# Fabrication and investigation of terahertz optics devices based on metal-dielectric photonic quasicrystals


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***Abstract* — The design, manufacture and study by methods of spectroscopy and microscopy of terahertz metal-dielectric photonic quasicrystal structures are considered.**



***Keywords — Terahertz radiation, photonic crystals, photonic quasicrystals***


## I. Introduction

The appearance of terahertz radiation sources [1] determines the importance for development of elements for tuning the radiation parameters in terahertz range. For fabrication of elements, the requirement of material and construction process is highly depend on the specific characteristics of terahertz radiation [2]. Polymers [3] and high resistive silicon [4,5,6] can be used as substrate material for fabricating the terahertz photonics for transmission purpose. Different metals are used as materials for reflection terahertz optics [7]. The selection of fabrication technology is connected with characteristics of material. For example, the RIE (reactive ion etching) technology (Bosch-process) was used for fabrication of silicon binary optical elements for terahertz range [4,5,8]. Hot embossing technology was used for fabrication of polymer THz elements [3]. The interference lithography technology is suitable for fabrication of polymer photonic-crystal structures [9,10], but it cannot be used for fabrication of non-periodical structures with pre-given topology such as photonic-quasicrystal structures [11,12]. However, photonic-quasicrystal structures have interesting features which could be used for effective control of radiation spectral parameters [13]. There are reflective terahertz elements such as lenses and free-form elements [8] can be realized by surface mechanical treatment technology, however mentioned technology is not suitable for realization of element with arbitrary complex 3D-topology. Wei et al. and Liu et al. reported that the 3D printing technology can be used for fabrication of polymer diffractive optical elements of terahertz range [14,15]. However the resolution of commercially available 3D printers is not enough usually for realization of terahertz diffractive micro relief with large enough number of steps (levels), which is important for achieving high diffraction efficiency (as minimum, for short-wave part of terahertz range). At the same time, 3D printing resolution is enough for realization of photonic-crystal structures (incl. 3D structures)–[16-18]. 3D printing technology is allowing to fabricate 2D and 3D photonic-crystal structures which would be practically impossible to realize by lithographic etching. In the present paper the method of fabrication of 2D photonic-crystal and photonic-quasicrystal metal-dielectric structures for terahertz and millimeter ranges based on 3D printing technology is described.

## II. Fabrication of photonic-quasicrystal structures in the terahertz range

For the manufacturing of metal-dielectric photonic-crystal (PC) and photonic-quasicrystal (PQC) structures, the process has been utilized similar to Agafonov et al. [19].

The quasicrystal approximants calculated by the method described by Gauthier et al. [20], according to which the PQC distribution is determined as the threshold function of light energy absorption, were chosen as test samples.

The distribution of light energy corresponds to the interference pattern of two waves:

$$I(\vec{r}) = \sum_{i=1}^{N} \cos^2(\vec{k}_i \cdot \vec{r}) \tag{1}$$

where $\vec{k}_i$ is the wave vector with coordinates:

$$\vec{k}_i = (kx_i, ky_i) \tag{2}$$

$$\vec{k}_i = |\vec{k}|(\cos(2\pi \cdot i/N), \sin(2\pi \cdot i/N)) \,. \tag{3}$$

Using this approach, energy distributions corresponding to quasicrystals with 2N rotational symmetry can be obtained.

The algorithm was implemented as function of the software that allows calculating the structures of the approximants of quasicrystals depending on the indicated wave vectors. As the initial data, the approximants considered by Dyachenko et al. has been used [21], in particular, the approximants of the 8th and 12th orders. The binarization parameter was utilized similar to reported by Dyachenko et al.-[21].


