applied sciences

MDPI

Article

Influence of Dielectric Plate Parameters on the Reflection Coefficient of a Planar Aperture Antenna

Vanja Mandrić *, Slavko Rupčić *, Snježana Rimac-Drlje and Ismail Baxhaku

Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, J. J. Strossmayer University of Osijek, 31000 Osijek, Croatia

* Correspondence: vanja.mandric@ferit.hr (V.M.); slavko.rupcic@ferit.hr (S.R.); Tel.: +385-996915352 (V.M.)

Abstract: In this article, an aperture antenna excited by a waveguide with a circular cross-section and covered with a dielectric plate was analyzed via simulation calculation and verified via measurements. The influence of the geometrical and electromagnetic parameters of the dielectric plate on the reflection coefficient S_{11} of the antenna opening was systematically analyzed. The geometrical parameters taken in this analysis are the thickness d and the width/length h_1/h_2 of the dielectric plate. The electromagnetic parameters used in this analysis are the real and the imaginary part of permittivity (ε_r, tan δ) and the electrical conductivity of the dielectric plate (σ). The simulation calculation and analysis included other structural and electromagnetic parameters of the dielectric plate (density of the radome material, relative permeability, and magnetic loss tangent (ρ, μ_r, and tan δ_μ, respectively)), but the results show that in the range of real values of these parameters for the materials used for the dielectric plate, they had no significant influence on the reflection coefficient. The results show that impedance-matched antennas with very low values of the reflection coefficients S_{11} at the resonant frequency can be realized by changing the geometrical and electromagnetic parameters of the dielectric plate material. The results are presented for a circular aperture antenna on a planar grounded plane with a dielectric plate on the opening, and the achieved lowest values of the S_{11} parameter were −45.17 dB (simulated) and −43.93 dB (measured) at the frequencies of 1.7820 GHz and 1.7550 GHz, respectively. The estimated values of the dielectric plate parameters in this case are thickness d = 11.08 mm (0.67 λ); width × length of grounded plane and dielectric plate $h_1 \times h_2$ = 423 × 450 mm^2 (2.51 × 2.67 λ); relative permittivity 2.5, tan δ = 0.09, μ_r = 1, tan δ_μ = 0.00, ρ = 1200 kg·m^{-3}; and electrical conductivity σ = 0 S/m. The simulation calculation results were verified by measuring the reflection coefficient S_{11} on the created laboratory model of the aperture antenna with the dielectric plate and showed a very good match.

Keywords: reflection coefficient; aperture antenna; dielectric plate; permittivity; loss factor; permeability; magnetic loss factor; electric conductivity; circular waveguide

check for updates

Citation: Mandrić, V.; Rupčić, S.; Rimac-Drlje, S.; Baxhaku, I. Influence of Dielectric Plate Parameters on the Reflection Coefficient of a Planar Aperture Antenna. *Appl. Sci.* **2023**, *13*, 2544. https://doi.org/10.3390/app13042544

Academic Editor: Daniele Funaro

Received: 6 January 2023
Revised: 8 February 2023
Accepted: 14 February 2023
Published: 16 February 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Antennas provided with radomes and their influence on the radiated electromagnetic field were investigated as early as the 1980s [1].

The antenna radome was originally intended as a form of physical protection of the antenna, connectors, cables, and all components of the antenna system against environmental influences. All these parts of such system can have a bad effect on the antenna reflection coefficients and, thus, affect the operation of the antenna at the desired wavelength. Several studies have been conducted that are focused on the antenna radome and its influence on the operation and parameters of antennas [2–7].

The authors in [2] provide the design of a dielectric radome created to protect the antenna from environmental conditions via a series of conductors in the structure that enables a lower reflection coefficient of incident electromagnetic waves at the operating wavelength of the antenna.

A modified Paris' model of a flat multi-layer radome structure (with anisotropic material) is presented in [3], and it is combined with a measuring method for accurate determination of the dielectric constant and dielectric loss.

The study presented in [4] reviews the design of antenna radomes (electrically thin, half-wave, A-sandwich, C-sandwich) and their influence on antenna parameters (RF reflection and insertion loss), and the authors conclude that a proper selection of the radome and its characteristics can help to improve the performance of the entire antenna system.

The quality and the impact of the dielectric-radome weather radar antenna are analyzed in [5] from the radiation pattern point of view to verify the antenna and radome specifications of the new Hohenpeissenberg radar. Measurements obtained from three different source locations in the far field of the antenna show that all major parameters of the antenna (i.e., 3-dB beamwidth, beam squint, and sidelobe levels) are satisfied with and without the radome.

In article [6], the author highlights a very important role of radar in air and sea communications, remote data reading, weather forecasting, and defense. The radome placed on the antenna serves several purposes. It protects the antenna and its constituent parts from external disturbances (such as snow, rain, wind, etc.), but research has shown that the exact choice of the material covering the antenna can significantly affect its properties and performance. The article explains the design and construction of the radome without compromising radar performance.

Another study [7] also recommends radome types such as polycarbonate, Teflon, and polystyrene to maintain good antenna performance and a satisfactory reflection coefficient, i.e., materials with the lowest possible dielectric constant and tangent loss. This describes the medium through which electromagnetic waves propagate, their dielectric constants, their effects on impedance matching, the ideal distance of the radome from the antenna, and the results of the antenna radiation pattern when the antenna radome is properly selected.

Article [8] deals with a similar topic in that the author describes in detail the properties and types of shield, the interaction with the antenna, the requirements for shielding, and the advantages of antenna shielding.

As can be seen from the above literature overview, covering antennas with a specific dielectric plays a very important role in the physical protection of antennas and radars and can even be used to improve antenna characteristics in the context of impedance matching, i.e., reflection coefficients [9].

The authors in [10] analyze the input admittance of a circular aperture antenna fed by a waveguide of a circular cross-section mounted on a spherical grounded surface. The analytical approach is based on the moment method in the spectral domain in the Fortran programming language. The aperture antenna is covered with a dielectric plate, and the changing of two parameters such as the thickness and permittivity of the radome has shown that it is possible to obtain rather good broadband admittance matching.

Similar research was carried out by the authors in [11], but it involved an aperture antenna fed by a waveguide with a circular cross-section mounted on a grounded plane. Moreover, the opening of the antenna is covered with a dielectric plate, and the research results showed that by changing only two parameters of the dielectric, it is possible to influence the reduction in the reflection coefficient of the antenna in question. Software for numerical calculation of the reflection coefficient S_{11} of an aperture antenna fed by a circular waveguide covered with a dielectric plate was Ansys HFSS (three-dimensional electromagnetic (EM) simulation software for the design and simulation of HF electronic element–antennas and antenna arrays). The theoretical and mathematical basis of the aforementioned software for solving problems in electromagnetism is the finite element method.

This article is a continuation of the research aimed at improving impedance matching of the aperture antenna and a detailed analysis of the structural and electromagnetic parameters of the dielectric plate placed on the antenna, [10–12]. References [10–12] analyze the influence of only two parameters (thickness and permittivity) of the dielectric on the admittance or reflection coefficient, whereas this article analyzes the influence of

all parameters of the dielectric plate (thickness of the material d in mm, density of the dielectric ρ in kg·m^{-3}, relative permittivity ε_r, conductivity of the dielectric σ in S/m, losses in the dielectric tan δ and tan δ_μ, and relative permeability of the material μ_r), and finally, simulation is validated with measured values. The aim of the article is to achieve the lowest possible reflection coefficient of the circular aperture antenna in order to accomplish the best impedance matching of the antenna itself.

Further study [13] considers polyurethane foams as dielectric materials in the construction of radomes. The study includes the following EM parameters of radomes: the relative dielectric constant and tangent loss at the frequencies ranging between 1 and 10 GHz.

The authors in [14] deal with the influence of water on the electrical conductivity and dielectric parameters of a microwave absorber, clarifying the difference between losses due to electrical conductivity and dielectric losses in the dielectric material (polarization).

