAsN-based photodiode with applied polymer-based 3D PhC woodpile structure. Prepared polymer woodpile structure shows very strong diffraction efficiency. It is a result of a structure period $a = 2$ μm and refractive index contrast of IP-Dip polymer dielectric columns and surrounding air (1.52/1). The effect of woodpile

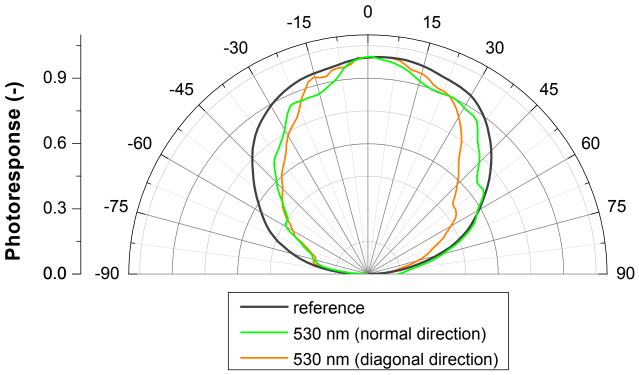


Fig. 9: Angular photoresponse of InGaAsN-based photodiode with applied 3D PhC woodpile structure measured in two different directions with respect to the woodpile shown by different colors and compared with reference photodiode.

structure on far-field diffraction pattern and angular photoresponse documents evident diffraction extremes caused by strong diffraction on woodpile structure. Such a polymer 3D PhC structure could be used as an effective diffractive element for application in different optoelectronic devices for radiation and coupling properties enhancement. Presented results document the capabilities of polymer 3D PhC structures prepared by DLW laser lithography with the possibility of easy application on photonic devices.

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About Authors

Petra URBANCOVA graduated (M.Sc.) in Photonics at University of Zilina in 2018. Her research interests include photonics and optics, micro- and nano-photonic structures, photonics materials and technologies.

Dusan PUDIS was inaugurated in Electrotechnology and Materials at Faculty of Electrical Engineering at University of Zilina in 2014. His research interests include solid state physics, optics and photonics, semiconductors and semiconductor structures, nanopatterning of nanostructures, passive and active optical devices, optical sensors.

Matej GORAUS graduated (Ph.D.) in Electrotechnologies and materials at University of Zilina in 2018. His research interests include optics and photonics, nanopatterning of nanostructures, photonics materials and technologies, passive and active optical devices, optical sensors.

Lubos SUSLIK graduated (Ph.D.) in Electrotechnologies and materials at University of Zilina in 2011. His research interests include photonics, optics and optoelectronics, semiconductors and semiconductor structures, light emitting devices - lasers and LEDs.

Beata SCIANA graduated (Ph.D.) in Electronics at the Faculty of Electronics of Wroclaw University of Science and Technology in 2000. Her research interests include epitaxial growth (using MOVPE method) and material characterization of AIIIBV-N semiconductor compounds for application in advanced micro- and optoelectronic devices - photodetectors, solar cells, quantum cascade lasers.

Wojciech DAWIDOWSKI received his M.Sc. from the Faculty of Microsystem Electronics and Photonics of Wroclaw University of Science and Technology in 2011. His research interests include epitaxial growth of AIIIBV-N semiconductor compounds for solar cells, their fabrication and characterization.

Jaroslav KOVAC graduated (Assoc. Prof.) in Electronics at Slovak University of Technology in Bratislava in 2014. His research interest include optoelectronics, semiconductors and semiconductor structures, focused on light emitting devices, lasers and photodiodes.

Jaroslava SKRINIAROVA received her degree (Ph.D.) from the Slovak University of Technology (STU), Bratislava, in 1986. In 1993 she joined the Microelectronics Department of STU. At present she is there engaged in the research of optoelectronic devices, especially of wet etching processes.