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Additive manufacturing of an antenna array

V. D. Burtsev [1]✉, K. A. Rogozhkin [1], T. S. Vosheva [1],
A. A. Khudykin [1], D. S. Filonov [1]

[1] Moscow Institute of Physics and Technology, Moscow, Russia
✉ burtsev.vd@phystech.edu

Abstract. Antenna arrays are essential elements in modern wireless communication technologies. Capabilities to perform real-time beamforming with millisecond-scale latencies enable supporting frontier 5G communication protocols. Being based on standard lithography methods, printed board antenna arrays are two-dimensional by design. However, exploration of the third dimension allows for obtaining new capabilities, including wide-angle scanning, broadband impedance matching, higher directivity, and several others. Here we demonstrate an additively manufactured volumetric antenna array, where each individual element is 3D-printed and subsequently metalized with the aid of electrochemical deposition. Additive manufacturing is foreseen to provide capabilities of a complete production cycle, including electronics and peripheries, being fabricated within the same machine. Here, the full potential of volumetric antenna arrays will be revealed.

Keywords: additive manufacturing, antennae, 3D print, radio frequency, telecommunications, electrodynamics, antenna arrays

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Аддитивное изготовление антенной решетки

В. Д. Бурцев [1]✉, К. А. Рогожкин 1, Т. С. Вошева [1],
А. А. Худыкин [1], Д. С. Филонов [1]

[1] Московский физико-технический институт, Москва, Россия
✉ burtsev.vd@phystech.edu

Аннотация. Антенные решетки на печатных платах, основанные на стандартных методах литографии, по своей конструкции являются двумерными. Однако открытие третьего измерения позволяет получить новые возможности, включая широкоугольное сканирование, широкополосное согласование импеданса, более высокую направленность и ряд других. Здесь мы демонстрируем аддитивно изготовленную объемную антенную решетку, каждый отдельный элемент которой напечатан на 3D-принтере и впоследствии металлизирован с помощью электрохимического осаждения.

Ключевые слова: аддитивные технологии, антенны, 3D печать, радиотехнологии, системы связи, электродинамика, антенные решеки

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Introduction

The development of various additive technologies has been gaining momentum recently [1]. Additive manufacturing technology is a mixture of several traditional manufacturing methods for layer-by-layer manufacturing of the final product. Additive technologies serve science in various industries, ranging from ordinary applications (surface anodizing, decorative metallization with a thin shiny metal layer of plastic coatings) and to space applications. A bright example of an additive technology is three-dimensional metal printing, when a powerful laser, sintering metal dust, forms the frame of the test sample [2, 3]. Also, there already exists a set of developments in the field of printing with conductive ink for the manufacture of electrical circuits for the needs of electronics [4]. The range of applications of additive manufacturing methods is quite large. Their scope of applicability extends in the field of radio engineering and data transmission. There are a number of works devoted to obtaining electrodynamic structures using laser sintering [5, 6], drawing with conductive ink [7–9], polymer deposition [10], and others [11–13]. Some researchers use electrically conductive plastic to make antenna frames, which are subsequently metallized in a galvanic bath [14, 15]. The antennas obtained by this method practically do not differ from all-metal analogues and are well predicted using numerical modeling [16].

However, in advanced works, mainly one-sided metallization of the skeleton is considered, implying that the plastic sublayer is covered with metal only on one side, while the other boundaries are opened. This entails locking up the energy of the electromagnetic field in the dielectric. In order to estimate the effective electrical length of such an antenna, it is necessary to know the exact value of the dielectric constant of the plastic. There are several basic methods for measuring this value, for example, the NRW method [17], slot-line based methods [18] or various measurement methods using microstrip lines [19–22]. These methods suit well for planar structures or structures of simple shapes. For 3D objects of complex shape, their impedance is difficult to calculate. To overcome this limitation, in this work we are targeting at the frequency of 2.0 GHz, since above 5 GHz plastic begins to have a strong negative effect on the emitter performance [23], while below it does not have such an impact.

In this paper, we are going to highlight the possibility of assembling antenna arrays based on additively manufactured antennas.

Methods

We use 3D printing on a BCN3D SigmaX device with PLA-plastic filling. After that, the surface of the skeleton is covered with a thin layer of electrically conductive varnish, which allows subsequent metal deposition onto its surface. After the coverage process the whole structure is believed to be an antenna array which should not significantly differ from the one that could be obtained from pure metal.