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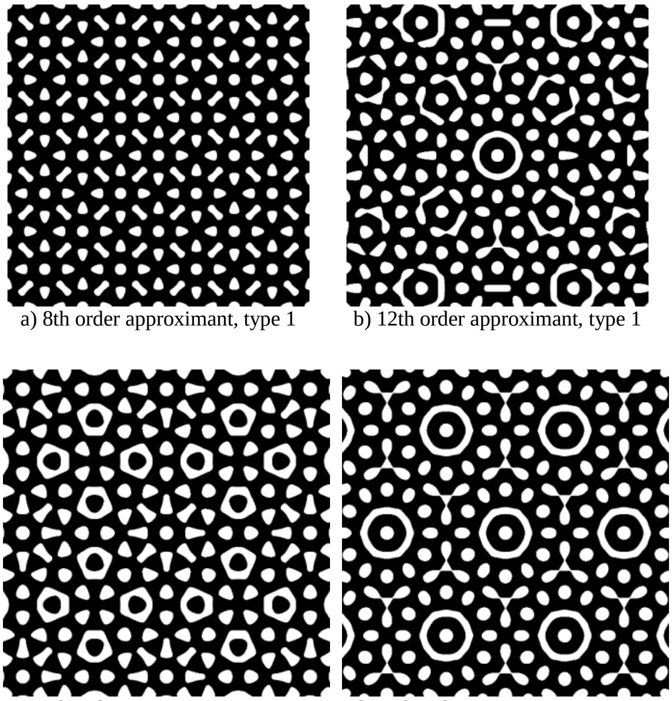
An example of the results of calculating the approximants of photonic quasicrystals is shown in Figure 1.



a) 8th order approximant, type 1 b) 12th order approximant, type 1

c) 8th order approximant, type 2 d) 12th order approximant, type 2

Fig. 1. Results of calculating of photonic quasicrystals approximants (black areas are filled with polymer, white areas are filled with Wood's alloy)

Black-and-white images obtained during the calculation were converted into vector format using the CorelDraw software, after which 3D models of the polymer parts of the PQC were built using the CAD Compass 3D (Figure 2). The resulting models were exported in STL format, after which they were manufactured. All format conversions were carried out with parameters ensuring conversion errors of less than 10 microns.

It should be noted that in Figure 1 b), c), d), there are areas in which polymer regions are completely surrounded by a conductor. It leads to the fact that they do not affect the PQC operation and can be replaced with Wood's alloy, which was done during the elements manufacture. An example of the resulting 3d model is shown in Figure 3.

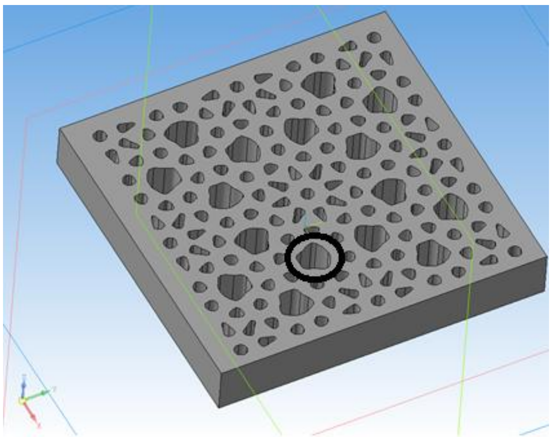


Fig. 3. An example of a 3d model of the photonic quasicrystal approximant. One of the zones with removed parts of the polymer, surrounded by a conducting region, is highlighted.

In contrast to the technique described in [9], in this work, PC atoms were formed not during exposure of the photopolymer, but during the filling of cavities formed during 3D printing by the PolyJet method with Wood's alloy. A similar technique using SLA printing is described more detailed in [19].

Examples of fabricated structures are shown in Figures 4 and 5.

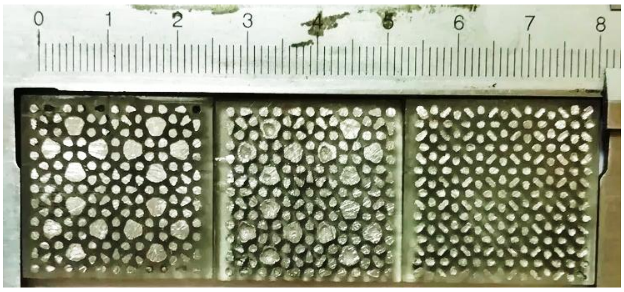


Fig. 4. Image of test photonic quasicrystals samples with different sets of approximants

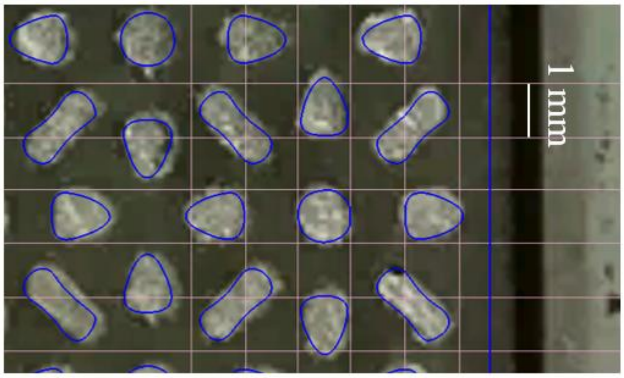



Fig. 5. Manufactured sample.

