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SUBWAVELENGTH DIFFRACTIVE PHOTONIC CRYSTAL LENS

I. V. Minin and O. V. Minin

Novosibirsk State Technical University
Russia

Y. R. Triandaphilov and V. V. Kotlyar

Samara State Aerospace University
Image Processing Systems Institute
Russian Academy of Sciences
Russia

Abstract—We designed two type binary 2D subwavelength (wavelength was $\lambda = 10\,\mathrm{mm}$) focus diffractive photonic crystal lens and calculated the diffraction of plane TE-wave by use FDTD-method (our program in C++). It has been shown that diffractive photonic crystal lens designs have not an unique solution. Diameter lens was in 5 times more than her width and full width half maximum diameter of focal spot was 0.48λ.

1. INTRODUCTION

One of the factors that have stimulated much of the recent interest in diffractive optics at any frequency waveband has been the increased optical performance of such optical elements and millimeter wave/microwave devices [1–3]. This allows the fabrication of optical elements that are smaller (compared to wavelength), lighter and cheaper to fabricate, are more rugged and have superior performance that the conventional optical or/and quasioptical components they often replace. Important, the design capabilities for binary optics now available can make possible the design and manufacture to components including antennas having optical and focusing properties never before produced. FZPL lens is one of the simple digital lenses or DOE [4]. Flat surfaces are two dimensional, therefore much cheaper to fabricate than three dimensional contour surfaces and allow to focusing of a radiation to a subwavelength focus distances [5].

One of the complex electromagnetic systems of interest to us is a photonic crystal [6], a periodic dielectric structure with lattice spacing of the order of the wavelength of the electromagnetic wave. Typical for a photonic crystal is that electromagnetic waves in a certain frequency range and/or with a certain polarization cannot propagate along certain directions in the crystal. This forbidden frequency range is called a stopgap. If the propagation of the electromagnetic wave is forbidden for any crystalline direction and any polarization, for a certain frequency range, then this forbidden frequency range is called a photonic band gap [6–8].

The idea of controlling light by means of photonic crystals has led to many proposals for novel devices [7, 9–10] including different types of focusing elements [11–13] and has motivated many researchers to investigate a plethora of ideas.

Below we have shown the possibility of subwavelength focus diffractive photonic crystal lens as a perspective focusing element.

2. SIMULATION

Numerical simulation has been conducted by using FDTD-method [14] with taking into account some of specific applications to PBG [15–17]. A program has been written in MS Visual C++ IDE. Input of plane wave with TE-polarization into a computation area is achieved with "total field-scattered field" technique [18]. Used discretization is 50 steps on wavelength. PML boundary conditions were used [19]. Averaging of field has been performed by one period. Program was running about 40 seconds on computer with processor frequency 2.33 GHz.

The optical length in the lens was calculated as follows [10]:

$$\Delta = N\left[2r_i(y) + (a - 2r_i(y))n\right]. \tag{1}$$

where: N is the number of holes in line, a is lattice parameter (period), $r_i(y)$ — the radius of holes, y is vertical axis. The rectangle lattices were used in our photonic crystal lens [21, 22]. From the Equation (1) it is followed that photonic crystal lens design have not an unique solution and at least of three different types of photonic crystal lens are possible.

Let us consider the first type of lens where $N = \text{const}$. The main parameters of diffractive photonic crystal lens are the following:

