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MILLIMETER WAVE BINARY PHOTON SIEVE FRESNEL ZONE PLATE: FDTD ANALYSIS

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Abstract—In this paper, we report the possibilities to apply photon sieve principle to binary diffractive lens in millimeter wave band. The FDTD simulation showing the idea of the photon sieve application to millimeter wave optics does not allow increasing resolution power, due to the small number of holes in the FZP aperture. But such simulation results may be used in simple computational experiments in millimeter wave which allows obtaining insight into physical systems characterized by nanometric objects because D/f and $D\lambda$ are almost the same.

1. INTRODUCTION

According to the IEEE Standard Definition of Terms for Antennas (IEEE Std 145–1993), Fresnel lens antenna is an antenna consisting of a feed and a lens, usually planar, which transmits the radiated power from the feed through the central zone and alternate Fresnel zones of the illuminating field on the lens. The simplest variant of Fresnel lens is Fresnel zone plate.

It is well known that Fresnel zone plates (FZP) can be used to focus and image [1, 2]. But it is directly related to the width of the zone. Spatial resolution of the conventional diffractive lenses, such as Fresnel zone plate, is in the order of the width of the outmost zone. Therefore, reducing feature size of the zone plates helps to improve the spatial resolution. According to the zone plates theory [1, 2], the width of zone from the center to the outer is decreased gradually, and especially the width of the outermost zone is very small.

To achieve higher resolution of well-known diffractive optics, Kipp et al. proposed the novel idea of the photon sieve [3]. Photon sieves (PS) are a type of diffractive optical elements (DOEs) developed for soft X-ray focusing and imaging. Unlike a zone plate that is

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composed of concentric rings, a photon sieve is composed of a great number of pinholes suitably arranged according to the ring pattern of a classical Fresnel zone plate. It can overcome the limitations of Fresnel zone plates in the case of a big number of pinholes.

For an infinite conjugate, the radial distance to the center of the nth bright zone of binary FZP, with focal length f at wavelength λ, is given by r_n [1, 2]:

$$r_n^2 = 2nf\lambda + n^2\lambda^2$$

The width w of each zone is such that the area in a paraxial approximation is a constant $(n\lambda f)$, so

$$w = \lambda f/(2r_n). \tag{1}$$

In its simplest version, the photon sieve consists of holes of diameter w located at a corresponding radial distance r_n. The holes can be distributed regularly or randomly in angle about the zone. According to the Rayleigh, the angular resolution of this PS will be directly proportional to the smallest hole (largest r_n).

Traditionally, position near the Fresnel radii, size and density of the pinholes can be used as design parameters. As we know, all the photon sieves reported so far work in far-field region with macro-scale dimensions, and their minimum hole diameter is larger than the incident wavelength λ.

FZP lenses, binary or phase correcting, have already turned into essential focusing and imaging elements also in the microwave [4, 5] and millimeter wave/terahertz systems [6–8]. But the focusing properties of PS FZP in millimeter wave were not considered in the literature yet. The interest in PS FZP in this waveband is determinate by the possible better resolution power, light weight and simple design. But taking into account that in millimeter wave band the number of Fresnel zones at the FZP aperture is small [4–8], the effect of photon sieve to resolution power is not evident.

Another advantage of FPS over the FZP arises from the fabrication point of view: the PS FPS can be constructed in a single structure without any supporting substrate.

In this paper, we report the possibilities to apply the photon sieve principles to diffractive lens in millimeter wave band.

2. CALCULATION EXPERIMENT TECHNOLOGY

The amplitude of the radiation passing through a specific pinhole is given by its area and the phase by its position. Positions in front of light and dark rings differ in phase by π. As a rule, amplitude photon sieve FZP consisting of a large number of precisely positioned holes distributed according to an underlying Fresnel zone plate geometry, while the holes at transparent and opaque circular rings of the FZP have a π phase shift. Compared to a conventional photon sieve, the binary photon sieve has a transmission two times more than amplitude PS and a diffractive efficiency approximately four times than amplitude PS.

The focusing characteristics of millimeter wave PS FZP were examined by numerical experiment with the following data: diameter of PS FZP $D = 230\,\text{mm}$, $f = 150\,\text{mm}$, $\lambda = 10\,\text{mm}$, the total number of Fresnel zones $n = 8$.

In this wave band, the hole diameter is comparable to the incident wavelength λ. So in our current research, we intend to use the Finite Difference Time Domain Method (FDTD) to observe the radiation pattern characteristics of PS FZP in comparison to classical FZP [8, 9].

