METHODS AND MEANS FOR RESEARCHING MICROWAVE DEVICES

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Abstract: This paper is considered to be a continuation of a previous publication devoted to applications of digital transformations and simulation modeling in aerospace engineering and security (IJITS, №3, 2023). The aim of the paper is to present methods and means for conducting microwave measurements and practical learning of real antennas, which are expressed in the design, modeling, and validation of the models and contribute to obtaining reliable simulation results. The theoretical framework of the study is supported by classifications of the main types of microwave devices and technologies used in innovative laboratories.

Key words: microwave technology, radar systems, horn antenna, planar antenna, dipole antenna, finite element method.

1. INTRODUCTION

Different methods for designing, simulating, and measuring multiple types of radio engineering devices are applicable in practice. For example, the Numerical Electromagnetics Code (NEC) uses “the method of moments (MOM) and was developed at Livermore National Laboratory” [1]. Its principle is expressed in the segmentation of antenna devices in order to study the impact of electromagnetic fields on each of their components, which leads to the generation of reliable results for microwave devices of small and medium sizes. Knowledge of their construction and parameters is required for this purpose. Therefore, the basic classification of the main types of microwave devices and the specialized classification of the microwave technologies contribute to better clarity related to the functionalities of key components of innovative microwave laboratories.

The research focuses on horn (from 300 MHz to 30 GHz) and planar antennas, which are among the most widely used and available for research in laboratory conditions as radio engineering devices in the microwave range (signals with a frequency of 300 MHz to 300 GHz and a length of the wave from 1 m to 1 mm) [2]. Horn antennas have several advantages for use in satellite communications and radar observation control, among which are high gain and strong directivity.
It should be noted that planar antennas are also suitable for certain applications in satellite communications where compactness is considered an advantage. An example of this is the small cube-shaped satellites, CubeSats, with an average size of 10 cm and the implementation of a secure, high-quality connection between satellites and ground stations. With their help, educational missions are successfully implemented, including those where multiple satellites are intended to function in sync to provide coverage over a large area of the earth's surface.

Specifically in relation to security, both types of antennas can be used for border control, video surveillance of important critical infrastructure assets, and navigation because horn antennas are a key component of radar surveillance systems and planar antennas provide connectivity to checkpoints. For greater clarity, the overall technological process can be divided into several stages, as follows:

- **First stage: generation of radio waves** – in the course of their propagation, they reach the objects and are reflected from them back to the source.
- **Second stage: analysis of signal parameters** - signal frequency and intensity.
- **Third stage: extraction of information about objects** - location, speed, and trajectory of movement. The time it takes for the waves to travel the distance to the objects and return to the source can actually be measured. Based on the time and speed, the distance to the objects can be calculated.
- **Fourth stage: visualization** - if the radar system has a system for visual reproduction of the digital data, the received information is visualized on a radar screen and is subject to real-time post-processing.

The representation of the study is divided into four sections. Section 2 describes methods for conducting microwave measurements with antenna devices and classifications of innovative microwave devices and technologies that are used in security alongside planar and horn antennas (phased array antennas, reflector antennas, microwave filters and detectors, signal switches between antennas, scanning devices, etc.). Section 3 includes the practical part of the study related to the design, modelling, and validation of selected basic types of microwave devices. Section 4 presents a simulation study conducted using the NEC method in two different software environments, as well as an evaluation and analysis of the generated results.

2. MICROWAVE MEASUREMENT METHODS WITH ANTENNA DEVICES

In microwave measurements with antenna devices, the areas of electromagnetic radiation are important. They are called reactive near field, near radiation field, and far field. Regarding the measured parameters, it is important to pay attention to a few factors related to gain, antenna phase error, and polarization, which will be explained in the next subsections.

2.1. Related work

This part of the paper is based on a free-to-use source entitled “Antenna measurements” [3] and a practical guide entitled “Microwave Integrated Circuits in the Laboratory“ [2]. According to the scientific information described in them the
reactive near field is located at a distance $0 < r < \lambda/2\pi$ from the antenna aperture and it is characterized by a reactive (imaginary) and three-component energy flow vector ($\text{Poynting vector } S = E \times H$), which has components along the three spherical coordinates $(r, \theta, \phi)$, where the angle $\phi$ ("Phi") measures the angular distance to the x-axis in the lateral plane, while the angle $\theta$ ("Theta") measures the angular distance from the pole that is located in the z-direction.

