3D Photonic Crystals for Direct Applications in Light Emitting Devices

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Abstract. *In this paper, we present IP-Dip polymer-based Photonic Crystals (PhCs), which are more and more attractive for photonic devices. These structures offer simple and cheap solutions, how to improve optical properties of these devices. In our experiment, we used Direct Laser Writing (DLW) lithography to create a three dimensional (3D) PhCs. We fabricated two types of PhC structure. The first structure was prepared from IP-Dip polymer and used for modification of the radiation pattern of the optical fiber. The second PhC structure was filled with liquid polymer PolyDiMethylSiloxane (PDMS) and directly placed on the LED chip. Quality of the prepared structures was confirmed by a confocal microscope. The modification of the far-field radiation patterns of LED and optical fiber was measured by a goniophotometer.*

Keywords

Light emitting diode, optical fiber, photonic crystal.

1. Introduction

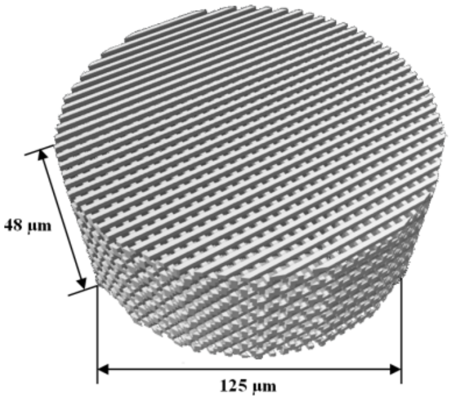
Photonic Crystals (PhCs) are still more attractive in different photonic devices and bring new solutions how to improve their optical properties. Modern technologies have the capability to fabricate PhC with submicrometer resolution. During last decades, interesting polymer-based structures with PhC were also described. Serious research was focused on improvement of Light Extraction Efficiency (LEE) and radiation pattern modification of Light Emitting Diodes (LED) using these structures and materials [1] and [2]. Most of papers presented the use of the surface patterning of a LED chip with Two-Dimensional (2D) PhCs or quasiperiodical PhCs. PhCs are typically created directly on the LED surface [3], or smart technology using siloxane-based membranes with embossed PhC was also developed [4]. The modern polymer-based technologies bring simple and cheap solutions how to improve optical properties of photonic devices.

Recently, we published interesting results about using patterned siloxane membranes with 2D PhC and Photonic QuasiCrystals (PQC), which were prepared by laser interference lithography. We showed the modification of a far-field radiation pattern of the commercial LEDs. The patterned polymer membranes with PhC and PQC diffracted light from the LED chip and modified the typical Lambertian radiation diagram [4]. Many papers favor Three-Dimensional (3D) PhCs as good candidates for these applications because of higher diffraction efficiency and complete photonic band gap.

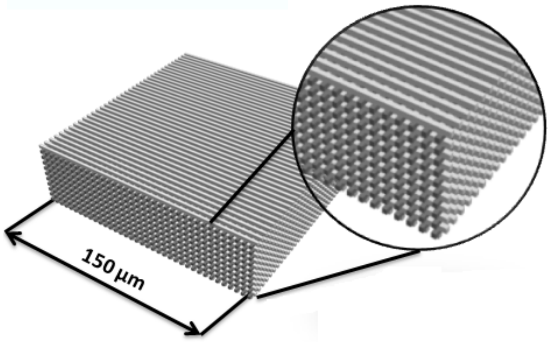
In this paper, we focus on the preparation of polymer-based 3D PhC structures. Some groups used implementation of 3D PhC in the LED surface to improve LEE. An interesting result represented the light-spectrum modification based on photonic band-gap effect of warm white-LEDs with 3D colloidal PhC to approximate candlelight. The highly efficient w-LED with 3D PhC produced a low correlated color temperature of 1963 K [1]. Another research group fabricated LED with active layer covered by 3D woodpile PhC layer to control a light emission [5]. The improvement of radiation properties of LEDs with these techniques brings often the high cost solutions. Our effort is to bring simple and cheap way how to modify optical properties of LEDs and photonic devices based on the fabrication of 3D polymer PhCs.

