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Research Networking Program

Scientific report on Short Visit Grant 7023

Title: ***Fresnel zone plates and 3D Fresnel dielectric lenses for imaging applications***

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Description of the project

Integrated lens antennas (ILAs), as it well known, are widely used at mm-waves for point-to-point communication and radar systems. The interest to this technology and the benefits it proposes are growing proportional to the operational frequency. In particular, it is considered as a key technology for automotive radars [1], imaging [2], and wireless backhaul systems [3].

However, at high frequencies, ILAs may suffer from high insertion loss due to material loss in dielectric lenses. A solution for this problem can be potentially found in using the so-called Fresnel Zone Plate (FZP) lens antennas [4]. Such antennas have been widely used in optics and later at microwaves [5, 6], whereas their usage for mm-wave and THz applications is limited until now, most probably due to the significant difficulties with integration between the FZP focusing system and mm / sub-mm receivers as well as due to the computational challenges associated with the accurate characterization of the diffraction phenomena on the lens corrugated surface. Three dimensional (3D) FZP focusing systems for mm-wave and THz applications allow to focus radiation below diffraction limit [7].

Many attempts have been made to improve the resolving power of optical imaging systems since Ernst Abbe discovered that the resolution of an imaging system is limited by diffraction. Wave diffraction is a phenomenon that manifests itself as a departure from the laws of geometrical optics under wave propagation.

As a first step, the behaviour of flat diffractive lenses with dimensions typical for mm-wave applications was studied both numerically and experimentally. Results of the focal fields of a phase correcting Fresnel lens studied using FDTD are described for several small values of *F/D* and with $F \le 2\lambda$. The values of $F \le \lambda$ are of interest because the subwavelength resolution (Fig.1) can be achieved.

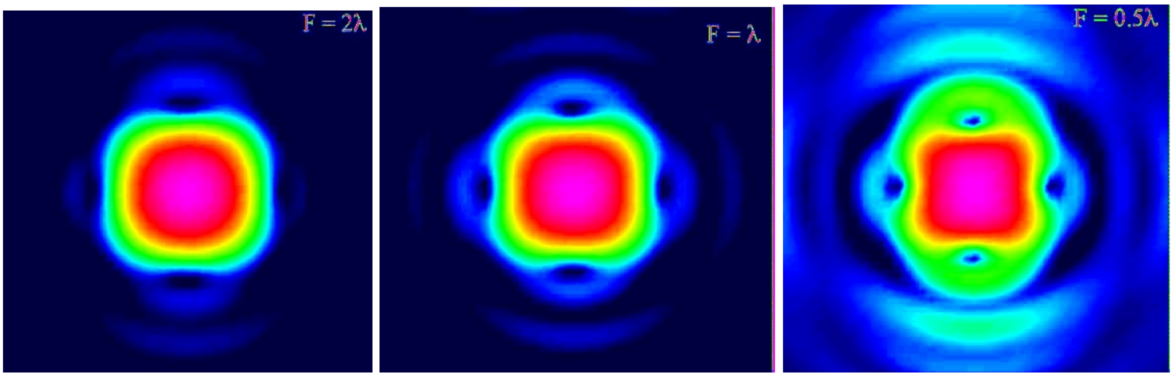

Fig.1. Focal spot for FZP with focal length F=(2, 1, 0.5) λ.

In particular, it was demonstrated that in the near field of a single phasereversal binary flat diffractive lens without of the immersion medium in free space a resolution of 0.3-0.4 wavelength can be obtained. The focal spot has a slight asymmetry and is no longer an Airy pattern (Fig.1). The reason for the slight axial asymmetry in the intensity patterns arises from the anti-symmetrical component of the electric field in the z-direction (direction of the incident wave). This component is significant for small values of *F/D*, since the focal spot is in the reactive near-field of the lens, and it causes the slight asymmetry in the intensity patterns. As the values of *F/D* increase, the amplitude of this component quickly decreases and thus does not contribute significantly to the intensity, resulting in a symmetric pattern. In this near field (F$\sim\lambda$), we may talk about evanescent waves, which are waves that are non-homogenous, non-propagating, and exponentially decaying away from the object's surface. They have a complex wave vector perpendicular to the surface and thus allow high wave vectors in the other two directions (i.e. in the plane of the sample). Large k-vectors correspond to small dimensions in direct space, and small directions imply high resolution. Compared to well-known scanning microscopy, this diffractive lens allows simultaneous imaging of a finite area close to the focus.