FDTD is the method of choice for accurate and fast simulations of electromagnetic wave interaction with different structures. FDTD analyzes the propagation of electromagnetic waves in a structure by solving Maxwell's equations as a function of time at discrete locations. First, the device under study is modeled by defining the geometry itself using 3-D cells, each cell being properly characterized with its electrical conductivity, permittivity, and loss tangent [10]. Each cell is referred as a Yee cell, in honor of Kane S. Yee, who originally developed the FDTD method in 1966 [11]. By stacking several Yee cells, an FDTD volume can be created. The structure under study is fabricated inside this volume. The equations are solved in a leap-frog manner, i.e., the electric field is solved at a given instant in time, then the magnetic field is solved at the next instant of time, and the process is repeated for the specified number of time steps [10].

Important considerations in the design of the geometry include that the ratio of the sides of the cell cannot exceed two and that the biggest cell dimension must be at least 1/20 of the highest frequency of interest. If these conditions are not met, the results are not reliable [10, 12]. We also successfully use FDTD methodic mentioned above for pattern reconstruction in millimeter wave metrology [12].

3. SIMULATION RESULTS

In Fig. 1, the results of PS FZP and classical FZP are shown. The red is an air and green the dielectric with dielectric constant equal to 3. The holes were distributed randomly in angle about the zone. The hole diameters were equal to the width of correspondent Fresnel zones.

The incident wave front was flat.

The field intensity distribution across the focal plane is shown in

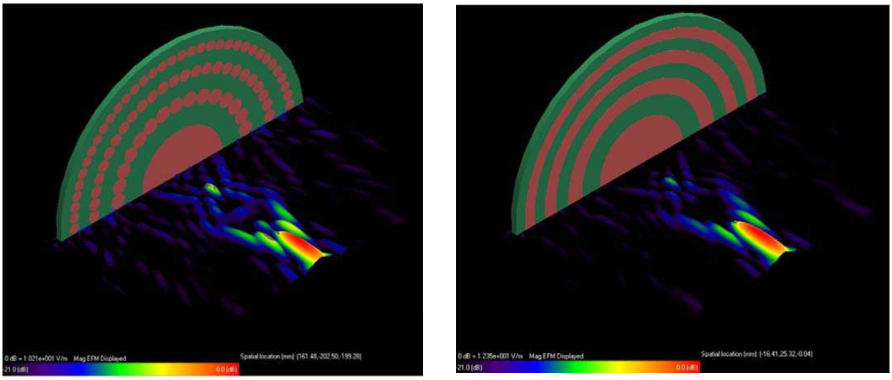

Figure 1. Field intensity distribution near the focus: above — the PS and below — the classical FZP.

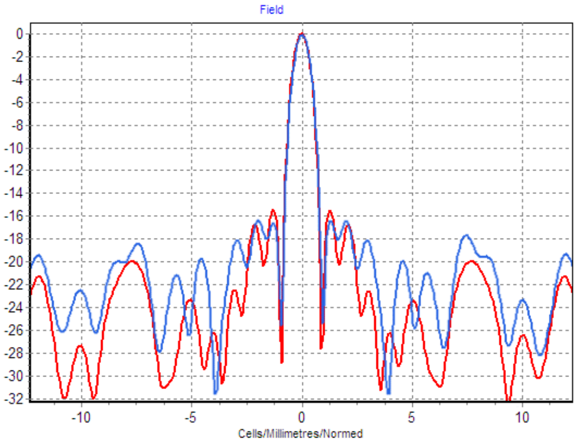

Figure 2. The field intensity distribution in dB in the focal plane for classical FZP (red) and PS FZP (blue).

the Fig. 2.

The analysis of simulation results show (see Figs. 1–2) that

1) The resolution power for PS FZP and classical FZP are the same,
2) The first sidelobe level for PS FZP is about 1 dB less than for classical FZP.

The gain of PS FZP is about 0.83 times less than for classical FZP.

4. CONCLUSION

In the paper, we report the simulation results of focusing properties of millimeter wave photon sieve FZP. The structure of the photon sieve is based on FZP, and therefore, their behaviors for the first diffraction order are similar. The main difference is that the higher-orders obtained with the FZP are highly reduced with the sieve. The investigation shows that the resolution power of PS FZP is equal to classical FZP, due to the small number of holes in the FZP aperture. For a zone plate, each ring contributes equally to the amplitude at the focus. This contribution drops abruptly to zero beyond the outermost ring which leads to strong intensity oscillations in the diffration pattern. With a photon sieve, the number of pinholes per ring can be readily adjusted to yield a smooth transition which minimizes the secondary maxima. Also the simulation has shown the first sidelobe level for binary PS FZP a few less than classical FZP. So the idea of the photon sieve application to millimeter wave optics does not allow increasing the resolution power. But this idea may be effective at THz waveband.

As known, nano-optics deals with optical effects occurring if light interacts with matter that has artificially structured features with sizes comparable to the wavelength [13]. From this point of view, we detail how the use of simple scale computational experiments in millimeter wave allows obtaining insight into physical systems which are characterized by nanometric objects because D/f and $D\lambda$ are almost the same.

Another advantage of PS FZP over the FZP arises from the fabrication point of view: the PS FZP can be constructed in a single structure without any supporting substrate.

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