The technology of manufacturing metal-dielectric photonic crystals for THz and millimeter ranges by 3D printing

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Abstract. The article considers the possibility of using 3D printing technologies to manufacture the photonic crystal structures of THz and millimeter ranges. This approach consists of the manufacturing of a polymer photonic crystal matrix by 3D printing based on photopolymerization, followed by filling the voids of the matrix with fusible material that reflects well in the terahertz range (the Wood alloy was used).

1. Introduction

The emergence of terahertz radiation sources [1,2] and devices [3,4,5] operating in the terahertz range posed the problem of forming the element base for controlling the characteristics of terahertz radiation. A method for creating passive elements of terahertz micro-optics based on additive technologies is proposed in this work.

Additive technology [6] allows the formation of two- and three-dimensional photonic crystal structures [7, 8, 9], which would be practically impossible to implement, for example, by the well-known lithography technology [1]. Note that interference lithography technologies and other “group technologies” used to create photonic crystal structures, in particular the IR range, have limitations associated with the inability to fabricate non-periodic photonic structures with arbitrary topology, in particular photonic-quasicrystalline structures. Such structures have several attractive properties from controlling the spectral characteristics before periodic photonic crystal structures. 3D printing technologies are free from this limitation and, in principle, allow the creation of almost any three-dimensional topology.

At the same time, the following problems associated with the implementation of photonic crystal elements using 3D printing remain unresolved:

1) The creation of “transmitting” photonic crystal structures (their action is based on the difference in the refractive indices of the optical materials of the photonic crystal lattice and filling nodes) requires the use of materials with a high value of the refractive index. This involves the efforts of researchers to create polymer composites with the inclusion of optically dense particles. The inclusion of optically dense particles (usually oxides) often leads to the destruction of the polymer structure. Besides, the resulting composite should have good transmittance in the THz range. The research aimed to create "transmitting" photonic crystals using 3D printing are mainly devoted to either the creation of fibers with a photonic crystal core, or the use of oxide powders for the manufacture of photonic crystal structures.

2) The limitations of the wavelength ranges in which 3D printing technologies are applicable for the manufacture of photonic crystal structures based on the resolution of the printer are not defined.

The resolution of modern 3D printers varies in a fairly wide range. The technology of 3D printing, the effect of which is based on the use of the multiphoton polymerization effect, has a resolution of 150-200 nm, which is quite enough to realize a multi-level microrelief and three-dimensional optical structures not only in the terahertz range, but also in a shorter wavelength optical one. However, the use of multiphoton lithography is limited by the recording speed and, as a rule, is used to create small photonics elements. At the same time, the problem of the practical use of the terahertz range requires the creation of elements with relatively large apertures (the diameter of the aperture of the diffractive optical element used in [10] for the formation of a rotating beam was 100 mm). Therefore, in this article, approaches to the creation of two and three-dimensional photonic crystal structures based on the use of "traditional" 3D printing without using the effect of multiphoton polymerization are investigated.

To create two-dimensional metal-dielectric photonic crystal devices (frequency filters, waveguides, beam splitters, splitters) of the long-wavelength terahertz range (1-3 mm), an approach was proposed for the first time in this work, which consists in manufacturing a polymer photonic crystal matrix using 3D printing followed by inversion of the matrix with a low-melting and well-reflecting material in the terahertz range – Wood alloy.

2. Choice of 3D printing method

According to [11], additive technology is the process of combining material to create an object from a model, usually layer by layer, in contrast to subtractive production technologies, which involve the removal of excess material.

Additive technologies are usually understood to mean various options for 3D printing, however, in the manufacture of optical microstructures it is also necessary to take into account methods that are usually not called 3D printing, in particular, methods based on the galvanic deposition of a material or complex methods, including both additive and subtractive stages, for example, LIGA and SIGA technology.

Currently, there is a wide variety of options for 3D printing, a review of which is devoted to a fairly large number of works. While manufacturing the optical structures by additive technologies, it is necessary to take into account the limitations that can be attributed to the following types:

1. Manufacturing accuracy (a certain level of surface roughness, element shape error, positioning error, material uniformity in volume, etc.)