It was also shown that the minimum diameter of the focal spot near the central circumferential step of binary diffractive axicon was equal to FWHM = 0,38λ (with D=12 λ at 100 GHz).

Subwavelength resolution beyond the Abbe barrier described above is possible for flat diffractive lens only with F<λ. In the second part of report, the innovative radiating structures such as a conical millimeter wave FZP lens (Fig.2) are proposed for subwavelength focusing. It has been shown that in contrast to the flat diffractive optics the curvilinear 3D diffractive conical optics allows for overcoming 3D Abbe barrier with focal distance F more than F>2λ.

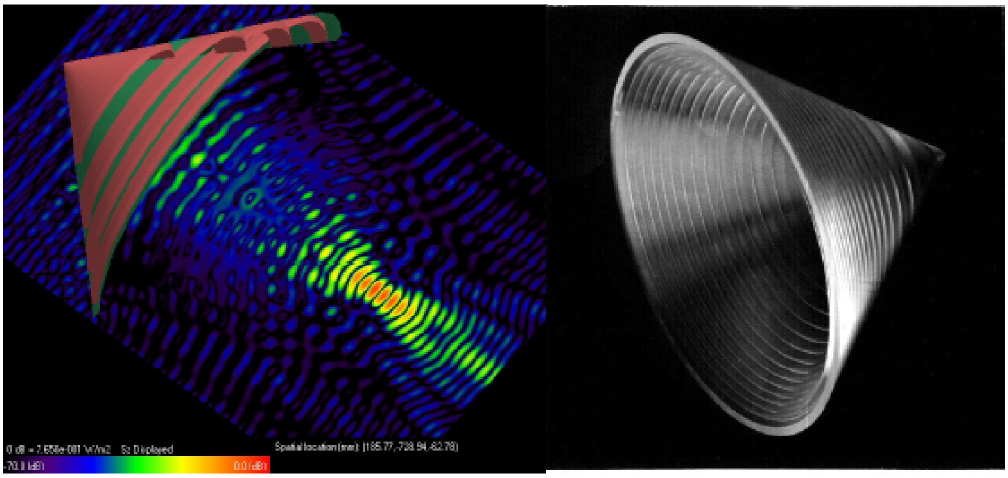

Fig. 2. FDTD simulation (left) and experimental design (right) of a conical 3D FZP lens.

