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# Omnidirectional Photonic Bandgap in Two-dimensional Photonic Quasicrystal Made of Near-Transparent Dielectric Material

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**Abstract.** Complete bandgap for all-dielectric photonic crystals in the microwave region can be obtained only by using high-contrast materials. This requires the usage of dielectric materials with high relative permittivity coefficient. In this paper, we study, both numerically and experimentally, a two-dimensional all-dielectric photonic quasicrystal made of polyurethane foam, which is considered in all microwave applications as a transparent material. The quasicrystal structure having an omnidirectional two-dimensional bandgap is mathematically generated by the direct inscription of Bragg's peaks of the structure in the reciprocal space. The sample of the quasicrystal was manufactured on CNC (computer numerical controlled) milling machine out of foam with very low dielectric permittivity of 1.254. The numerical simulations and the experimental study are in good agreement with the theoretical model.

## INTRODUCTION

Over the past 30 years, photonic crystals have become an integral part of photonics. The main property, which makes them useful in many applications, is their ability to stop the propagation of electromagnetic waves in a certain wavelength range referred as to *photonic band gap* [1]. Although photonic band gaps exist for certain directions even at low refractive index contrast, the omnidirectional photonic band gap can be observed only for relatively high contrast [2-3].

One of the possible ways to overcome the symmetry limitations of photonic crystals is to consider photonic quasicrystals [4–5]. The quasicrystals possess the properties of both ordered structures and structures with disorder. In this paper, we consider the method first proposed in [6], which allows one to obtain 2D and 3D photonic quasicrystals with omnidirectional bandgaps. We consider here a two-dimensional quasicrystal, which depends on two coordinates only. For a two-dimensional structure, the omnidirectional bandgap is defined for all in-plane directions.

We present for the first time the results of numerical and experimental study of this model. A sample of the crystal is fabricated by means of computer numerical controlled (CNC) milling machine with polyurethane foam used as the material. The photonic density of states is measured experimentally in a parallel-plane waveguide for single TM polarization.

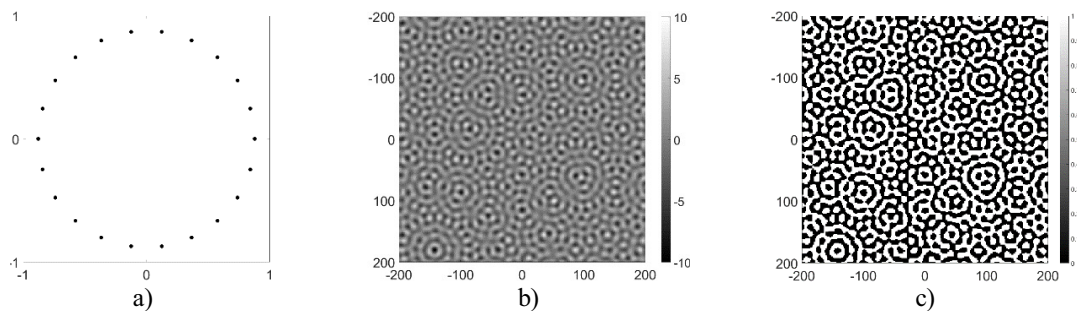


## THEORETICAL MODEL

In this paper a method of building a quasicrystal as a superposition of several 1D gratings with sinusoidal distribution of dielectric permittivity, which was first proposed in [6], is considered. The normals to these gratings are chosen to be uniformly distributed over a unit half-circle in the two-dimensional case. The formula for the refractive index variation for the superposition of  $N$  gratings reads:

$$\Delta n_g(\mathbf{r}) = \sum_{i=1}^N \Delta n_i \sin(\mathbf{g}_i \cdot \mathbf{r} + \varphi_i).$$

Here  $\mathbf{g}_i$  is the direction of the normal to the grating with number  $i$ ,  $\Delta n_i$  is the amplitude of the  $i$ -th grating refractive index variation,  $\varphi_i$  is the random phase term of each grating, introduced to obtain an isotropic structure. The Fig. 1, a) shows an example for the 22 Bragg peaks distribution in a reciprocal space, which corresponds to the sum of 11 gratings. On Fig. 1, b) an example of the sum of 11 gratings is plot as a function of coordinates.