2. Specific requirements for the material of optical structures (specified optical, mechanical, thermophysical properties, etc.)

In some cases, it is necessary to take into account the requirements for the speed and cost of manufacturing a single sample. Thus, the requirements to optical microstructures for controlling the radiation characteristics of the terahertz range (in particular, photonic crystals and quasicrystals and photonic crystal waveguide structures) significantly limit the range of technologies suitable for their manufacture. It should be noted that there are a fairly large number of additive technologies that allow the formation of structures with micron and submicron accuracy, which is redundant for the entire THz wavelength range. A review of such technologies is given in [12]. As a rule, such technologies are quite complex and require expensive equipment, which makes their use in the commercial production of optical structures of the THz range impractical. At the same time, some of the most common 3D printing technologies provide accuracy comparable to those required and the possibility of their use requires further study.

The most common 3D printing methods are based on the following processes [12]:

• Vat photopolymerization. During photopolymerization, a liquid photopolymer in a container is selectively cured with actinic radiation.

• Material jetting. While inkjet application of the material, the print head selectively applies the material to the required areas. Typically, photopolymers are applied with recycled materials used to create support structures during the assembly process. The applied structure is cured with UV radiation.

• Material extrusion. When the material is extruded, the thermoplastic material is forced through a heated nozzle and deposited on the platform.

• Powder bed fusion. When melting in a powder layer, particles of a material (for example, plastic, metal) are selectively fused using a heat source, such as a laser.

• Binder jetting. Particles of material are selectively bonded together using a liquid bonding agent (e.g., glue).

• Sheet lamination. When sheet laminating, thin sheets of material (for example, plastic or metal) are joined together using various methods (glue, ultrasonic welding, etc.) to form an object. Each new sheet of material is placed on top of the previous layers. A laser or knife is used to trim the border around the desired part, and unwanted material is removed.

• Directed energy deposition. Focused thermal energy is used for the local melting of a material (usually metal) during its deposition.

The most common FDM technology in the consumer segment is limited by the accuracy of the mechanical positioning system and nozzle diameter, which significantly limits the possibility of its use in the production of optical structures in the THz range.

Metal printing technologies, as a rule, also have limitations associated with the positioning system of the print head and the diameter of the wire used, and in the case of powder printing, with the presence of a sufficiently large zone of incomplete sintering (width up to 0.3 mm) [13], which also limits their applicability.

Thus, from the above printing methods, the following SLA and DLP methods using photopolymerization are potentially accurate enough for the manufacture of THz optical structures. The resolution along the vertical axis is determined by the properties of the polymer used and the accuracy of the mechanical positioning system of the table (up to 5 μm), and along the plane by the resolution of the optical system and radiation scattering in the polymer layer (up to 30 μm).

3. Production of test structures

In this article, it is proposed to fill the voids made by 3D printing of a polymer matrix with metals or alloys. For the manufacture of test structures using the DLP method, a Wanhao Duplicator 7 printer with a Wanhao Resin photopolymer was used, and for SLA printing, Formlabs Form2 with Formlabs Clear photopolymer was used.

The main parameters of the applied equipment are shown in table 1.

Table 1. The main parameters of applied 3D printers

Parameter	Form2	Wanhao Duplicator 7
XY Resolution	140 μm	400 μm
Minimum layer thickness	25 μm	35 μm
Build area	14.5 × 14.5 × 17.5 cm	12 × 6.8 × 20 cm

As a metal alloy, Wood's alloy was used to fill the voids in the dielectric matrix. The choice of this alloy is primarily conditioned by the low melting point, which allows the use of a wide range of polymers with a melting point above 70°C as dielectric matrices.

To measure the reflection and transmission spectra (in the case of a polymer), a Tera K-8 pulsed terahertz spectrometer manufactured by Menlo Systems Gmbh was used.

The reflection measurements of both samples were carried out at an angle of 45 degrees to the radiation source. To measure the background, a golden mirror was used (pure gold without coating; layer thickness up to 3000A; quartz glass substrate). Both the samples and the golden mirror were installed in the same holder, without its adjustment during the measurement process. Three consecutive background sample measurements were performed. Further, the signal from the sample was divided by background and multiplied by 0.985 to account for reflection from gold. A Wanhao sample was measured for transmission at a normal angle of incidence. The sample was mounted in the constriction (focus) of the optical system of lenses. Three consecutive background sample measurements were performed. Further, the signal from the sample was divided into the background.