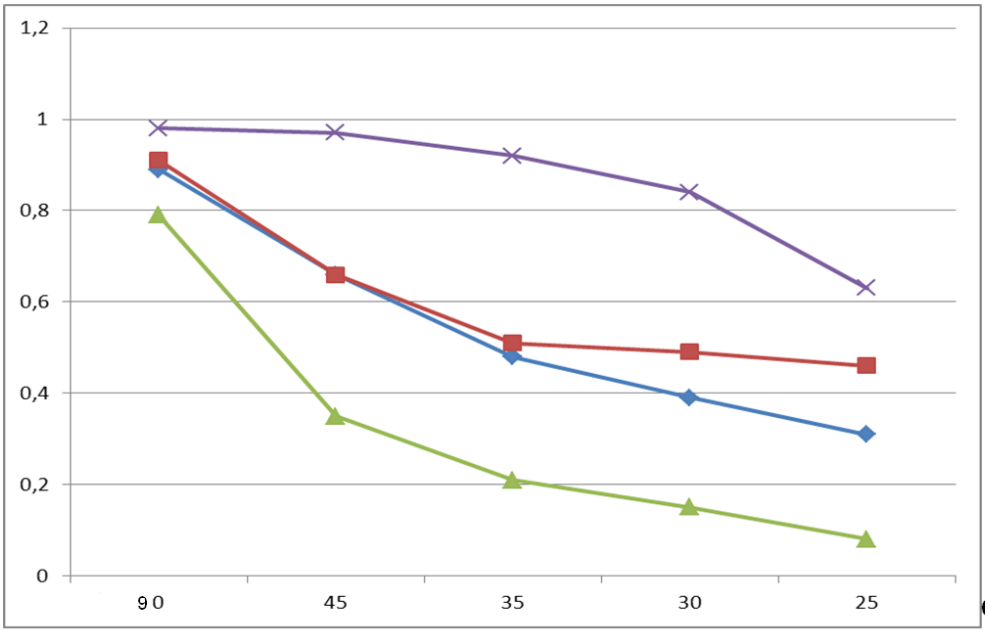

Fig.3. FDTD simulation of resolution power of 3D conical diffractive lenses: blue – Δx, red – Δy, green – Δz, the purple curve indicates the asymmetry of the focal spot Δx/Δy. The value of Δz is in the unit of classical depth of focus. All other values are in the unit of Rayleigh radius. At the horizontal axis the cone half-opening angle α is shown.

The analysis of the experimental results and simulations (Fig.3) shows:

* half-width (at half-height) of the field intensity distribution along the optical axis for a “conical” diffractive optical element, with parameters as shown above, is twice as narrow as that of an equivalent zone plate (when radiation is incident on the side of the apex of the diffractive optics) and less than $\Delta_z<2\lambda$;

* when radiation is incident on the side of the base of the diffractive optical element, the width of field intensity distribution along the optical axis is approximately 2.5 times wider than for the equivalent zone plate ;

* the resolution power of conical lens is about 0.7 wavelength with full cone angle of 70 degree in the first case.

It could be noted that the distance from the base of the cone to the focal point ΔF/λ is always ΔF>2λ. Therefore, the longitudinal resolving power (axial resolution) of the diffractive optical element can be controlled by choosing the flexure of the diffractive optical element surface and its spatial orientation and could be less than Abbe barrier. So the "Abbe barrier" was completely broken by such diffractive lenses with unique 3D super resolution.

Also a pilot study into design of high resolution imaging systems at mm-waves based on therajet phenomenon [8] has been performed. The results will be presented in a forthcoming paper.

It could be noted that *diffractive focusing elements* are crucial components of major range communications and instruments including nano-systems. Their design and manufacturing would be much faster and cheaper if one could avoid costly prototyping and measurements. To minimize design delays as well as to propose innovative radiating structures, it is necessary *to develop a scale model.* So investigations in millimeter wave/THz taking into account the scale effect may be transfer directly to optical and nanooptical bands.

According to the author's point of view, the development of 3D diffractive optics and nanophotonics are actual in the following main directions:

• Research of extraordinary effects formed in diffraction of electromagnetic waves on heterostructures containing a regular system of curvilinear steps or gaps aiming at overcoming the diffraction limit. These researches are based on free space 3D diffractive optics development by the author with coauthor in millimeter and THz bands. So an important element in the study of diffractive structures with curved areas is the creation of efficient computational methods of electromagnetic simulation.

• A photonic terajet (nanojet) formation based on diffraction effects on 3D arbitrary shape dielectric particles both in transmitting and reflecting modes are of great interest [9]. Such diffractive structures were developed to provide the most effective solutions for specific practical problems and are designed to best confine the nanofields. New devices containing dielectric particles, can significantly extend the component base of nanophotonics. In this frame, on-chip optical focusing elements and photonic jets produced by 3D particles of arbitrary shape integrated with hollow-core fibers could be investigated and constructed.

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2. D. B. Rutledge and M. S. Muha, "Imaging antenna arrays," *IEEE Trans. Antennas Propag.*, vol. 30, no. 4, pp. 535-540, Jul. 1982.

3. S. Koenig et al., "Wireless sub-THz communication system with high data rate," *Nature Photonics,* vol. 7, 977–981, 2013.

4. H. D. Hristov et al., "The grooved-dielectric Fresnel zone plate: an effective Terahertz lens and antenna," *Microw. Opt. Tech. Lett.*, vol. 54, no. 6, pp. 1343–1348, 2012.