There are several methods to fabricate PhC structures, such as laser interference lithography, Direct Laser Writing (DLW), near-field scanning optical microscope lithography, nanoimprint, electron or ion beam lithography [4], [6] and [7]. By these methods, we can create PhC structure in two dimensions in photoresist and different semiconductor surfaces. More complex methods must be used for fabrication of 3D structures. The laser interference lithography with two-axial sample holder [8] or colloidal self-assembling of semiconductor spheres [1] were successfully used. By these methods, only periodical structures can be created. Very promising method for 3D fabrication is maskless DLW lithography.

We prefer DLW lithography method as an effective tool for fabrication of the 3D PhC structures from optical acceptable polymer IP-Dip. To fabricate 3D PhC a commercial DLW system Nanoscribe was used. The fundamental principle of DLW method is Two-Photon Absorption (TPA) in the volume of the IP-Dip photoresist. The first design uses the directly prepared PhC structure of woodpile geometry from IP-Dip photoresist. The second type of structure was filled and covered with PolyDiMethylSiloxane (PDMS) to create the thin PDMS membrane with implemented 3D PhCs structure inside. Both types of structures with 3D PhCs were applied on the LED chip and on the output of the optical fiber coupled to the LED. The quality of prepared structures was investigated by a confocal microscope. Modification of the far-field radiation pattern of LED and optical fiber was measured by a goniophotometer.



(a) Design of 3D PhC woodpile structure of a cylinder shape.



(b) Design of the 3D PhC woodpile structure with a square base and detail of the structure.

Fig. 1: Design of 3D PhC woodpile structure.

2. Structure Design

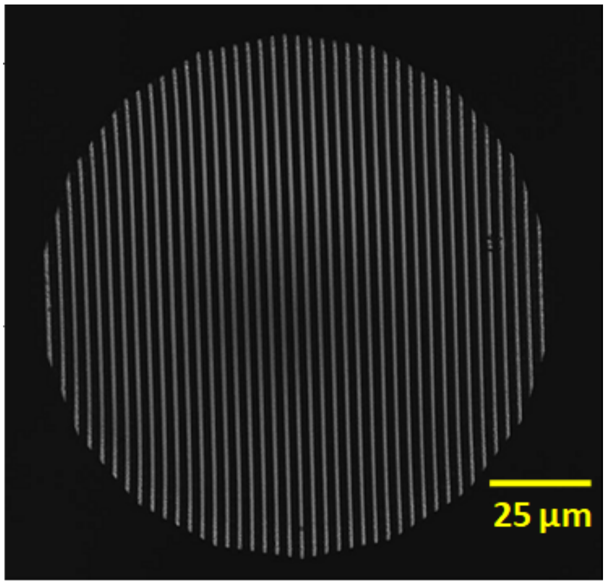
For the optical fiber application, we designed 3D woodpile PhC structure of a cylinder shape with a circular base with a diameter of 125 µm. The goal was to cover the output of the optical fiber with core diameter of 105 µm and cladding diameter of 125 µm. The designed structure is formed by a stack of alternating orthogonal oriented columns with width of 1.5 µm and height of 2 µm. Columns are arranged in body-centered lattice with period of 4 µm.

Woodpile structure consists of four-layer (ABCD-ABCD...) sequence, in which the third (C) and the fourth (D) layers are shifted by 2 µm relative to the first two layers (A and B). Design and dimensions of the structure are shown in Fig. 1(a). For the LED application, we designed woodpile structure with period of 4 µm with rod dimensions $2\times2\times150$ µm^3. To cover the entire LED chip with 3D PhC, we fabricated area of 2×2 structures. Design and detail of the 3D woodpile PhC structure for LED application are shown in Fig. 1(b).