- Wavelength $\lambda = 10\,\text{mm}$,

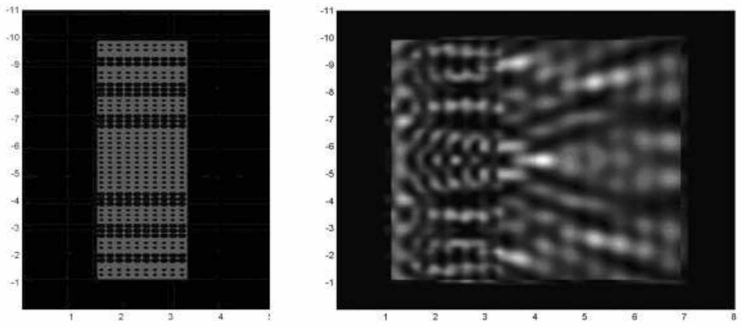
- Diameter $D = 10\lambda$,
- Width of a lens $l = (0.83 + 1)\lambda = 18.3\,\text{mm}$
- Lattice parameter $a = l/10 = 1.83\,\text{mm}$
- Radii of a circular holes: $r_1 = 0.25a = 0.457\,\text{mm}$, $r_2 = r_1 + 0.227a = 0.87\,\text{mm}$
- Lens positions at z-axis: $15 - 33\,\text{mm}$
- Index of refraction $n = 1.6$

The radii of a Fresnel zones were calculated by classical formula [4] in the geometric optic approximation:

$$R_i = \sqrt{i\lambda F + \left(\frac{i\lambda}{2}\right)^2} = \lambda\sqrt{i(1 + i/4)}, \tag{2}$$

where F is the focal distance equal to $F = \lambda$.

The correspondent Fresnel numbers of a lenses $(\pi D^2/(\lambda F))$ are about 300. The result of FDTD simulation is shown in the Figure 1, where $|E_x|^2$ is the intensity of an electric field.



(a) (b)

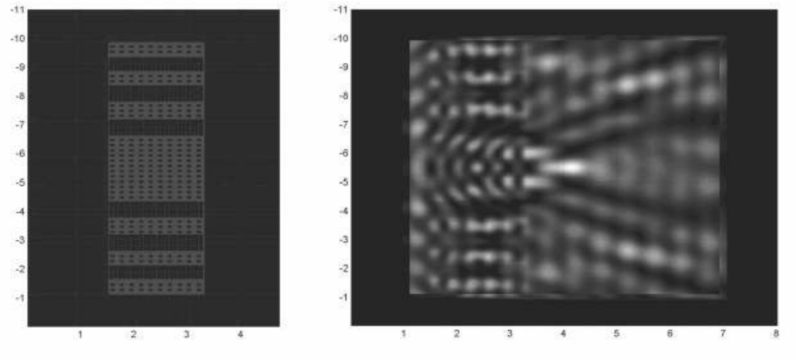
Figure 1. Diffractive photon-crystal lens of the first type (a) and field intensity distribution along optical axis $|E_x|^2$ (b). The relative units on the vertical axis (y axis) and horizontal axis (z axis) are in wavelength.

For the lens of second type where $r_1 = r_2$ and $N \neq \text{const}$ the main parameters of diffractive photonic crystal lens are the following:

- Wavelength $\lambda = 10\,\text{mm}$,
- Diameter $D = 10\lambda$,
- Width of a lens $l = (0.83 + 1)\lambda = 18.3\,\text{mm}$
- Lattice parameter $a = l/10 = 1.83\,\text{mm}$

- Radii of a circular holes: $r = qa_1 = 0.2a = 0.366\,\mathrm{mm}$,
- Array constant $a_2 = a_1/\left(1 + \frac{n-1}{2q}\right) = 0.732\,\mathrm{mm}$
- Lens positions at z-axis: $15 - 33\,\mathrm{mm}$
- Index of refraction $n = 1.6$.

Diffractive photon-crystal lens of second type and field intensity distribution along optical axis are shown in the Figure 2.



(a) (b)

Figure 2. Diffractive photon-crystal lens of second type (a) and field intensity distribution along optical axis (b). The relative units on the vertical axis (y axis) and horizontal axis (z axis) are in wavelength.

Figure 3 shows the intensity distribution along (a), (b) and across (focal plane) (c), (d) optical axis for photonic crystal lens of the first (a), (c) and second (b), (d) types.