The first section provides an overview of existing research on the performance of the dielectric radome, its parameters, and its influence on the overall performance of the antennas on which it is mounted. In the second section, a theoretical description of the incident wave on a dielectric single-layer material is given with analytical equations of the material parameters of the dielectric plate. Furthermore, all structural–geometric and electromagnetic (EM) parameters of the dielectric single-layer plate are presented, which are processed in the article by both simulation and measurement. Section 3 presents in detail the simulation results that describe the influence of the specified parameters of the dielectric plate on the aperture reflection coefficients of the antenna where the dielectric plate is located. Section 4 contains the measurement results of the reflection coefficients that are compared with the simulation results. The last section provides a detailed explanation of the results obtained for the influence of the dielectric plate parameters on the reflection coefficients of the antenna aperture with the dielectric plate.

In this article, the reflection coefficient S_{11} of the TE_{11} mode aperture antenna fed by a circular waveguide covered with dielectric is simulated and measured.

2. Analysis of the Parameters of the Dielectric Plate on the Antenna Aperture

2.1. The Thickness and Width × Length of the Antenna Aperture Dielectric Plate

Although a waveguide of a circular cross-section does not form a plane wave (TEM) but transverse electric (TE) wave or transverse magnetic (TM) wave reflection, the transmission and absorption of the EM wave when encountering the dielectric layer is identical. Namely, reflection at the first boundary and all transmitted multiple reflected waves created from the transmitted wave into the dielectric planar layer; these multiple reflected waves return to the waveguide and, at the same time, constructively or destructively interfere with the existing reflected wave at the first boundary result in a reflection coefficient.

2.1.1. Propagation and Reflection of a Plane Wave at the Boundary of Two Mediums

A simplified analysis of this problem uses a plane wave. In the case of a plane wave, the wave that arrives at the boundary of the two mediums consists of the electric and magnetic field strength *E* and *H*. These two fields are perpendicular to each other and, at the same time, perpendicular to the propagation plane of the total EM wave. The wave that arrives at the boundary is called an incident wave (E_i and H_i), whereas the wave that passes the boundary under certain conditions is called the transmitted wave (E_t and H_t). At the same time, part of the wave is reflected at the boundary and is called a reflected wave (E_r and H_r). A simplified situation is shown in Figure 1.

In such a case, the reflection coefficient S_{11} is calculated according to the following relation:

$$S_{11} = \frac{E_r}{E_i} = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}} = \frac{Z_{c2} - Z_0}{Z_{c2} + Z_0}, \quad (1)$$

where:

E_r—the electric field strength of the reflected wave in V/m;

E_i—the electric field strength of the incident wave in V/m;

Z_{c1} = Z_{c3}—characteristic impedance of the first and the third medium—the impedance of air in the waveguide is equal to the impedance of free space Z_0 in Ω;

Z_{c2}—characteristic impedance of the second medium–dielectric plate, also in (Figure 1).

The characteristic impedance of the medium through which the EM wave is propagated can be determined as follows:

$$Z_{ci} = \sqrt{\frac{\mu_i}{\varepsilon_i}},\ i = 1, 2, \tag{2}$$

where:

μ_i—the i-th medium permeability;

ε_i—the i-th medium permittivity.

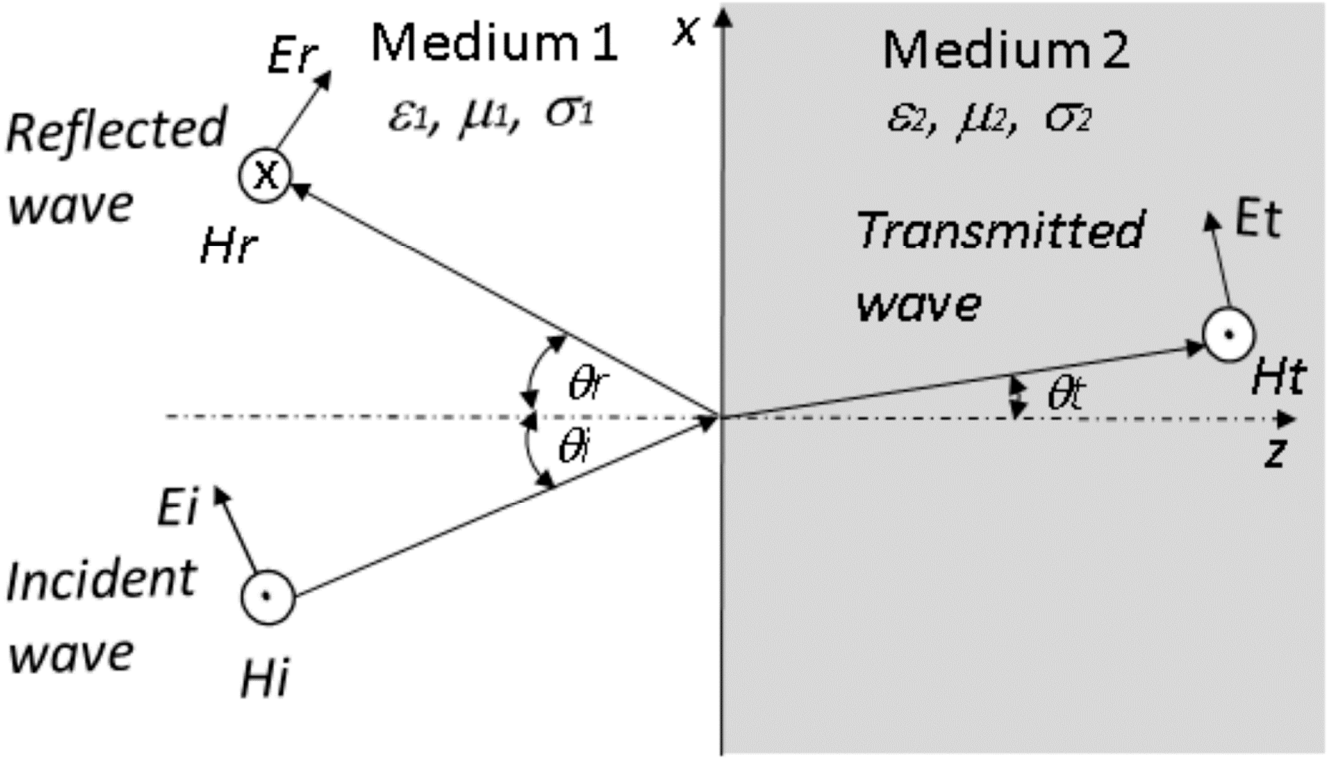
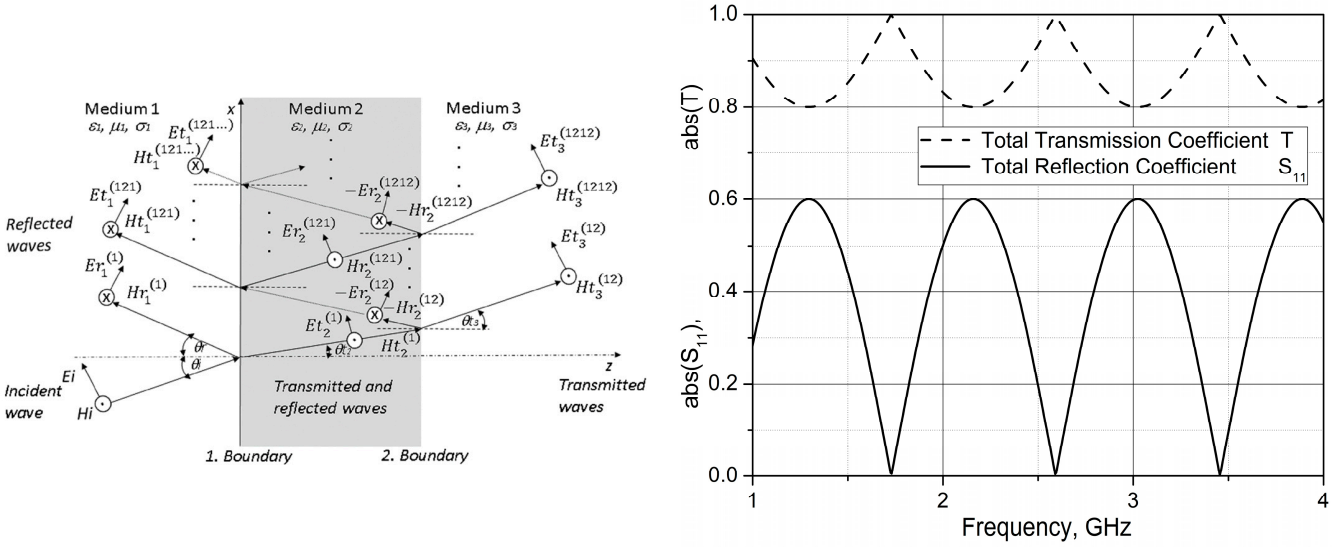


Figure 1. Incident and reflected waves in medium 1 and the transmitted wave in medium 2.