The near radiation field (near field or Fresnel) is located at a distance from the antenna in the interval $\lambda/2\pi < r < 2D^2/\lambda$, where $D$ is the maximum size of the aperture (antenna opening). Its effective area represents the amount of energy that the antenna can transmit or receive, while the far field (Fraunhofer region) is characterized by a real Poynting vector, which in this case is two-component and is described by $\theta$ and $\phi$ since $r > 2D^2/\lambda$, $r > 10\lambda$ (for relatively small antennas). The gain indicates how efficiently the antenna converts the input power of the signal emitted by the source into the output power of the radio waves emitted by the antenna, as it is directly proportional to the directivity of the signal and the efficiency factor $\eta$, while it is acceptable in some particular cases to assume the gain and directivity to be equal [4].

Inaccuracies in directivity diagrams may be observed in far-field measurements. In this case, it is necessary to calculate the phase error of the antenna (the difference between the phase centres of the reflected waves and the antenna), for which it is necessary to compare the directivity diagrams under ideal and real conditions. Simulation studies allow the position of the phase centre to be determined with high accuracy. Essential for improving the quality of communication is polarization, as it determines the orientation of the electric field $E$ of the waves, which in the most used linear polarization is oriented in one plane but can move in a horizontal direction (parallel to the earth's surface) or vertical direction (perpendicular to the earth's surface).

Due to the wide variety of modern devices in the microwave range, it is necessary to initially systematize them in a basic classification, which will subsequently be upgraded to a specialized classification of microwave technologies for specialized applications. It is necessary to clarify that passive devices do not contain active elements (for example, transistors), unlike active ones, and do not use an external electrical power supply.

- examples of passive devices: dipole antenna; microstrip line; microstrip resonator; planar microstrip hybrid bridge; planar microwave filter; microstrip antennas; and antenna arrays, etc.

Some passive devices contribute to higher efficiency by amplifying the signal energy. For example, the microstrip resonators are characterized by a resonant frequency, which means that the frequency of the input signal matches the natural frequency of the system to achieve the highest signal amplitude. Microstrip antennas can be designed as a patch antenna or a microstrip dipole, the structure of which includes an active part (the radiator) for emitting or receiving radio waves and a feeder through which the radiator is connected to an external device for signal processing and transmission.
• **examples of active devices:** Gunn diode microwave oscillator; microwave oscillator and reflection amplifier with an IMPATT Diode; hybrid balanced mixer; bipolar transistor microwave oscillator; field effect transistor microwave amplifier; digitally controlled microwave phase regulators, etc.

The Gunn diode microwave oscillators find applications in radar and microwave communication systems because of their compact structure, which combines semiconductors to increase device efficiency.

There are other advanced microwave technologies that are applied in security, as follows:

• **Microwave Intruder Detection System (MIDS)** - its main components are Microwave Security Sensors that register presence or motion through changes in the microwave electromagnetic field.

• **Massive Planar Antenna Arrays for Physical Layer Security** – they are based on the wireless communication technology (MIMO - Multiple-Input and Multiple-Output) and contribute to strengthen the security of the physical layer due to the increase in the number of devices connected to the Internet. The co-transmission and jamming technique enhances physical layer security and helps prevent passive eavesdropping [5].

• **microwave cameras** – used for detecting hidden objects in real time by a parabolic reflector and scanning devices in order to improve aviation security and screening procedures at airport checkpoints.

It should be noted that the author's previous research work in the field of microwave techniques and technology is related to the 3D modelling and simulation of radio engineering devices of different structures, functionality, and purposes after preliminary software calculations of their parameters. Among them are those printed using 3D printers (pyramidal horn and exponential antennas for frequencies 4 and 8 GHz) or machine-produced (planar antennas for a frequency of 2.45 GHz) with a view to building functional prototypes for conducting measurements in specially equipped microwave laboratories by different methods.

Under laboratory conditions, research methods in the near area are feasible using the Near-field Scanning, which involves scanning an antenna using a scanner (planar, cylindrical, or spherical) and measuring the properties of the antenna and the amplitude and phase of the electric and/or magnetic field with a measuring probe (typically an open-ended waveguide). The response of the antenna is examined using a vector network analyzer, and all results are processed and examined using a computer. In this case, some clarifications need to be made. When a cylindrical scanner is used, it rotates in the horizontal azimuthal plane, and the probe performs vertical movements, describing a cylindrical surface around it. The advantage of using a spherical scanner (the measured antenna rotates in two planes and the probe is stationary) is expressed in "complete coverage of the field around the antenna", therefore the method is suitable for "antennas with wide directivity patterns, i.e., small amplification factors“ [3].

If a special channel to place the antenna is used (Channel Sounding), the material for its manufacture is essential. For example, fiberglass is a suitable choice in terms of strength and quality to minimize negative climate impacts. In addition, it does not allow the passage of electric current through individual parts of the antenna. Dielectrics
(glass, ceramics), metals, metal alloys, and plastics are also suitable.