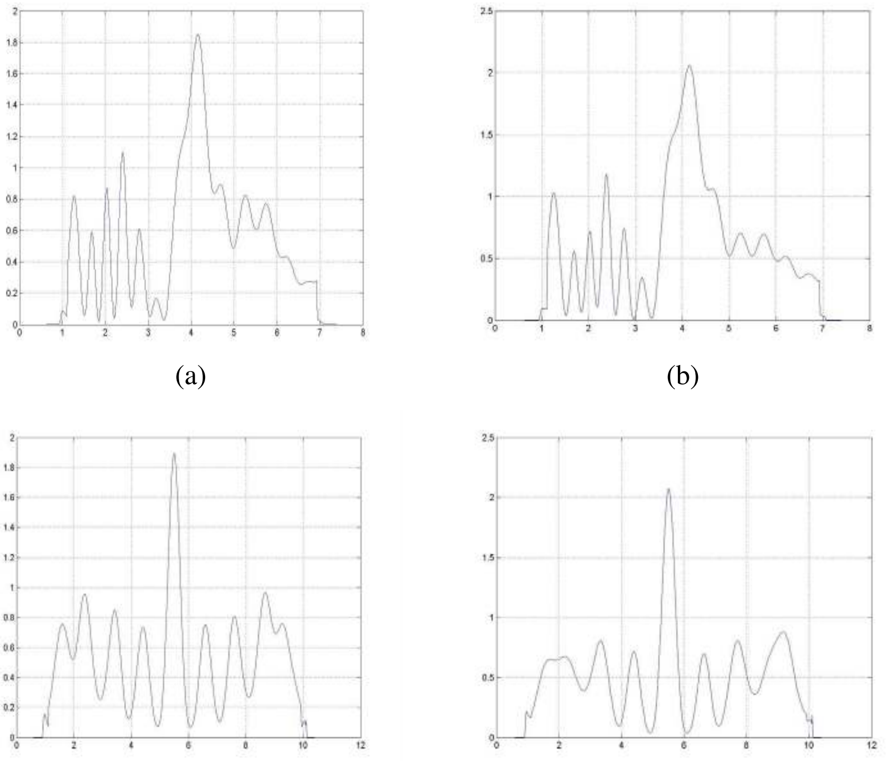
It could be noted that the even and odd Fresnel zones has a different band gap [23] and the frequency properties of such a lenses will differ from the classical Fresnel zone plate.

For diffraction-limited optical and quasi-optical systems, which are subject to the paraxial approximation, the Rayleigh criterion gives the spatial resolution, Δx, for a circular lens of diameter D and focal length F as [7]:

$$\Delta x = 1.22\lambda \frac{F}{D}. \tag{3}$$

From (3), it is seen that the spatial resolution decreases linearly with F/D.

The diameter of beamspot (spatial resolution) at focus was equal to full width half maximum (FWHM): FWHM $= 0.48\lambda$, and the spatial resolution of the two lenses were also estimated from the location of the first nulls in the spot-beam pattern was about the wavelength.



(a) (b)

(c) (d)

Figure 3. Field intensity distribution along (a), (b) and across ("focal spot") (c), (d) optical axis for photonic crystal lens of the first (a), (c) and second (b), (d) types. The relative units on the x-axis are in wavelength.

From the results (Figure 3) it is followed that the intensity in the focus increase on 12% and sidelobe level decrease up to 15%. Comparisons shown that the diffractive photonic lens of second type has better focusing characteristics. It could be noted the described results shown only a possibility of diffractive photon crystal lens realization and could be optimized. For example, the optimization is possible to change the reference phase of the Fresnel zone radii from the standard 0° to a more optimal value between 0° and 180° [4].

3. CONCLUSION

Thus we applied the principles of photonic crystal devices to the millimeter wave portion of the electromagnetic spectrum. For the lens, we have observed their collimation and imaging ability both shown in the amplitude and phase. It has been shown that diffractive photonic crystal lens designs have not an unique solution. The results described above shown that the diffractive photon crystal lens is a perspective candidate to subwavelength focus lens itself and as a lens array element [24].

Also the authors believe that the results will also be of interest to designers of optical systems because, with scaling effects taken into account, the characteristics of diffractive quasioptical elements are valid for diffractive focusing elements of integrated optics.

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