5. O.V. Minin and I.V. Minin, *Diffractional optics of millimetre waves*, IoP Publishing 2004

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7. I.V. Minin and O.V. Minin. "3D diffractive lenses to overcome the 3D Abbe subwavelength diffraction limit," *Chinese Optics Letters*, vol. 12, no. 6, 2014, 12(06): pp.060014

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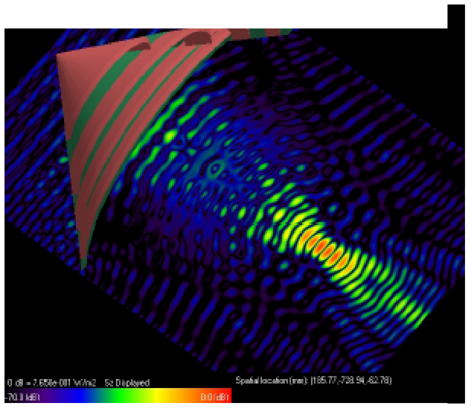
9. I.V.Minin, O.V.Minin. "Photonics of isolated dielectric particles of arbitrary 3D shape – a new direction of optical information technologies," Vestnik NGU, ser. Information technology, 4, 2014 – in Russian

Seminar announcement

The Institut d'Electronique et de Télécommunications de Rennes (IETR) invites you to attend a talk of

Prof. Igor MININ, full professor at the Siberian State University of Geosystems and Technology, Russia

Fresnel zone plates and 3D Fresnel dielectric lenses for imaging applications



Venue: Campus de Beaulieu, Bat. 11C, Conference room.

Date: February 20, 2015

Abstract: Many attempts have been made to improve the resolving power of optical imaging systems since Ernst Abbe discovered that the resolution of an imaging system is limited by diffraction.

In the first part of the presentation the behaviour of flat diffractive lenses, known as Fresnel zone plates (FZP), will be described for several small values of F/D and with focal distance F<2λ. The values of F<λ are of interest because the sub-wavelength resolution may be observed. The diffractive photonic crystal lenses will be also discussed. It will be shown that the minimum diameter of the focal spot near the central circumferential step of a binary diffractive axicon is equal to 0,38λ near it surfaces with D=12λ at 100 GHz band.

In the second part of the presentation, the new focusing structures, such as a curvilinear 3D millimeter wave FZP lens, will be discussed for sub-wavelength focusing. It will be shown that, in contrast to the flat diffractive lenses, the curvilinear 3D diffractive conical lens enables one to overcome the 3D Abbe barrier with more than F>2λ. As it will be noted, these effects observed in the MM and THz ranges taking into account the scale effect can be transfer directly to the optical and nano-optical bands.

Igor V. Minin received the Ph.D. degree in radio-physics and quantum physics from the Leningrad Electro-Technical University, Russia in 1986 and the D.Sc. degree in calculation experiment technology and microwave antennas from the Novosibirsk State Technical University, Russia, in 2004.

He worked as a Visiting Researcher at the DaimlerChrysler AG, Germany; Harbin Institute of Technology, China; Samsung Electronics, Korea; and University of Chile. He served as an Invited Lecturer at several universities and institutions, and as a co-chairman of several IEEE conferences and symposiums. In the years 2001-2006, he was with the Novosibirsk State Technical University, Russia, as a Full Professor at the Department of Information Protection. Currently, Igor Minin is a full professor at the Siberian State University of Geosystems and Technology, Russia.

Prof. Minin is a co-author of 8 books including Diffractive optics of millimeter waves (IOP Publisher, London, 2004), Basic Principles of Fresnel Antenna Arrays (Springer, 2008). He was also an editor and co-editor of the following books: *Microwave and Millimeter Wave Technologies from Photonic Bandgap Devices to Antenna and Applications* (InTECH, 2010) and *Microsensors* (InTECH, 2011). He has co-authored more than 300 technical papers in international journals and conference proceedings and holds 40 patents. He is a member of SPIE.

Prof. Minin was awarded several international diplomas and commendations including from Defense Ministry of Russia. His biographical data was included into Marques Who is Who in Science and Engineering. He is the editorial member of several international journals. Prof. Minin was the expert of COST 284 "Innovative Antennas for Emerging Terrestrial & Space-based Applications", IASTED. He is a Federal expert of Russian government scientific found