If it is assumed that mediums 1 and 2 (dielectrics) have the same relative permeability value, then the reflection coefficient at the first boundary can be calculated according to the equation:

$$|\Gamma_1| = |S_{11}| = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}};\ \text{and for } \varepsilon_1 = \varepsilon_0, |\Gamma_1| = |S_{11}| = \frac{1 - \sqrt{\varepsilon_r}}{1 + \sqrt{\varepsilon_r}}. \tag{3}$$

For the purpose of this research, there are two boundaries, the first is air–dielectric plate, and the second is dielectric plate–air (Figure 2a). The one-boundary approach is applicable to the case of multiple boundaries and to each of the boundaries individually. For example, for the case of two boundaries: (a) for the first boundary $\varepsilon_1 = \varepsilon_0$ (the permittivity of the air in the waveguide), and ε_2 is the dielectric constant of the dielectric plate; (b) for the second boundary, conversely, ε_1 is the permittivity of the dielectric plate, and $\varepsilon_2 = \varepsilon_0$. In the geometry of the two boundaries (the space inside the waveguide–dielectric plate and the dielectric plate-free space), the electric field strength *E* (incident, transmitted, and reflected) in each of the mentioned mediums is presented in detail in Figure 2a.



(**a**) (**b**)

Figure 2. Propagation of an EM wave through a dielectric plate of thickness d (one dielectric layer): (**a**) existing electric field strengths (incident, transmitted, and reflected); (**b**) the absolute value of the reflection and transmission coefficient S_{11}.

Figure 2a shows that part of the incident wave E_i passes the boundary between two mediums (E_t), whereas part of the wave is reflected (E_r).

In the problem of the EM wave arriving at two boundaries, the reflected wave in the first medium will consist of the reflected wave at the first boundary and all the waves that are transmitted into the first medium after multiple reflections between the two boundaries (within the dielectric plate). The total reflection coefficient S_{11} for two mediums is (Figure 2b) as follows:

$$S_{11} = \frac{E_r}{E_i} = \frac{\Gamma_1\left(1 - e^{j2k_2 d}\right)}{1 - \Gamma_1^2 e^{j2k_2 d}}. \quad (4)$$

The wave number of the second medium can be written as:

$$k_2 = \sqrt{\varepsilon_r} k_1, \quad (5)$$

where:

Γ_1—the first medium reflection coefficient;
S_{11}—the total reflection coefficient;
d—dielectric plate thickness;
k_1—the wave number of the first medium.

In the labels referring to electric and magnetic field strengths in Figure 2a, the numerical value of the index indicates the medium in which the fields propagate, whereas the numerical value of the exponent of these fields indicates the order of the boundary at which reflection or transmission occurs. Letters *i*, *r*, and *t* in the index indicate the incident, reflected, and transmitted wave, respectively. A minus sign represents a reflected wave propagating from boundary 2 to boundary 1, whereas a plus sign represents the opposite direction.

The total reflected wave is obtained by superposition of all waves coming from the direction of the first boundary into the first medium. These are the first reflected wave at the first boundary and all transmitted waves from the second medium (dielectric plate) to the first medium (air) (Figure 2a). The total transmitted wave is obtained by superposition of all waves passing the second boundary from medium 2 to medium 3 (Figure 2a).

2.1.2. Propagation and Reflection of an EM Wave Generated in a Circular Cross-Section Waveguide at the Boundary of Two Mediums

Due to the simplicity of the construction, the microwave antenna with a circular opening is very widely used (Figure 3).

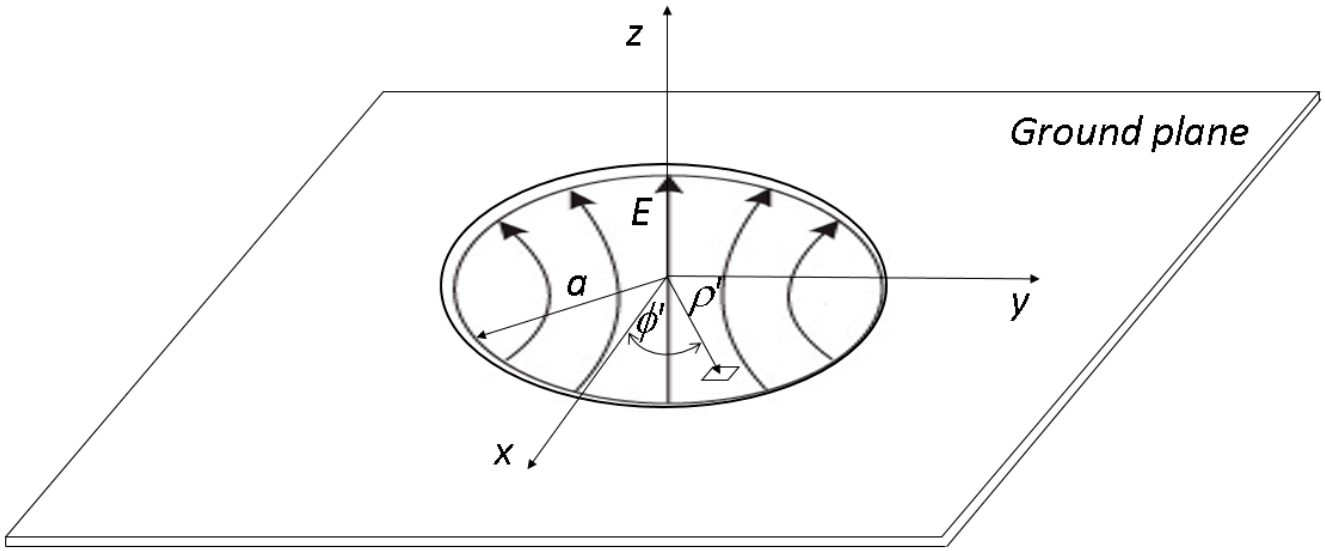


Figure 3. Dominant TE_{11} mode distribution aperture on the grounded plane.

A circular aperture antenna is most often excited by a circular cross-section waveguide. Waveguide modes are generated in a circular waveguide excited by a quarter-wave monopole antenna (probe). The mode with the lowest cut frequency is the dominant mode. In the case of a circular waveguide, it is mode TE_{11}. Figure 4 shows the *E* and *H* field lines of the dominant mode of a circular cross-section waveguide The straight line of the arrow indicates the strength of the electric field *E*. The dashed arrow indicates the strength of the magnetic field *H* (the *H*-field is perpendicular to the *E*-field). The signs × and dot indicate the direction of the *H*-field—inwards and outwards respectively.