Some widely used far-field methods are: Compact Antenna Test Range (CATR), Far-field Antenna Test Range (FATR), Antenna Range (AR), and Holographic Imaging. FATR uses a measuring station and signal electronics, while AR is realized by a rotating antenna, a spectrum analyser, and a measuring system with probes. In the CATR method, it is practiced creating a virtual aperture for the antenna, which is achieved by using a large-sized parabolic reflector in which the antenna itself is placed. Far-field measurements are simulated on the principle of reflection of the radio waves that the antenna emits, thereby recreating conditions for remote transmission. An innovative analogous far-field measurement method is HI, where a larger virtual holographic aperture is created using multiple compact antenna probes spaced apart to help distribute signals efficiently. Simulation products like CTS Studio Suite and ANSYS are powerful tools for recreating conditions for far-field measurements.

3. DESIGN, MODELING, AND VALIDATION OF MICROWAVE DEVICES

The method of simulation modeling is suitable for studying different types of microwave devices, given the wide variety of technological solutions that exist. The software product chosen for the present study is Antenna Magus, which enables the design, modelling, and validation of more than 350 microwave devices [6]. Its main advantage is the possibility of selecting conventional devices for implementation of a specific microwave technology, which in this case is suitable for radar applications ("mm-band") in the frequency range of 110-300 GHz, containing specific radar frequency bands (126-142 GHz, 144-149 GHz, 231-235 GHz and 238-248 GHz, which are below 275 GHz). The basic input parameters set by the author are consistent with these constraints and summarized in Table 1.

<table>
<thead>
<tr>
<th>Groups of input parameters</th>
<th>Input Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency bands</strong></td>
<td>f\text{\text{_min}} - minimum frequency, GHz</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>f\text{\text{_max}} - maximum frequency, GHz</td>
<td>248</td>
</tr>
<tr>
<td></td>
<td>bw-bandwidth), %</td>
<td>3</td>
</tr>
<tr>
<td><strong>Radiation pattern</strong></td>
<td>Dir-directivity, dBi</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>G-gain, dBi</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>bw3dB – beamwidth, deg (°)</td>
<td>360</td>
</tr>
<tr>
<td><strong>Materials and physical</strong></td>
<td>Frequency for substrate parameters (f), GHz</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>\varepsilon – relative permittivity</td>
<td>1-100</td>
</tr>
<tr>
<td></td>
<td>\mu_r – relative permeability</td>
<td>1-100</td>
</tr>
</tbody>
</table>

Based on these input parameters for the radar system, the software allows two choices of compatible devices: a waveguide-fed pyramidal horn antenna and a linear resonant slotted-waveguide array, the main input parameters of which are shown in Fig. 1. In this simulation research, the scientific and applied contribution of the author is expressed in proposing options for the optimization of the designed radar system.
based on the advantages of the two devices. While the directivity and strong gain characteristics of the pyramidal horn antenna are well recognized and can be applied to radar systems in order to achieve high precision coverage of a certain area by changing the azimuth of the antenna to determine the signal's direction of arrival and increasing the radar resolution by narrow beams, the linear resonant slotted waveguide array has some important advantages for optimizing the radar system, as follows:

- **fast scanning capability** - the transmitted signal direction may be quickly changed by resonant tuning the slots to various frequencies.
- **individual slot management** - enables radiation in different directions and various forms of the radiation pattern.
- **variable gain and pattern** - the gain and form of the radiation pattern can be adjusted to adapt to specific scenarios by controlling the individual slots.

Fig. 1. Main input parameters of a waveguide-fed pyramidal horn antenna and linear resonant slotted waveguide array.

### 3.1. Assessment and analysis of the simulation results

The radiation patterns of both devices (Fig. 2) show positive equivalent values of the gain $G$, but it should be noted that the gain of the linear resonant slotted waveguide array gradually increases at higher frequencies because a more narrowly focused directivity pattern can further increase the effective gain in certain directions. Based on the parameters entered in Table 1, a clarification must be made regarding the dielectric permittivity and magnetic permeability of the materials to be used. The improvement of the efficiency of microwave devices is achieved at higher values of dielectric $\varepsilon_r = D/E$, where $D$ is the vector of electric displacement (electric flux density, $[C/m^2]$), and $E$ is the vector of the electric field $([V/m])$, because materials with a high value of dielectric permittivity are characterized by their insulating properties.

In terms of the magnetic permeability $\mu_r = B/H$, where $B$ is the vector of magnetic flux density ($[T]$) and $H$ is the vector of the magnetic field $([A/m])$, higher values help to maintain the magnetic fields but carry the risk of magnetic saturation and reduced efficiency. In a simulation environment, it is permissible in some of the scenarios to set maximum values of both quantities in order to evaluate and analyse the functioning of the systems under extraordinary conditions.