To test the proposed method of 3D printing and electroplating, it was decided to use a model of an antenna array consisting of four three-dimensional antennas (2x2) located in the corners of a square with a side of 120 mm. The design of each standalone antenna was taken from a work on 3D evolved antennas prototyping [24].

Fig. 1,*a* shows the general geometry of the printed circuit board (PCB) layout for this antenna, where all the dimensions are given in millimeters. The thickness of the metallization is about 0.1 mm. The thickness of substrate is 1.5 mm. The reverse side of the PCB is the full metal ground. Fig. 1,*b* shows the general 3D view of the constructed antenna array.

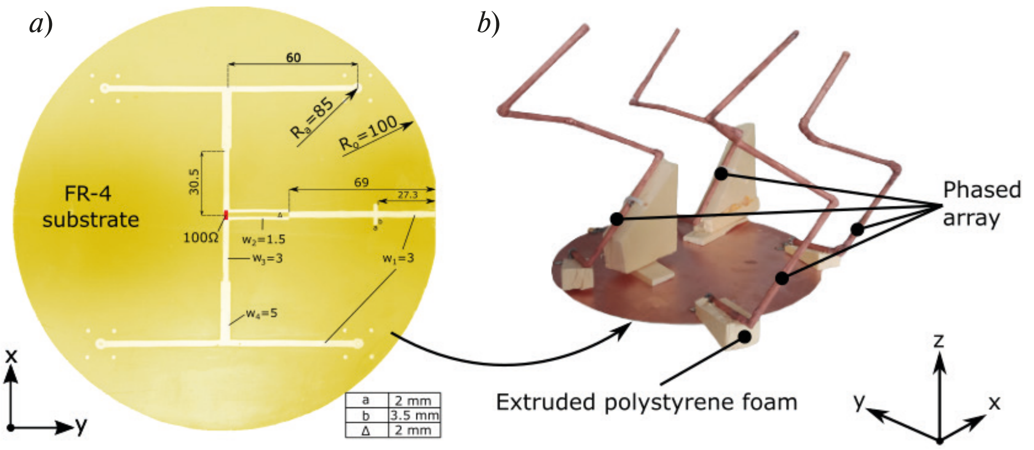

Fig. 1. Geometry properties of the antenna array: design of power supply wiring on the PCB with FR-4 substrate (*a*), photo of the general view of the antenna array (*b*)