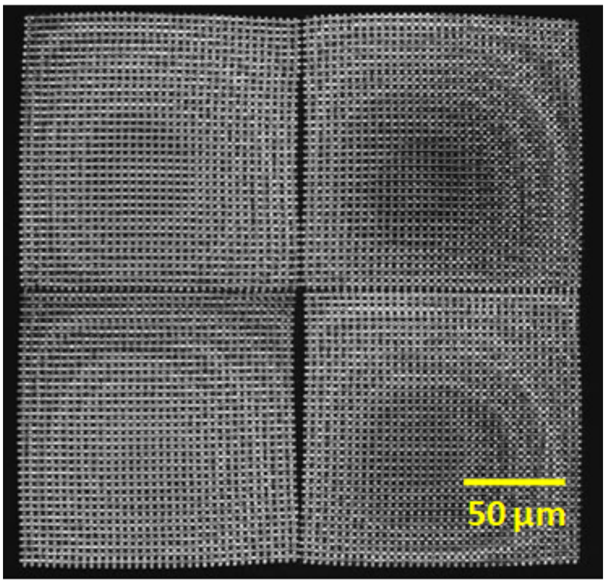
3. PhC Fabrication Technology

In our experiment, we used commercial Nanoscribe DLW system based on nonlinear Two Photon Absorption (TPA) in volume of IP-Dip photoresist. Principle of DLW is based on the layer by layer scanning the focused laser beam in the volume of photosensitive material. The system uses femtosecond fiber laser with wavelength 780 nm and special IP-Dip photoresist. In our system with 63× objective, a scanning area is app. 200×200 µm^2 and the focused laser voxel in IP-Dip photoresist is better than 200 nm laterally and 500 nm axially, which determines a resolution of this experiment.

The patterning process was provided by photoresist exposure of the IP-Dip photoresist applied on a glass substrate. After this process, samples were developed in PGMEA developer and rinsed in deionised water. The quality of prepared structures was confirmed by confocal microscope as shown in Fig. 2(a) and Fig. 2(b).



(a) 3D PhC woodpile structure from IP-Dip photoresist.



(b) PDMS membrane with embedded 3D PhC woodpile structure.

Fig. 2: Confocal microscope image of top surface.

The IP-Dip photoresist shows good transparency in visible and near-infrared spectral region and has refractive index 1.52 at 780 nm. The IP-Dip is the specially designed photoresist for Nanoscribe's Dipin Laser Lithography (DiLL) technology. IP-Dip serves as immersion and photosensitive material at the same time by dipping the microscope objective into this liquid photoresist. IP-Dip guarantees ideal focusing and highest resolution for DiLL [9]. The PhC structure was mechanically separated from the glass substrate. Afterwards, it can be directly applied on the LED chip or on the end of optical fiber.

Another technology uses the embedding process of prepared structures in liquid PDMS. After developing, the PhCs were filled with liquid PDMS of Sylgard 184 (Dow Corning). PDMS consists of two components mixed with the curing agent in ratio 1:10. Finally, samples were cured at 40 °C for 4 hours [10]. This process created thin PDMS membranes of thickness up to 100 µm with embedded PhCs. The membrane with 3D PhC woodpile structure inside was mechanically separated from the glass substrate and directly placed on the LED chip. The membrane fabrication process is shown in the Fig. 3.

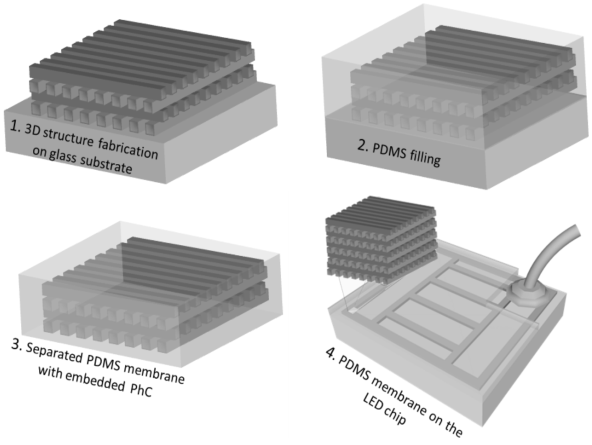
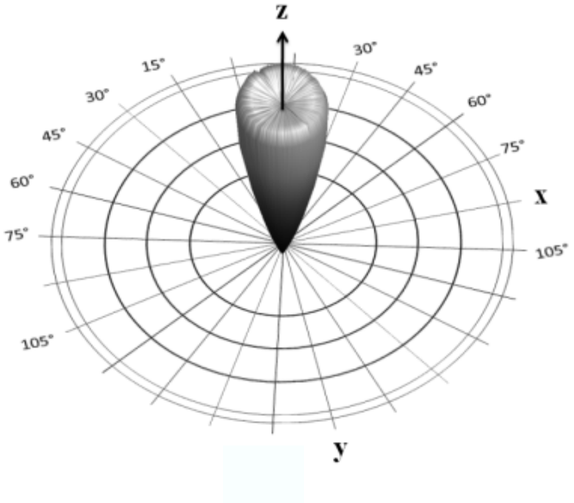