An example of the reflection and transmission spectra of one of the photopolymers (Wanhao) is shown in Figures 1 and 2.

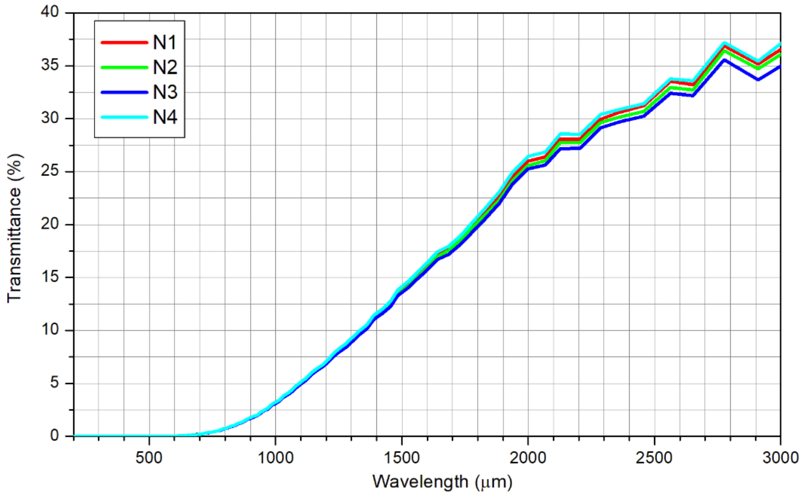

Figure 1. Wanhao Resin Photopolymer Transmission Spectrum.

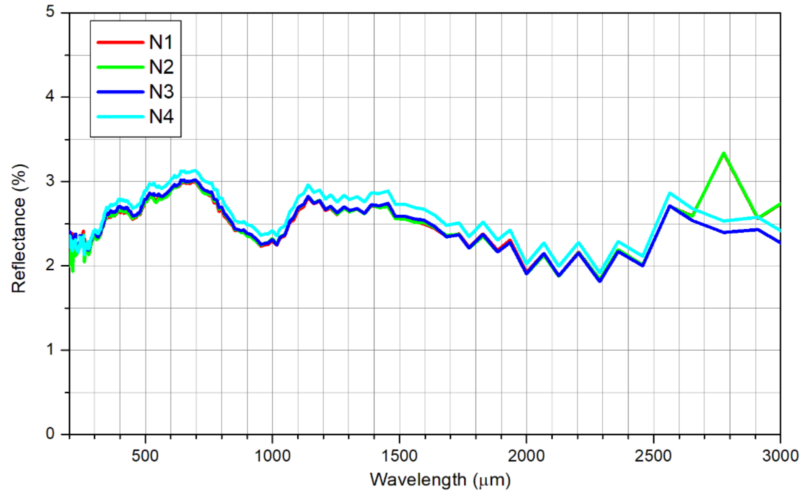

Figure 2. Wanhao Resin Photopolymer Reflection Spectrum.

The reflection spectrum of the Wood alloy is shown in Figure 3.

We note the high reflectivity of the Wood alloy in the long-wavelength region of the terahertz spectrum, which, together with its fusibility (the melting point of the Wood alloy is about 70°C), allows us to count on its use as reflecting elements of the terahertz periodic metal-dielectric optical structure made by the method of inverting a polymer photonic crystal matrix, made using 3D printing. The optical properties of Wanhao polymer make it possible to use it as a dielectric filler (after filling voids with Wood's alloy) in case the high energy efficiency of the waveguide device is not required. If the high energy efficiency of the device is required, a fabricated two-dimensional periodic structure can be extracted from the polymer matrix in some cases.

Arrays of holes with diameters of 0.8 mm, 1.2 mm, 1.5 mm, 2 mm in square plates 15x15 mm with 4 mm thickness were used as test models. The development of 3D models was carried out in the Compass 3D package, after which export to the SLA format was carried out for subsequent printing.