It is necessary to pay attention to the fact that both devices are of linear polarization, which is most often used due to the following advantages: good compatibility with different radio systems, easier orientation, and the possibility of mixing two linearly polarized signals at an angle.
4. A SIMULATION STUDY CONDUCTED USING THE NUMERICAL ELECTROMAGNETICS CODE METHOD

The NEC-2 is suitable for modelling wire and pipe structures “possibly connected through networks of lumped components or transmission lines” that operate in a vacuum. It is used for “analysis and design of many types of antennas” and actually, the “open source essentially focuses on the method of Finite Differences in the Time Domain (FDTD)” [7] and on the Method of Moments (MoM)” [8, 9].

4.1. Simulation modelling of a planar microstrip patch antenna using software 4nec2

If the input parameters frequency 2.45 GHz (Edit > Input (.nec) file > Freq./Ground: Frequency-start) and geometry for a planar rectangular microstrip antenna (Run > Geometry Builder > Patch) are entered into the 4nec2 simulation product, as shown in Fig. 3, the generated results (Calculate > NEC output-data > Generate) are shown in Fig. 4. In the next step, a 3D visualization can be made from (Window > 3D Viewer) of the directivity diagram presented in Fig. 5.
Fig. 4. Generation of simulation results for the far-field radiation pattern of a rectangular microstrip antenna at frequency $f = 2.45$ GHz.

Fig. 5. 3D visualization of the radiation pattern of a rectangular microstrip antenna at frequency $f = 2.45$ GHz.

4.2. Simulation modelling of a planar dipole antenna using software EZNEC

The simulation environment EZNEC [10] has a built-in library of models that can be imported after pressing the Open button and visualized in the workspace by pressing the View Ant button (Fig. 6). The description of the selected "Dipole in free space" device for a maximum frequency of 2.45 GHz is contained in the Ant Notes. The main advantages of this type of antenna, which make it suitable for aerial and mobile applications, are expressed in its simple structure and low profile, which explains why it is used for flat and non-flat surfaces [11].
Fig. 6. Open a dipole antenna model from the built-in EZNEC library.

The frequency range settings are entered in the window SWR (Standing Wave Ratio) Sweep Parameters after pressing the SWR button, which generates the so-called standing wave ratio and, more precisely, the ratio of the maximum to the minimum voltage of the transmission line [12]. The diagram in Fig. 7 illustrates the dependence of SWR on frequency as well as the radiation pattern of a planar dipole antenna at 2.45 GHz.

Fig. 7. SWR as a function of the frequency and the radiation pattern of a planar dipole antenna at 2.45 GHz.
4.3. Assessment and analysis of the simulation results

Regarding the specific shape of the diagram in EZNEC, which shows the dependence of SWR on frequency, it should be concluded that resonant frequencies are present or the antenna is not functioning efficiently enough at all frequencies due to various external factors. However, the maximum gain in this case has a positive value of $G = 4.74$ dBi, which can be seen after visualizing the directivity diagram in Fig. 7 by pressing the *FF Plot* button. The generated result can be defined as satisfactory compared to an ideal isotropic antenna, assuming that at $f = 2.45$ GHz, an average gain of 2 dBi is considered standard.

The evaluation of the generated data from the simulations using EZNEC and 4nec2 shows that software products whose built-in algorithms are based on the method NEC are characterized by possibilities for conducting extended experimental studies for the purposes of microwave technology and security because the values of the gain $G$ in both cases at the same frequency are in the same range and almost equal: the total gain in 4nec2 is equal to 4.52 dBi and the $G = 4.74$ dBi in EZNEC. Consequently, it can be assumed that the minimal difference is due to the constructional features of the antennas, and the two simulation environments are suitable for mutual verification and validation.

5. CONCLUSION

The methods and technologies described in the paper are part of the overall process of building functional prototypes of microwave devices that can be used to conduct measurements in specially equipped microwave laboratories. Simulation studies of horn and planar antennas using different software products contribute to the construction and improvement of antennas for specific applications and allow the evaluation of their performance in various scenarios and settings. Besides, simulation models can help detect “different types of faults through monitoring the electric, voltage, power, and frequency values” [13].

The development of more precise and effective modelling and measurement techniques for microwave devices and antennas is the main focus of ongoing research trends in this field. Therefore, this study can also be extended to explore the prospects of optimizing microwave devices and adapting them to specific environmental conditions and applications, such as in the field of security and in sensing and communication systems.

Microwave technology is also constantly being improved from a design point of view. Research into new shapes, materials, and structures can lead to more efficient and compact antennas that meet the specific requirements of a wide range of applications. For example, the development of the Internet of Things (IoT) requires the miniaturization and integration of microwave devices, which opens up new possibilities for monitoring, sensing, and communication because IoT is based on “device-to-device communication” [14].
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