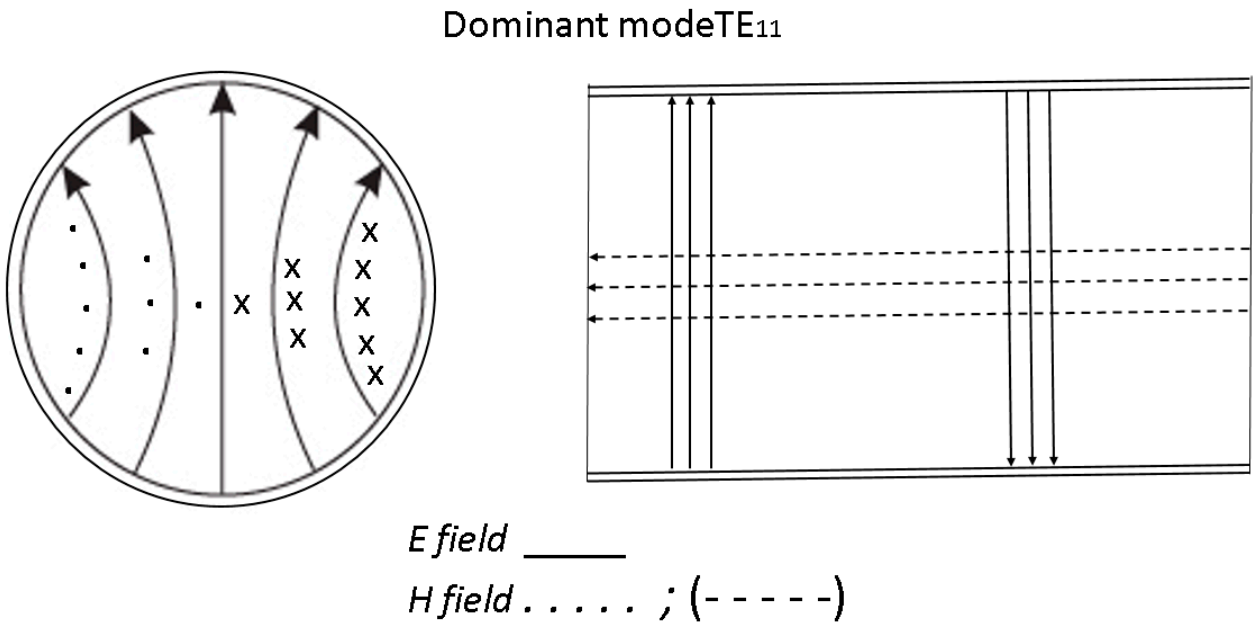


Figure 4. Lines *E* and *H* of the dominant mode (TE_{11}) of waveguides with a circular cross-section.

The tangential component of the TE_{11} mode electric field inside the waveguide can be expressed by the equation:

$$E_w = \hat{a}_\rho E_\rho + \hat{a}_\varphi E_\varphi, \tag{6}$$

where $\hat{a}_\rho$ and $\hat{a}_\varphi$. are unit direction vectors, and electric field components E_ρ and E_φ. are:

$$E_\rho = \frac{E_0}{\rho\prime} \cdot J_1\left(\frac{x'_{11}\rho\prime}{a}\right) \cdot \sin\varphi\prime \cdot e^{-j\beta_w z} \tag{7}$$

$$E_\varphi = E_0 \cdot J'_1\left(\frac{x'_{11}\rho\prime}{a}\right) \cdot \cos\varphi\prime \cdot e^{-j\beta_w z}, \tag{8}$$

and for z = 0, we have the tangential component of the TE_{11} mode electric field at the waveguide aperture (antenna aperture) [15]:

$$E_\rho = \frac{E_0}{\rho\prime} \cdot J_1\left(\frac{x'_{11}\rho\prime}{a}\right) \cdot \sin\varphi\prime \tag{9}$$

$$E_\varphi = E_0 \cdot J'_1\left(\frac{x'_{11}\rho\prime}{a}\right) \cdot \cos\varphi\prime, \tag{10}$$

where E_0 is the amplitude of the electric field; J_1 and J'_1 are the Bessel function of the first order and its derivative, respectively; $x'_{11} = 1.841$ is the zero point of the derivative of the Bessel function of the first order; $\rho\prime \leq a$ is a waveguide radius variable; $\varphi\prime$ is the variable of the azimuthal angle of the waveguide; $\beta_w = \sqrt{\omega^2\mu\varepsilon - \left(\frac{1.841}{a}\right)^2}$ is the propagation constant in a circular waveguide; and the label $\prime = \frac{\partial}{\partial\rho\prime}$ is a partial derivative by the radius variable.

The opening of the antenna is usually protected by a dielectric shield (radome), which has the primary role of protecting the antenna from atmospheric influences and damage. Nevertheless, this radome can significantly improve the radiation properties of the antenna by choosing a dielectric that allows for less reflection and better adjustment of the antenna impedance. Mounting radomes on the antenna opening leads to the problem of EM wave propagation through a layered medium.

This article has examined a total of three mediums through which an electromagnetic wave is propagated. The first medium refers to the space inside the waveguide of the circular aperture antenna. The second medium is the dielectric plate, and the third medium has the properties of free space. This scenario is illustrated in Figure 5. The first and the third medium have the same dielectric properties.

Due to the geometry of the problem, in the case of excitation of the antenna aperture with a waveguide, the incident wave arrives at the first boundary at an angle of $\Theta_i = 0°$. It can be easily concluded that the other two angles are $\Theta_r = 0°$and $\Theta_t = 0°$.

In addition to the electromagnetic parameters of the dielectric plate, the analysis will include two aspects related to the dimensions of the dielectric plate itself. These are the thickness of the dielectric plate and the width/length in relation to the grounded plane. The thickness has a significant influence on the values of the S_{11} parameter, whereas the width/length of the dielectric plate is about the connection between the majority of the grounded plane and possible diffraction problems.

In the remainder of the article, simulation analysis using the HFSS application routine will solve the problems of reflection and transmission, and the emphasis will be placed on determining the minimum of the reflection coefficient S_{11} with different parameters of the protective shield (radome).