It should be noted that converting to SLA format provides some error in the geometry of the model, in particular, the cross-sections of the holes are described by polyhedra. Reducing the influence of such defects is another problem, which is partially described in [14].

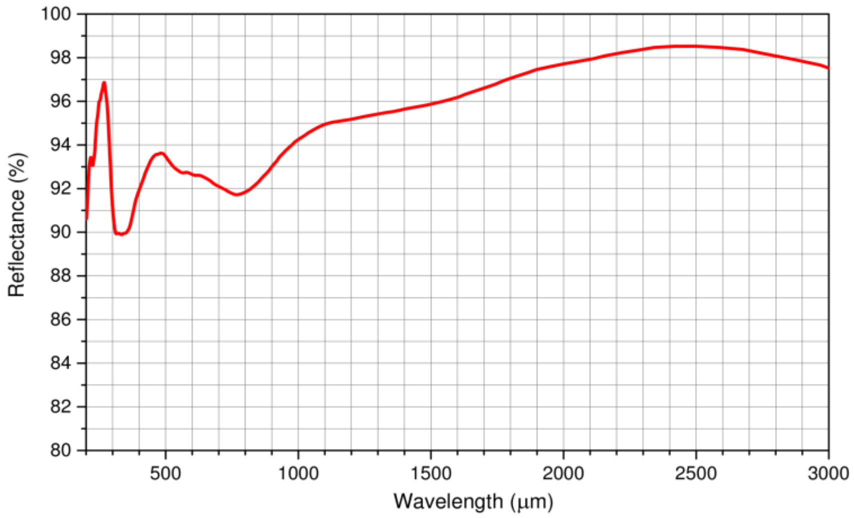

Figure 3. Wood Alloy Reflection Spectrum.

Printing results on a Wanhao printer turned out to be unsatisfactory, with hole diameters of less than 2 mm, the hole sizes were significantly distorted due to the relatively thick layer of photopolymer, relatively low resolution and the influence of proximity effect.

An example of printing results on a Form2 printer is shown in Figure 4.

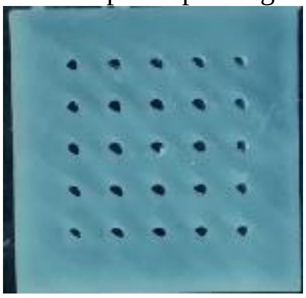

Figure 4. Appearance of samples after printing on a Form2 printer. Hole diameter is 1.2 mm.

Enlarged images of the holes are shown in Figures 5 and 6.

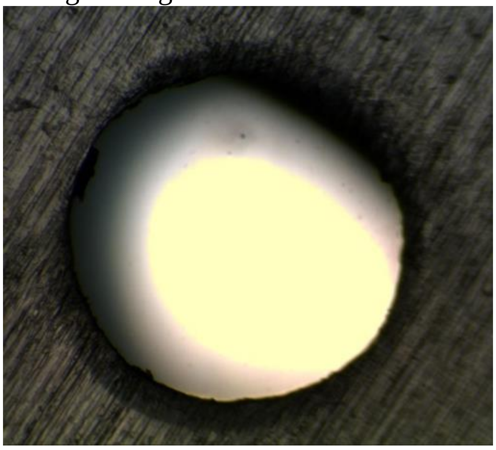

Figure 5. Single hole with 1.5 mm diameter.

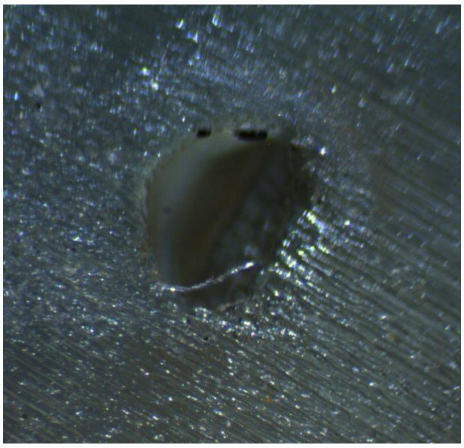

Figure 6. Single hole with 0.8 mm diameter.