The PolyJet technology used in fabrication has demonstrated the possibility of more accurate structures fabrication compared to the SLA options used in [19]. One of the main advantages of this technology is the possibility of using a support material in the manufacture of holes, which prevents their deformation during the manufacturing process. The main limiting factor of all 3D printing options used in this work is the need to use a polymer matrix, which, however, can be overcome by switching to wax printing followed by casting into plaster molds or using chemically soluble polymers.

## III. Study of photonic-quasicrystal structures in the terahertz range

Implemented structures were investigated by methods of optical and scanning electron microscopy. Optical microscopy results are presented in Fig. 6,7.

A cross-sectional image of one of the manufactured samples is shown in Figure 6.

Fig. 6. Cross-section of the PC sample

As can be seen from the picture shown in Figure 6, Wood's alloy fills the cavities in the polymer to the full depth.

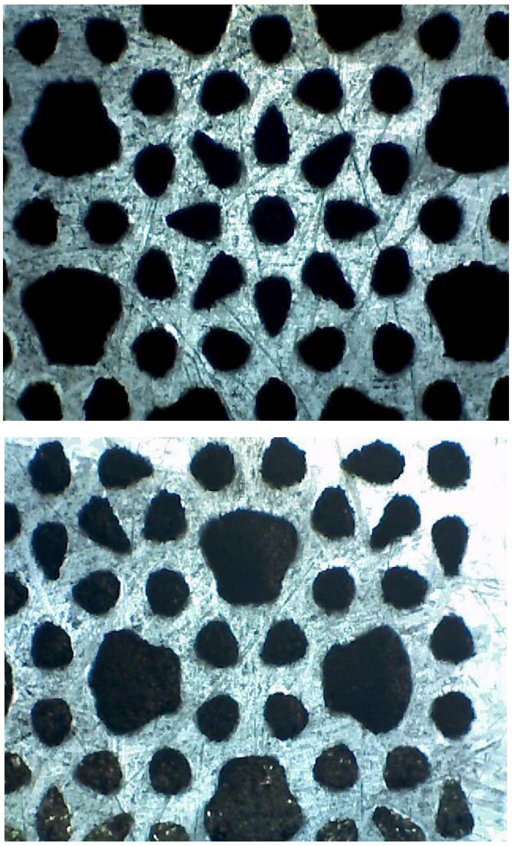
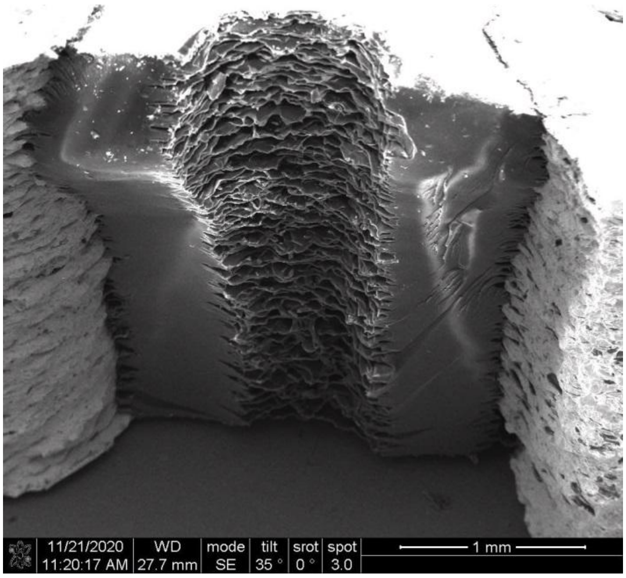