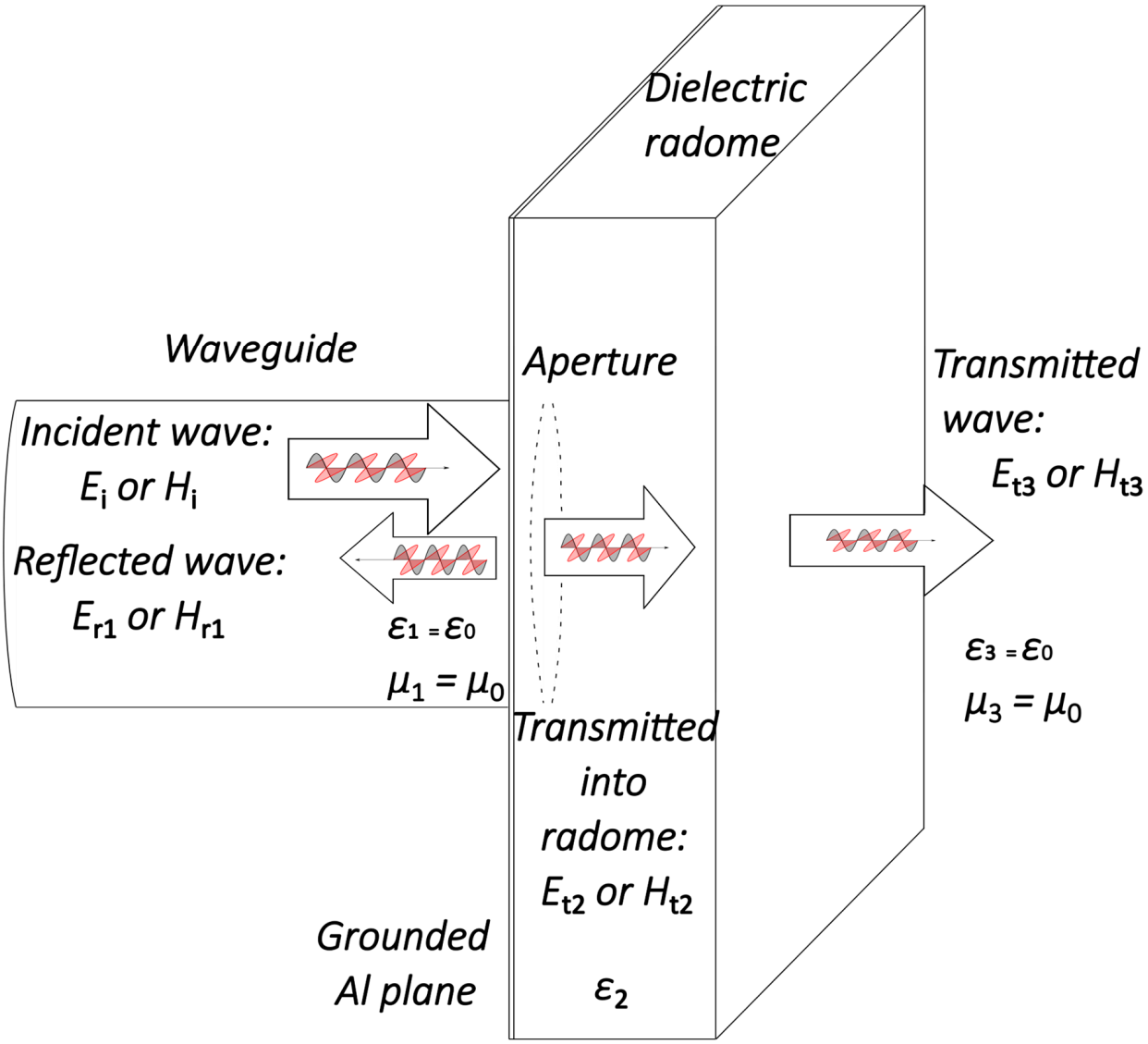


Figure 5. Electromagnetic wave propagates through three mediums: space in the wave-guide, a dielectric plate on the aperture antenna, and free space.

2.2. Permittivity and Electrical Conductivity of the Dielectric Plate

The importance of a material's dielectric properties in industrial applications has recently increased. These properties provide valuable information for improving product design, processing, quality, and control.

The permittivity ε is generally a complex number that describes the interaction of a material with an electric field [13,16]. Low values of the relative permittivity are values that characterize insulators [11,12].

The permittivity can be expressed as follows: $\varepsilon = \varepsilon' - j\,\varepsilon'' = |\varepsilon|e^{-j\delta}$, where $\varepsilon' = \varepsilon_0\,\varepsilon_r$ is the real part of the permittivity ε that represents the stored electric field, and $\varepsilon'' = \varepsilon_0\,\varepsilon_r''$ is the imaginary part of the permittivity that stands for the loss factor-a measure of the amount of energy dissipated. δ is the dielectric loss angle. The parameter tan δ is loss tangent or the dissipation factor DF.

If the material is not a perfect dielectric, the losses in the material can be expressed as losses in the dielectric (ε_d'') and losses due to electrical conductivity (ε_c'') of the material:

$$\varepsilon_r'' = \varepsilon_d'' + \varepsilon_c'' = \varepsilon_r \tan\delta + \frac{\sigma}{\omega\varepsilon_0}, \tag{11}$$

where ε_r'' is the relative imaginary part of the complex permittivity, ε_d'' is the relative dielectric component of the imaginary part of the complex permittivity, ε_c'' is the relative conductive component of the imaginary part of the complex permittivity, σ is electrical conductivity, $\omega = 2\pi f$ is angular frequency of an electromagnetic wave, and ε_0 is the vacuum permittivity.

Electrical conductivity is found in the second term of the sum (Equation (1)), which depends on the frequency, and its influence is expressed at lower frequencies. At low frequencies, this conductivity can be caused by various factors, but most often, it is due to conduction by free ions that exist in the presence of moisture in the material.

This relationship for the relative dielectric constant is incorporated in the mathematical model of the HFSS simulation routine.

As the most important factor describing the properties of the dielectric plate, the reflection coefficient S_{11} depends on the complex electrical permittivity, the complex magnetic permeability, and layer thickness. Because the moisture of the material has an effect on the imaginary part of the complex permittivity, in addition to the previously mentioned parameters, S_{11} is also affected by moisture (electrical conductivity) and temperature [15]:

$$S_{11} = \frac{\sqrt{\frac{(\mu\prime - j\mu'')}{(\varepsilon\prime - j\varepsilon'')}}\tanh\left(j\frac{2\pi fd}{c}\sqrt{(\mu\prime - j\mu\prime)(\varepsilon\prime - j\varepsilon'')}\right) - 1}{\sqrt{\frac{(\mu\prime - j\mu'')}{(\varepsilon\prime - j\varepsilon'')}}\tanh\left(j\frac{2\pi fd}{c}\sqrt{(\mu\prime - j\mu'')(\varepsilon\prime - j\varepsilon'')}\right) + 1}, \tag{12}$$

where S_{11} is the reflection coefficient, $\varepsilon\prime$ and ε'' are the real and the imaginary part of the complex electric permittivity, $\mu\prime$ and μ'' are the real and the imaginary part of the complex magnetic permeability, f is the frequency of an electromagnetic wave, c is the speed of light, and d is material thickness.

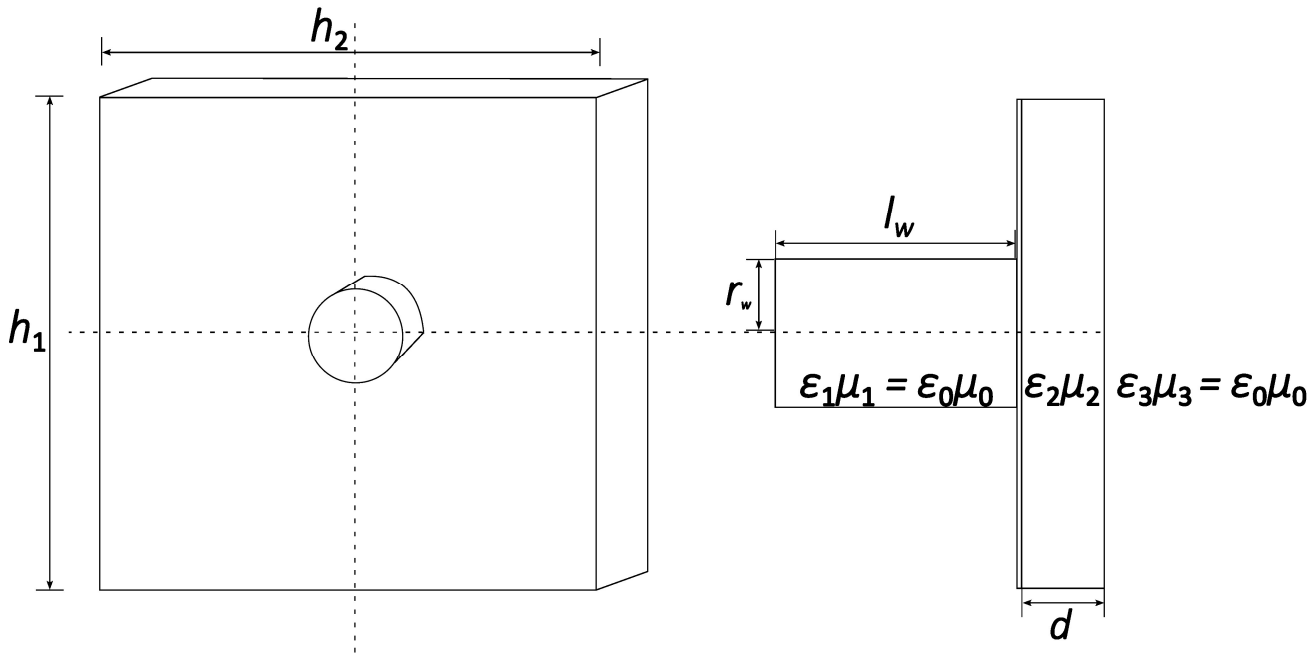
3. Numerical Results

The goal of this article is to investigate the influence of all possible parameters of the dielectric plate on the change in the total reflection coefficient S_{11}. The parameters are divided into structural–geometric (thickness d and dielectric density ρ) and electromagnetic parameters (relative dielectric constant ε_r, dielectric losses tg δ and tg δ_μ, dielectric conductivity σ, and relative dielectric permeability μ_r).