Fig. 3: Fabrication process of PDMS membrane with embedded 3D PhC structure based on combination of IP-Dip photoresist and PDMS.

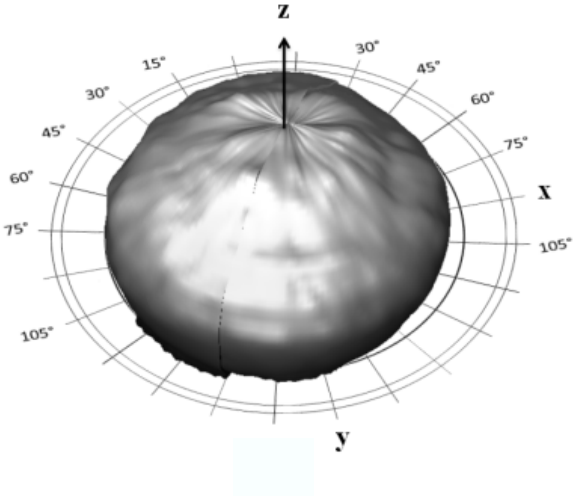
4. Results

The experimental analysis consisted of optical measurement of the far-field radiation pattern of PhC structures applied on the optical fiber and the LED chip. The LED chip with central emission wavelength at 625 nm was measured by 3D distribution of optical field at full range of azimuthal and elevation angles. The radiation pattern with resolution of 5° was measured by goniophotometer with Si detector placed app. 80 mm above the LED chip surface. The radiation pattern of optical fiber with 3D PhC structure was similarly measured as a 3D distribution of optical field with resolution of 5° by goniophotometer. However in this measurement, as an illumination source, the LEDs with different central emission wavelengths were coupled into the input of optical fiber.

Reference radiation pattern of the optical fiber was measured using LED with wavelength of 625 nm, which has typical cone shape caused by a numerical aperture of the optical fiber (0.22) as we can see in Fig. 4(a). Far-field patterns of the optical fiber with directly applied 3D PhC woodpile structure at the output of optical fiber were measured by fiber coupling to the conventional LEDs with central emission wavelengths at 625 nm, 780 nm, 940 nm and a broadband white LED diode with wavelength range of 470–850 nm. In measured radiation pattern of the optical fiber with 3D woodpile PhC structure, different shape of optical field was observed as documented in Fig. 4(b).



(a) 3D far-field radiation pattern of reference optical fiber measured using LED with central emission wavelength of 625 nm.



(b) 3D far-field radiation pattern of optical fiber with applied 3D PhC structure.

Fig. 4: 3D far-field radiation patterns.

The radiation patterns (see Fig. 5) document the widelight distribution caused by applied 3D woodpile structure at the output of optical fiber. The diffraction on the 3D PhC structure caused the spatial enhancements for higher diffraction angles in radiation pattern also dependent on the wavelength of used LED. Diffraction efficiency is significant, which is caused by high contrast of refractive indices of IP-Dip polymer and surrounding air.