**FIGURE 1.** a) Vector directions for 11 gratings (both positive and negative directions are shown) b) An area of the 2D quasicrystal structure continuous refractive index variation for 11 gratings. The coordinate units is mm, the structure is designed to have a bandgap at the frequency of 10 GHz c) An area of the 2D quasicrystal structure after the binarization.

To fabricate the structure out of two materials, we apply the binarization process to the model, where one material takes the volume assigned to positive and the other to negative  $\Delta n_g(\mathbf{r})$ . A result of the binarization of the structure shown on Fig. 1, b) is shown on Fig. 1, c).

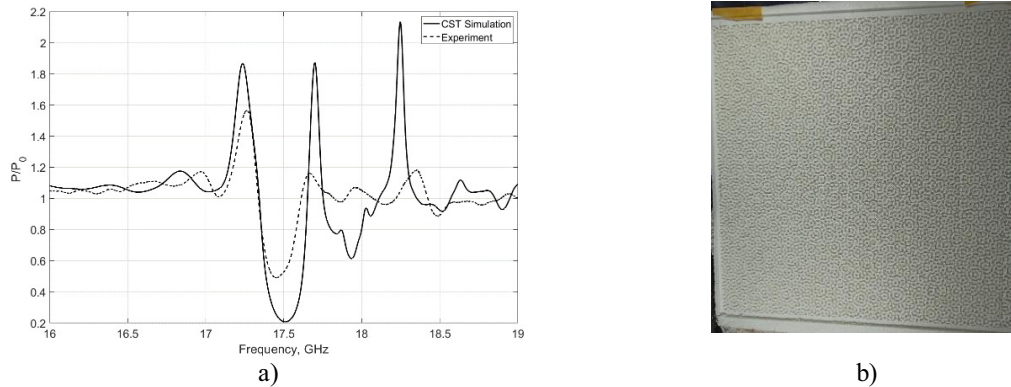
## NUMERICAL SIMULATION

We consider a sample of the proposed quasicrystal in the numerical simulation. Two materials for the binarized structure have relative permittivity of 1 and 1.254. We set the number of gratings equal to 11, see [6] for the formula. We design the quasicrystal structure to have a complete photonic bandgap at the frequency of 10 GHz. The size of the structure is  $1200 \times 1200 \times 5$  mm<sup>3</sup>. The goal is to simulate the local photonic density of states as the function of the frequency (see [7]). We put a small electric dipole inside the structure and simulate the ratio of power radiated by this dipole to the power radiated by the same dipole in the isotropic medium with dielectric permittivity equal to average value of 1.13. The simulations were performed in commercial software CST Microwave Studio. For TM polarization, the boundary conditions on Z axis are set to  $E_z = 0$ , and the dipole is aligned with Z axis. The simulated ratio  $P/P_0$  is presented on Fig. 2, a), solid line. Strong suppression in the radiated power corresponds to the low density of states, which indicates the photonic bandgap.

## EXPERIMENT

We fabricate an experimental sample with the parameters as above by using a CNC milling process. The sample of total 5 mm thickness is carved from the commercially available polyurethane foam panel. We scale down the model by the factor 1.75 to fit the sample to the CNC milling machine working area. The picture of the fabricated sample is presented on the Fig. 2, b). The bandgap frequency for the sample is then expected to be 17.5 GHz instead of 10 GHz. The material has the relative dielectric permittivity of 1.254 at 20 GHz. This value was obtained by using a special

setup for dielectric properties measurement. The experimental sample was enclosed between two copper plates, which form the parallel plane waveguide, which allows us to consider TM polarization. The local photonic density of states was measured by putting a small electric dipole antenna inside the structure via the hole in one of the metallic planes. Then the  $S_{11}$  parameter was measured by means of a VNA and recalculated into the radiation impedance, which is presented on the Fig. 2, a), dashed line. The obtained results are in a good agreement with CST simulation.



**FIGURE 2.** a) The ratios  $P/P_0$  for TM polarization for quasicrystal simulated in CST (solid line) and obtained from the experiment (dashed line). b) An experimental sample fabricated of polyurethane foam

## CONCLUSION

In this paper we considered an all-dielectric photonic quasicrystal made of almost-transparent material. The quasicrystal structure was obtained by the method of summation of gratings. This allows obtaining the desired microwave properties of the final structure. The quasicrystal has the omnidirectional bandgap. To check the results, we measure the local photonic density of states. The results were proven both numerically and experimentally.

## ACKNOWLEDGMENTS

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