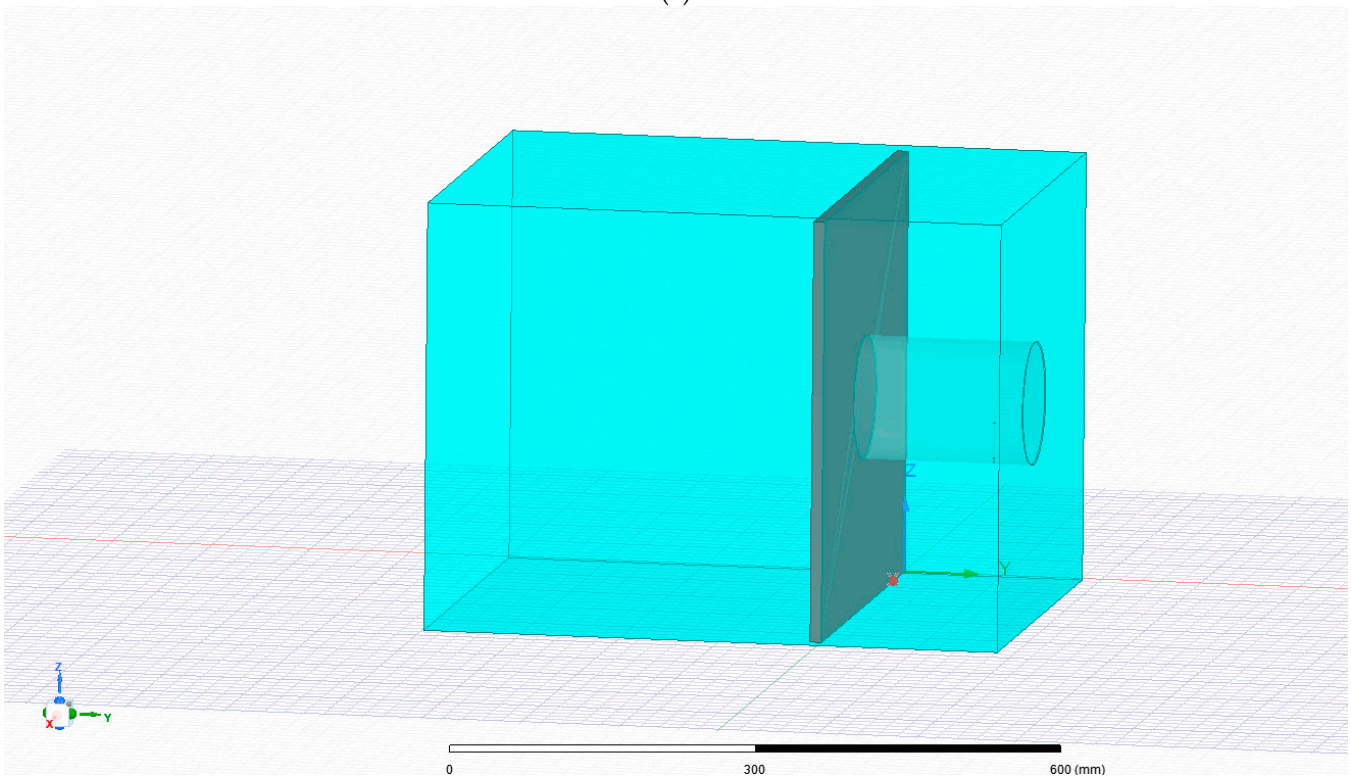
The antenna and the dielectric plate are modeled with Ansys HFSS simulation software for solving electromagnetic problems using the finite element method. The antenna model is shown in Figure 6.

The dimensions (width h_1, length h_2) of the grounded plane and dielectric plate are h_1 = 423 mm (2.51 λ) and h_2 = 450 mm (2.67 λ), and the radius and length of the waveguide are r_w = 61 mm (0.276 λ) and l_w = 171 mm (1.02 λ), respectively. The space inside the waveguide is defined by ε_1 and μ_1 (the waveguide is air-filled). The dielectric plate is characterized by ε_2, μ_2, and the thickness d. The space following behind the dielectric plate is free space, and it is characterized by ε_0, μ_0.

The dominant mode of the waveguide with a circular cross-section is TE_{11} with the corresponding cut-off frequency f_{cTE11}. The next mode is TM_{01} with the cut-off frequency f_{cTM01}. Therefore, numerical calculations were carried out in the frequency range $f_{cTE11} < f < f_{cTM01}$.



(**a**)



(**b**)

Figure 6. (**a**) Block diagram of the geometry of the problem; (**b**) HFSS model of an aperture antenna fed by a circular waveguide placed on a grounded planar surface with dielectric plate.

3.1. The Influence of the Structural–Geometric Parameters of the Dielectric on S_{11}

As already mentioned, the structural–geometric parameters of the dielectric include the thickness d in mm, dielectric plate dimensions $h_1 \times h_2$, and the density ρ of the dielectric plate in $kg \cdot m^{-3}$.

3.1.1. Influence of Dielectric Plate Thickness d on the Reflection Coefficient

In this subsection, the focus is on the influence of the change in the thickness of the dielectric layer d on the reflection coefficient S_{11} at the opening of the waveguide. The thickness d ranges from d = 0 mm to d = 13 mm, assuming all other parameters: $\varepsilon_r = 2.5$, $\mu_r = 1$, $\sigma = 0$ S/m, tg $\delta = 0.09$, tg $\delta_\mu = 0$. Some values of these parameters were carefully selected according to [11,17,18].

The simulation results show that the amplitude of the reflection coefficient S_{11} decreases with increasing dielectric plate thickness d, namely from −12.57 dB (d = 0 mm) to −43.43 dB (d = 11 mm). After that, for dielectric plate thickness of 13 mm, the value of the reflection coefficient increases (−27.10 dB). This is consistent with the theoretical considerations in Section 2 and the minimum absolute value of the parameter S_{11} (between 1 and 2 GHz) shown in Figure 2b. It can be seen that the resonant frequency increases (shifts to the right) with increasing dielectric plate thickness at the antenna aperture. After reaching dielectric plate thickness of about 11 mm (and the minimum value of parameter S_{11}), the resonant frequency decreases with increasing dielectric plate thickness. The reason for this is that the reflected waves from the first (air-dielectric plate) and the second (dielectric plate-air) boundary at this thickness (about 11 mm) are in destructive interference, resulting in the minimum value of the reflection coefficient S_{11}. Figure 7 and Table 1 show the change in the reflection coefficient as a function of the change in the thickness of the dielectric d. The minimum values of the coefficient S_{11} for certain values of d are listed in Table 1 together with the associated frequency f.