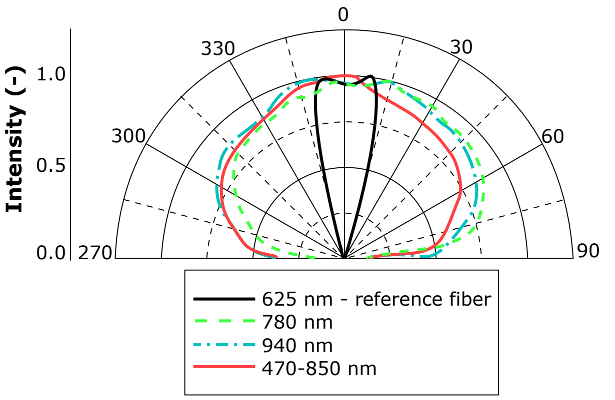


Fig. 5: The comparison of radiation pattern of optical fiber with applied woodpile 3D structure for different wavelengths.

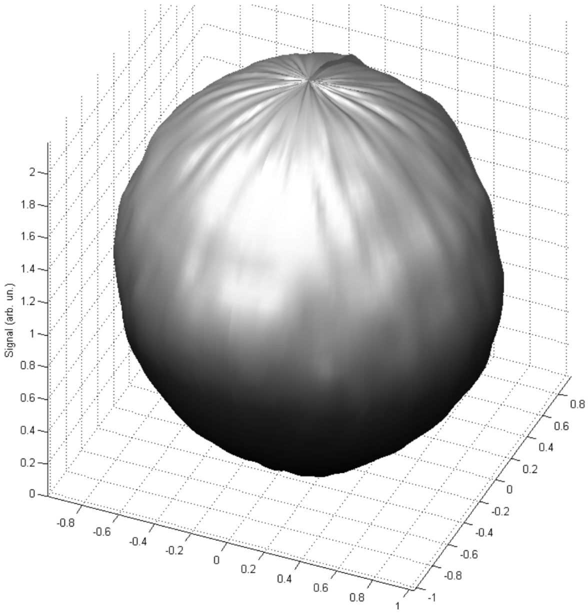


Fig. 6: 3D far-field radiation pattern of LED (with central emission wavelength of 625 nm) with applied PDMS membrane with 3D PhC woodpile structure inside.

In next measurement, we focused on optical characterization of LED after implementation of PDMS membrane with the 3D PhC structure on the surface of the LED chip. We measured the modification of typical Lambertian radiation pattern of the conventional LED. Far-field radiation pattern diagram of LED was measured by goniophotometer at LED driving current 2 mA (see Fig. 6). This system enables intensity measurement in spherical coordinates in azimuthal and elevation angle with resolution of 5°. In Fig. 7, there is shown a comparison of conventional LED with typically Lambertian pattern and the radiation pattern of the LED with applied PDMS membrane with 3D PhC structure. In the diagram with the PDMS membrane,

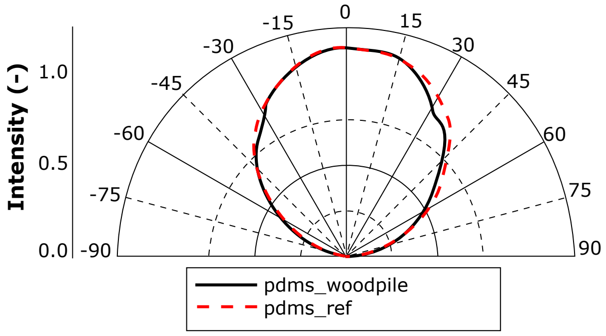


Fig. 7: The comparison of radiation pattern of reference LED chip and LED chip with applied PDMS membrane with 3D PhC structure.

we measured weak side diffraction extremes. The local spatial enhancements in radiation pattern diagram are caused by the diffraction on the 3D PhC structure.

The weak effect of the structure is caused by weak diffraction efficiency of the structure. A contrast of refractive indexes of PDMS and IP-Dip is very low, approximately 0.1 [9] and [10]. This fact rapidly decreases diffraction efficiency of the structure. For the future experiments, the contrast of refractive indices needs to be increased by using other polymers or by using the air as surrounding material. Also, the structure period should be decreased to achieve the photonic band-gap effect and higher diffraction angles.