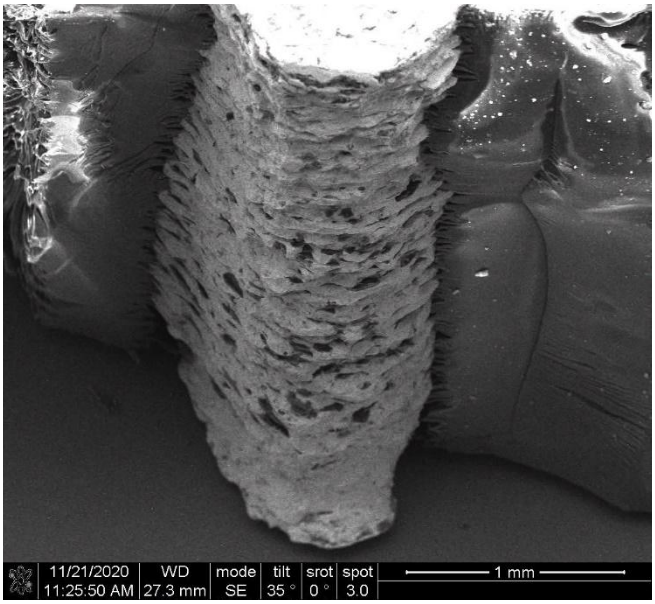
Fig.7. Images obtained by optical microscopy

Presented results are demonstrating that metallic structures have clear borders. Top layer damages have been appeared during surface mechanical treatment after cavities filling by Wood’s alloy.

The sample cross-section image obtained by scanning electron microscopy is presented in Fig.8.




a)




b)

Fig.8. Image of sample cross-section obtained by scanning electron microscopy. (a) In the center – polymer (after removing of the element of PQC structure), outside center – Wood’s alloy. (b) In the center - Wood’s alloy.

Results of scanning electron microscopy make it possible to estimate the non-uniformity of inner PQC structures surfaces. For investigated samples, the element sizes deviation from layer to layer was nearly 100 microns. The additional chemical treatment could be used for surface quality improvement.

Fabricated PQC structures samples were preliminary investigated by method of spectroscopy (beam incident angle was of 45 degrees). Experimentally measured reflectance spectrum for polymer and PQC samples is presented in Fig. 9-11.

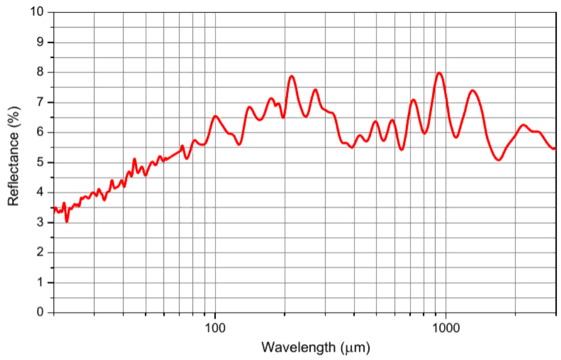



Fig. 9. Reflectance spectrum of used polymer in terahertz range

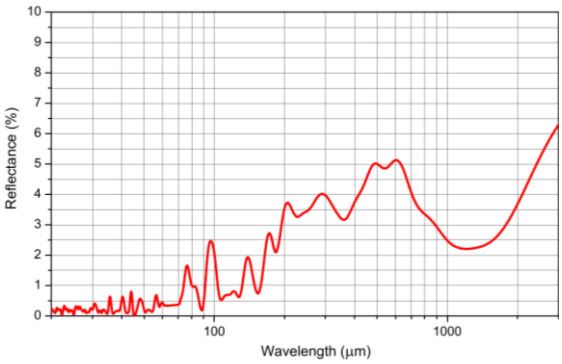



Fig. 10. Reflectance spectrum of sample with approximants of 8 order (type 1)

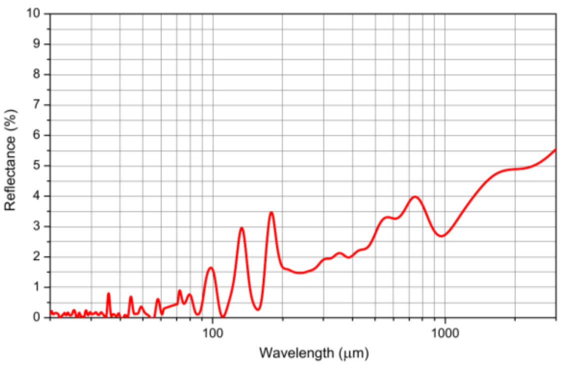



Fig. 11. Reflectance spectrum of sample with approximants of 8 order (type 2)

Experimental results demonstrate strong dependence of spectrum on the sample structure.

# I. Conclusion

Metal-dielectric photonic-quasicrystal structures have been designed, fabricated and preliminary investigated by spectroscopy and microscopy methods. The dependence of PQC spectral characteristics on the sample structure has been demonstrated. PQC structures implemented by the proposed method (after its improvement) can be used potentially in analytical (spectroscopy) and telecommunication equipment.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