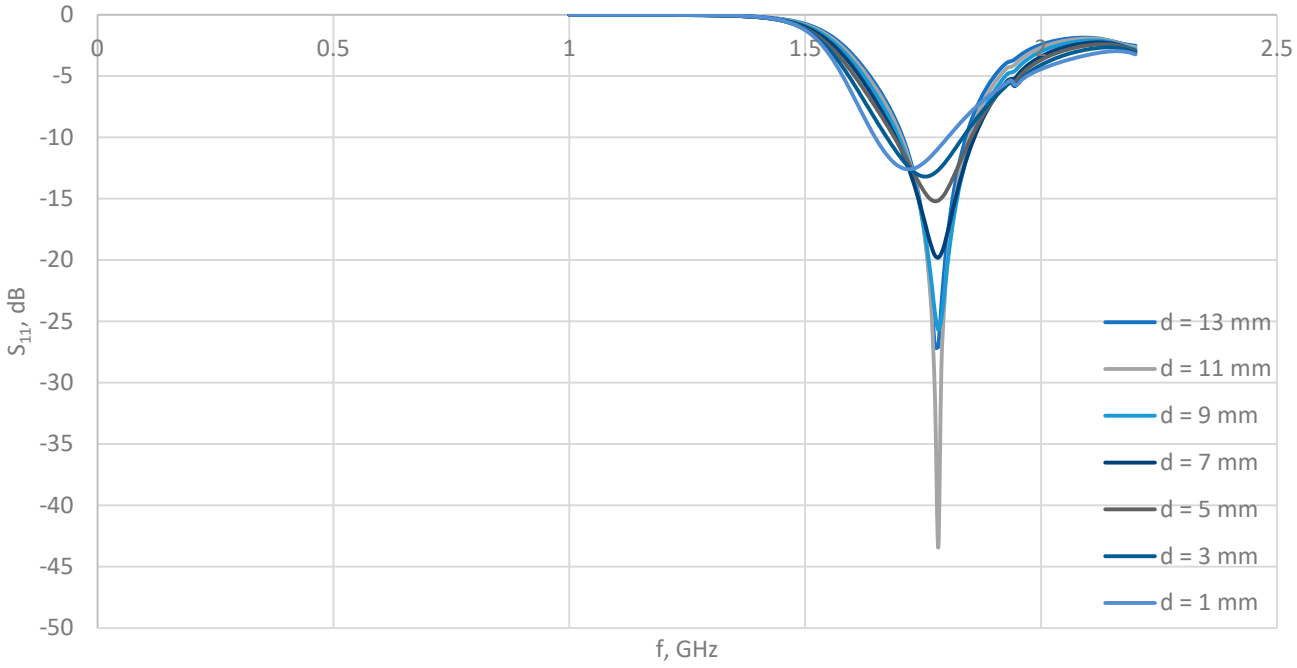


Figure 7. The simulated reflection coefficient S_{11} for an aperture antenna with plate width in the range of d = 1–13 mm.

Table 1. Simulated values of S_{11} for different dielectric plate thickness d.

d, mm	f, GHz	S_{11}, dB
0	1.7011	−12.57
1	1.7213	−12.60
3	1.7550	−13.19
5	1.7753	−15.21
7	1.7820	−19.81
9	1.7820	−25.68
11 (0.67 λ)	1.7820	−43.43
13	1.7753	−27.10

3.1.2. Influence of the Dielectric Plate Dimension $h_1 \times h_2$ (Width × Length) on the Reflection Coefficient and the Radiation Pattern of the Antenna Opening

First, it is necessary to point out that simulation calculations of the reflection coefficient S_{11} were performed to change the dimensions of the dielectric plate $h_1 \times h_2$ by ±20%, which resulted in negligible changes in the reflection coefficient S_{11}.

3.1.3. Influence of Dielectric Plate Density ρ on the Reflection Coefficient

The structural parameters of the dielectric covering the antenna include, as already mentioned, the density of paper ρ in kg·m^{-3}. The calculations showed a constant value of the reflection coefficient $S_{11} = -43.43$ dB (f = 1.7820 GHz) for ρ ∈ [500, 1800] kg·m^{-3}. Therefore, for all further simulations of the reflection coefficient according to [19], it is assumed that ρ = 1200 kg·m^{-3}.

3.2. The Influence of the Electromagnetic Parameters of the Dielectric on S_{11}

3.2.1. Influence of the Dielectric Plate Relative Permittivity ε_r on the Reflection Coefficient

In this study, simulations of the reflection coefficient S_{11} for $\varepsilon_r \in [1.5, 10]$ were carried out under the condition that the thickness of the dielectric d is fixed at 11 mm (the best value from the previous subsection). The other dielectric parameters remain as given in Section 3.1.1. The simulation results are presented in Figure 8 and Table 2.

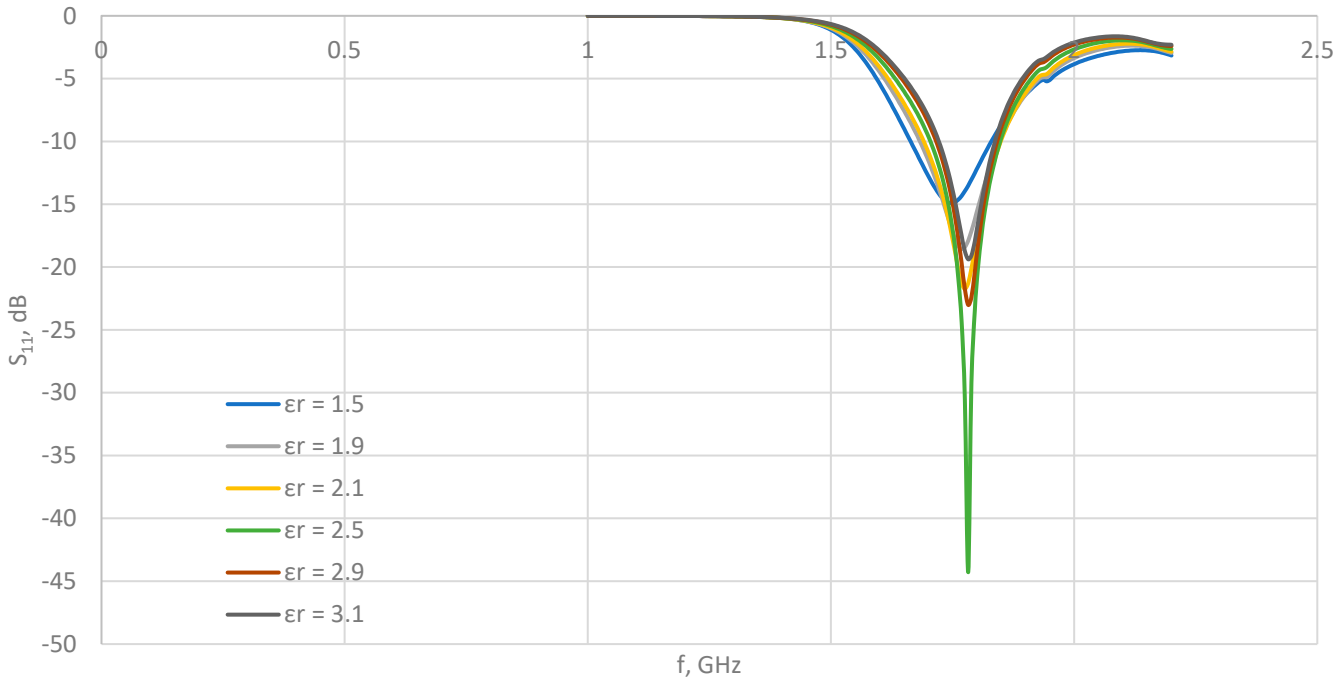


Figure 8. The simulated reflection coefficient S_{11} for an aperture antenna with dielectric plate permittivity $\varepsilon_r \in [1.5, 3.1]$.

It can be seen from the simulations that the value of the reflection coefficient S_{11} is minimal at the dielectric constant $\varepsilon_r = 2.5$, which, according to the literature cited above, proves that a material with such dielectric constant value is an excellent choice for the antenna radome.

The frequency of the minimum value of the curve $S_{11}(f)$ and ε_r = const, which also corresponds to the resonant frequency of the aperture antenna, increases (it moves to the right towards higher frequencies) with an increase in the permittivity constant. This increase in resonance occurs up to the value of the permittivity 2.5, at which the value of the reflection coefficient S_{11} reaches the minimum value of −43.43 dB at the frequency 1.7820 GHz. With a further increase in the permittivity, the value of the resonant frequency decreases, whereas the minimum value of the curve $S_{11}(f)$, ε_r = const, increases.

Table 2. Simulated values of S_{11} for different dielectric plate permittivity ε_r.