It should be noted that almost all holes with a diameter of 0.8 mm have defects similar to those shown in Figure 6, which indicates the need to improve printing techniques or use more accurate equipment when creating holes of this or a smaller diameter. The influence of the proximity effect is also noticeable in a sample with a diameter of 1.2 mm. The measured value of the hole diameter was 0.9 mm.

After creating the system of holes, they were filled with molten Wood alloy. The holes were filled by dipping into the melt at a temperature of about 80°C. Special casting techniques were not used. The holes with a diameter of 0.8 mm were not filled due to the unsatisfactory quality of the sample after 3D printing. After filling the holes with the melt, the temperature of the samples decreased to room temperature and the mechanical removal of alloy residues from the surface of the samples was carried out. The appearance of the samples after mechanical removal of excess Wood alloy is shown in Figures 7 and 8.

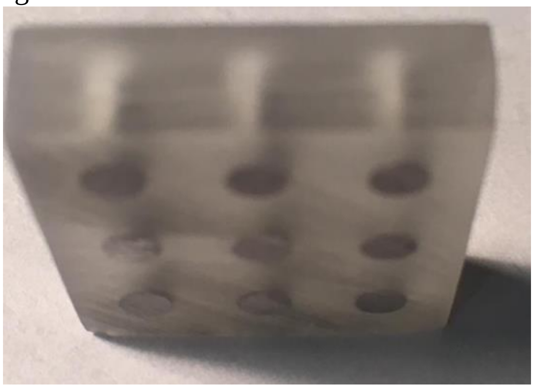

Figure 7. Appearance of samples after filling holes with Wood alloy. Hole diameter is 2 mm.

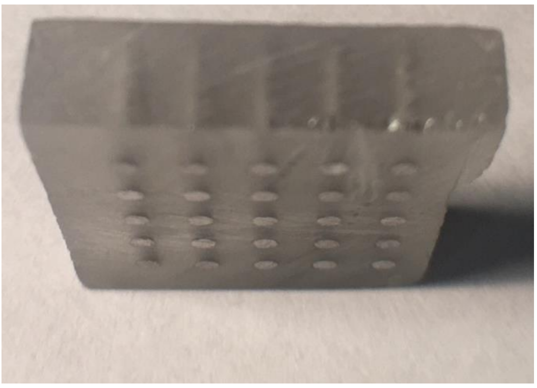

Figure 8. Appearance of samples after filling holes with Wood alloy. Hole diameter is 1.2 mm.

At the ends of the samples, it is noticeable that the alloy passed through the entire depth of the holes. Images of single holes after filling with Wood alloy are shown in Figures 9 and 10.

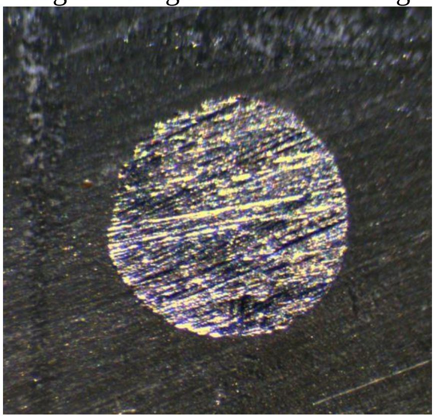

Figure 9. The appearance of a single hole after filling with Wood alloy. Hole diameter is 2 mm.

Figure 10. The appearance of a single hole with a defect in shape at the sample boundary (in the volume the hole has a cylindrical shape) after filling with Wood alloy. Hole diameter is 1.2 mm.

Despite the presence of such defects, the alloy fills the free space in the holes. Also, as mentioned above, the presence of the proximity effect leads to a decrease in the diameter of the hole relative to the design, i.e. in the experiment, a design hole of 1.2 mm corresponded to a real one with a diameter of about 0.9 mm.

4. Conclusion

In this work, we propose a method for manufacturing of photonic crystal structures for THz and millimeter-wave ranges using 3D printing methods, experimentally demonstrating the possibility of manufacturing such structures based on polymer matrices obtained by SLA printing with subsequent filling of voids with Wood's alloy.

The totality of the results indicates the potential use of such methods for the manufacture of photonic crystal structures with holes with a diameter up to 0.5 mm, which, however, requires additional experimental verification.

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6. References

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