5. Conclusion

This paper is focused on the modification of radiation pattern of optical fiber and LED using 3D PhC woodpile structures. The 3D PhC structures were fabricated by DLW lithography, and their quality was confirmed by confocal laser microscope. The optical properties were determined from far-field radiation pattern measurements of the optical fiber and LED chip with applied 3D PhC woodpile structure. Presented results document the application possibilities of polymer 3D PhC structures prepared by the DLW lithography. We bring a new concept and technique of modifying optical properties of optical fibers, LEDs and other photonic devices.

Acknowledgment

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References

[1] LAI, C. F., C. L. HSIEH and C. WU. Light-spectrum modification of warm white-light-emitting diodes with 3D colloidal photonic crystals to approximate candlelight. *Optics Letters*. 2015, vol. 38, iss. 18, pp. 3612–3615. ISSN 0146-9592. DOI: 10.1364/OL.38.003612.

[2] IWAMOTO, S., S. TAKAHASHI, T. TAJIRI and Y. ARAKAWA. Semiconductor three-dimensional photonic crystals with novel layer-by-layer structures. *Photonics*. 2016, vol. 3, iss. 34, pp. 1–12. ISSN 2304-6732. DOI: 10.3390/photonics3020034.

[3] JIANG, S., Y. FENG, Z. CHEN, L. ZHANG, X. JIANG, Q. JIAO, J. LI, Y. CHEN, D. LI, L. LIU, T. YU, B. SHEN and G. ZHANG. Study on light extraction from GaN-based green light-emitting diodes using anodic aluminium oxide pattern and nanoimprint lithography. *Scientific Reports*. 2016, vol. 6, iss. 21573, pp. 1–10. ISSN 2045-2322. DOI: 10.1038/srep21573.

[4] SUSLIK, L., D. PUDIS, M. GORAUS, R. NOLTE, J. KOVAC, J. DURISOVA, P. GASO, P. HRONEC and P. SCHAAF. Photonic crystal and photonic quasicrystal patterned in PDMS surfaces and their effect on LED radiation properties. *Applied Surface Science*. 2017, vol. 395, iss. 1, pp. 220–225. ISSN 0169-4332. DOI: 10.1016/j.apsusc.2016.07.051.

[5] OGAWA, S., M. IMADA, S. YOSHIMOTO, M. OKANO and S. NODA. Control of light emission by 3D photonic crystals. *Science*. 2004, vol. 305, iss. 5681, pp. 227–229. ISSN 1095-9203. DOI: 10.1126/science.1097968.

[6] JANDURA, D., D. PUDIS and P. GASO. Capabilities of DLW for fabrication of planar waveguides in PDMS. In: *19th Polish-Slovak-Czech Optical Conference on Wave and Quantum Aspects of Contemporary Optics*. Jelenia Gora: SPIE, 2014, pp. 8–12. ISBN 162-8-4155-68. DOI: 10.1117/12.2175902.

[7] KIM, S. H., K. D. LEE, J. Y. KIM, M. K. KWON and S. J. PARK. Fabrication of photonic crystal structures on light emitting diodes by nanoimprint lithography. *Nanotechnology*. 2007, vol. 18, no. 5, pp. 1–5. ISSN 0957-4484. DOI: 10.1088/0957-4484/18/5/055306.

[8] LAI, N. D., W. P. LIANG, J. H. LIN, C. C. HSU and C. H. LIN. Fabrication of two- and three-dimensional periodic structures by multi-exposure of two-beam interference technique. *Optics Express*. 2005, vol. 13, iss. 23, pp. 9605–9611. ISSN 1094-4087. DOI: 10.1364/OPEX.13.009605.

[9] IP Photoresists. In: *nanoscribe.de* [online]. 2018. Available at: `http://www.nanoscribe.de/en/products/ip-photoresists/`.

[10] Product datasheet: DownCorningSylgard 184 Silicone Elastomer. In: *dowcorning.com* [online]. 2018. Available at: `http://www.dowcorning.com/DataFiles/090276fe80190b08.pdf`.

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