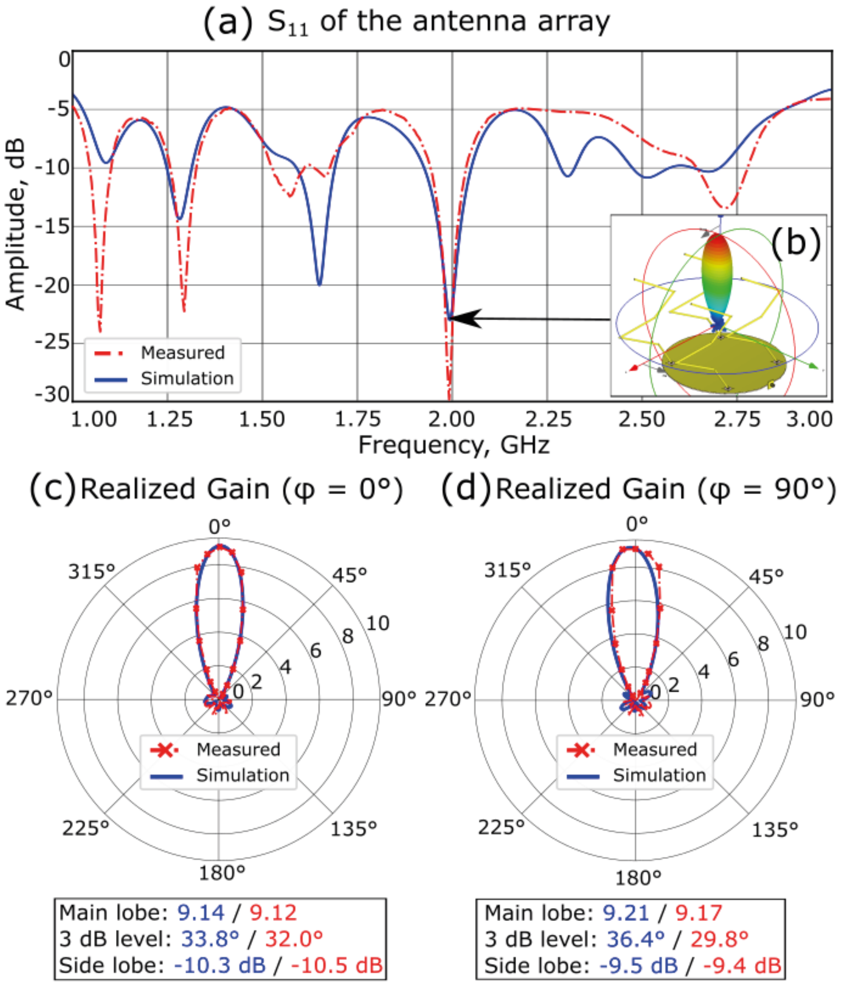

Fig. 2. Radiation properties of the antenna array: experimental (red dot-dashed line) and numerical simulation (blue line) data representation in comparison of reflection coefficient of the antenna array (*a*), radiation pattern at 2.0 GHz in numeric simulation (*b*), comparison of the realized gain patterns in orthogonal cuts φ = 0° and φ = 90° for experimental setup (red dot-dashed line with X marks) and computational results (blue line) (*c*) and (*d*)

The antenna array was prototyped in the CST Studio Suite software package. It was assumed that an antenna array with an aperture of 200 mm, consisting of 4 monopole antennas, should create a highly directional beam with a relatively high realized gain. Numerical modeling of the antenna was carried out by two different methods. The first of them is a simulation in the Time Domain Solver based on the finite integration method, when a solver in a wide frequency band calculates the development of an electromagnetic field propagating from the energy supply port of the system, launching a pulse. This method made it possible to obtain all the electrodynamic characteristics of the antenna in a wide frequency band. The second, clarifying method was modeling in the frequency domain, when Maxwell's equations are solved in the frequency domain, determining which part of the signal exists at the calculation frequency. This method made it possible to specify the exact frequencies of dips on the reflection coefficient graph (Fig. 2,*a*).

After the numerical simulation, to verify its results, the experimental study has been performed. The antenna measurements were carried out using the vector network analyzer Keysight P9374A, the signals from which were fed to the inputs of the measured antenna array and the measuring logoperiodic antenna with known efficiency. The reflection coefficient of the measuring antenna over the entire measured frequency range is below -12 dB, which allows us to assert the effectiveness of signal transmission at these frequencies. The distance between the antennas satisfied the far-field criterion, and was also much larger than the characteristic size of the antenna array. The angular dependences of the realized gain (Fig. 2, *c*, *d*), blue) are based on the matrix of the S-parameters of the antenna and represent S_{21}-parameter taken at the same frequency using a rotary device and VNA. Fig. 2,*a* demonstrates the similarity between reflection coefficient from the simulation and from the real experiment. Numerical have shown that at 2 GHz, the antenna array has radiation pattern of single beam (inset in *b*). The discrepancies in this plot are explained by incomplete impedance matching of PCB structure and 3D emitters and irregularities in FR-4 substrate. Fig. 2 (*c* and *d*) shows a complete comparison of the emitted beam for a numerical experiment and for a real antenna array manufactured using additive technologies. It is noticeable that the results shown by the metallized antenna array agree well with the prediction of the computational algorithm. The gain is slightly lower due to additional losses in the dielectric, as well as power cables. The angle at the level of -3 dB from the main lobe remains, and the level of the side lobes remains approximately the same, which suggests that the signal will not have noticeable distortions when transmitting it using this antenna array.

Conclusion

In this paper, a 2x2 antenna array with three-dimensional emitters was described, manufactured using additive 3D printing technologies and selective metallization in a galvanic solution. Numerical simulation predicted results of the antenna array performance, and the results obtained in a real experiment coincide with the data of the computational algorithm with high accuracy. Thus, 3D antenna arrays can be used for receiving and transmitting information.

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THE AUTHORS

BURTSEV Vladimir
burtsev.vd@phystech.edu
ORCID: 0000-0002-7988-5213

ROGOZHKIN Kirill
rogozhkinkirill@gmail.com

VOSHEVA Tatyana
Vosheva.ts@mipt.ru
ORCID: 0000-0002-5786-4972

KHUDYKIN Anton
khudykin.aa@mipt.ru
ORCID: 0000-0001-7992-7981

FILONOV Dmitry
filonov.ds@mipt.ru
ORCID: 0000-0002-5394-8677

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