ε_r	f, GHz	S_{11}, dB
1.5	1.7483	−14.90
1.9	1.7685	−18.55
2.1	1.7753	−21.74
2.5	1.7820	−43.43
2.9	1.7820	−23.01
3.1	1.7820	−19.38
5	1.7753	−08.22
7	1.7685	−05.03
10.0	1.7550	−03.24

3.2.2. Influence of Dielectric Plate Electric Conductivity σ on the Reflection Coefficient

The electrical conductivity of the materials to be used as a dielectric shield should be as low as possible. With this analysis, we try to determine the influence of this electromagnetic parameter on the reflection coefficient of an aperture antenna protected by such a material. Simulations were performed for the reflection coefficient S_{11} with a change in conductivity $\sigma \in [0, 10]$. The calculated values of S_{11} are given in Table 3 and shown in Figure 9. The other dielectric parameters remain as given in Section 3.1.1, with d = 11 mm and $\varepsilon_r = 2.5$ (the last best achieved values).

Table 3. Simulated values of S_{11} for different dielectric plate conductivity σ.

σ, S/m	f, GHz	S_{11}, dB
0	1.7820	−43.43
1.0×10^{-12}	1.7820	−43.43
1.0×10^{-3}	1.7820	−43.41
1.0×10^{-1}	1.7550	−21.55
1	1.7348	−4.85
10	1.7416	−1.59

The results show the best value of the reflection coefficient $S_{11} = -43.43$ dB at a dielectric conductivity of 0 S/m. With increasing conductivity values, S_{11} decreases drastically (for example, for $\sigma = 1$ S/m, $S_{11} = -4.85$ dB).

Therefore, in all other simulation calculations, electrical conductivity is set to 0 S/m.

By comparing the relative dielectric and conductive component of the imaginary part of the complex permittivity, the importance of each of them can be determined from Equation (11). Let us consider the case in which the minimization of the reflection coefficient is achieved. For the values of electrical conductivity for which the following condition is satisfied: $\frac{\sigma}{\omega \varepsilon_0} << \varepsilon_d''$ (in the frequency range from 1 to 2.5 GHz), the reflection coefficient has a minimum value (Table 4).

Table 4. Verification of condition: $\frac{\sigma}{\omega \varepsilon_0} << \varepsilon_d''$ of simulation results for different dielectric plate conductivity σ, according to Equation (11).

σ, S/m	$\frac{\sigma}{\omega \varepsilon_0}$; (f = 1.0 GHz)	$\frac{\sigma}{\omega \varepsilon_0}$; (f = 2.5 GHz)	$\varepsilon_d'' = 2.5 \tan\delta$	S_{11}, dB
0	0	0	0.225	−43.43
1.0×10^{-12}	1.80×10^{-11}	7.19×10^{-12}	0.225	−43.43
1.0×10^{-3}	1.8×10^{-2}	7.19×10^{-3}	0.225	−43.41
1.0×10^{-1}	1.8	7.19×10^{-1}	0.225	−21.55
1	$1.8 \times 10^{+1}$	7.19	0.225	−4.85
10	$1.8 \times 10^{+2}$	$7.19 \times 10^{+1}$	0.225	−1.59

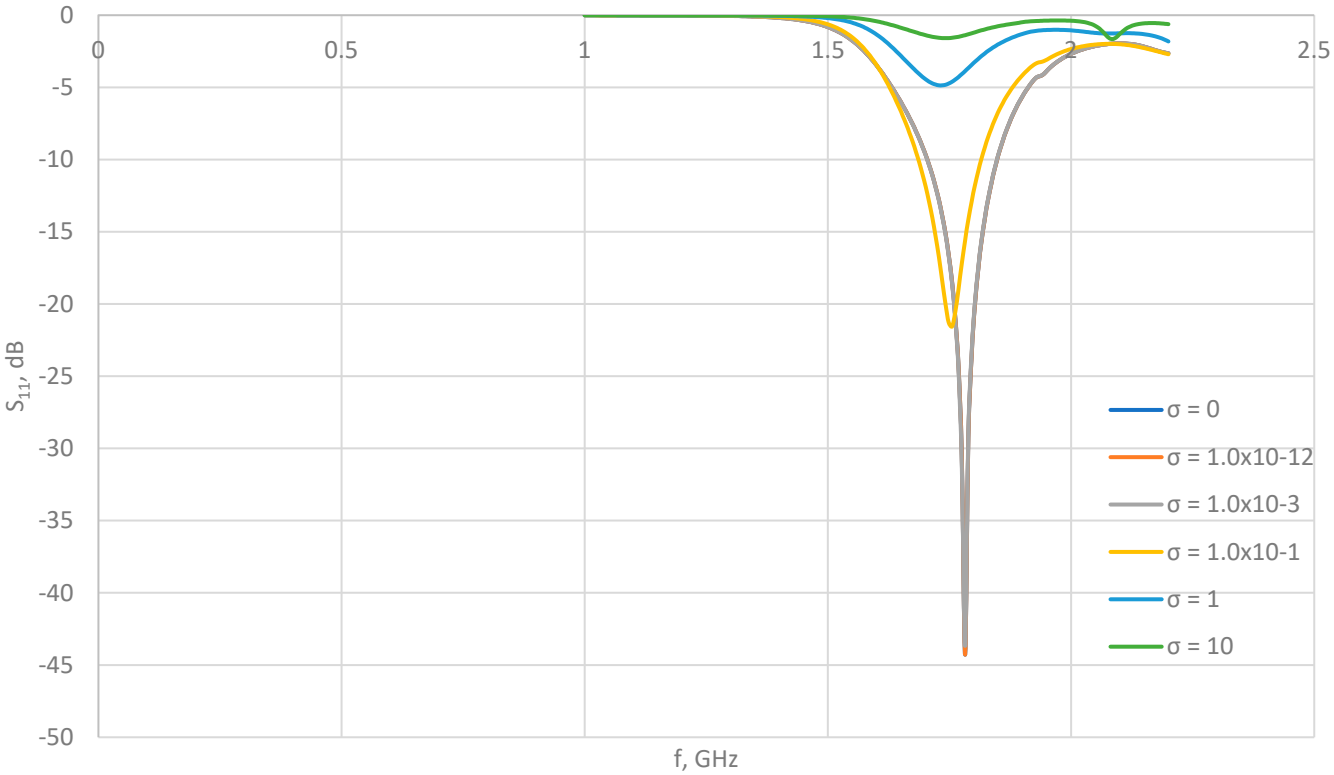


Figure 9. The simulated reflection coefficient S_{11} for an aperture antenna with dielectric plate conductivity $\sigma \in [0, 10]$.

For those electrical conductivity values for which this condition is not met (from 1.0×10^{-1} to 10 S/m), the electrical conductivity component prevails, and the material is no longer considered a good dielectric. Therefore, the reflection coefficient increases significantly, as expected for a conductive material. Thus, due to moisture in the dielectric material, which causes a change in electrical conductivity of the material, and depending on moisture content, electrical conductivity can cause a significant change in the reflection coefficient S_{11}.

3.2.3. Influence of Dielectric Plate Dielectric Losses tan δ on the Reflection Coefficient

The imaginary part of the complex permittivity ε is a complex quantity that (Section 2.2) indicates the dissipation in the material. Because the material we analyze is a dielectric that is not perfect, this part of the permittivity over the dielectric and conductive components speaks of losses in the dielectric and conductive part of the material that is in the electric field. In this simulation calculation, the focus is on the dielectric part of the imaginary component of the permittivity.

According to [19], the loss tangent ranges up to about 0.09 in the frequency range of 0.5–2.5 GHz. With this tan δ range, simulations for S_{11} were carried out, and the best value was achieved for tan δ = 0.09—Figure 10 (i.e., $S_{11} = -43.43$ dB).

All dielectric parameters were set as in Section 3.1.1, and with the best values achieved in previous simulations.

Note: A large number of tan δ simulations were performed (very high resolution), but only the most relevant values are listed in Table 5.

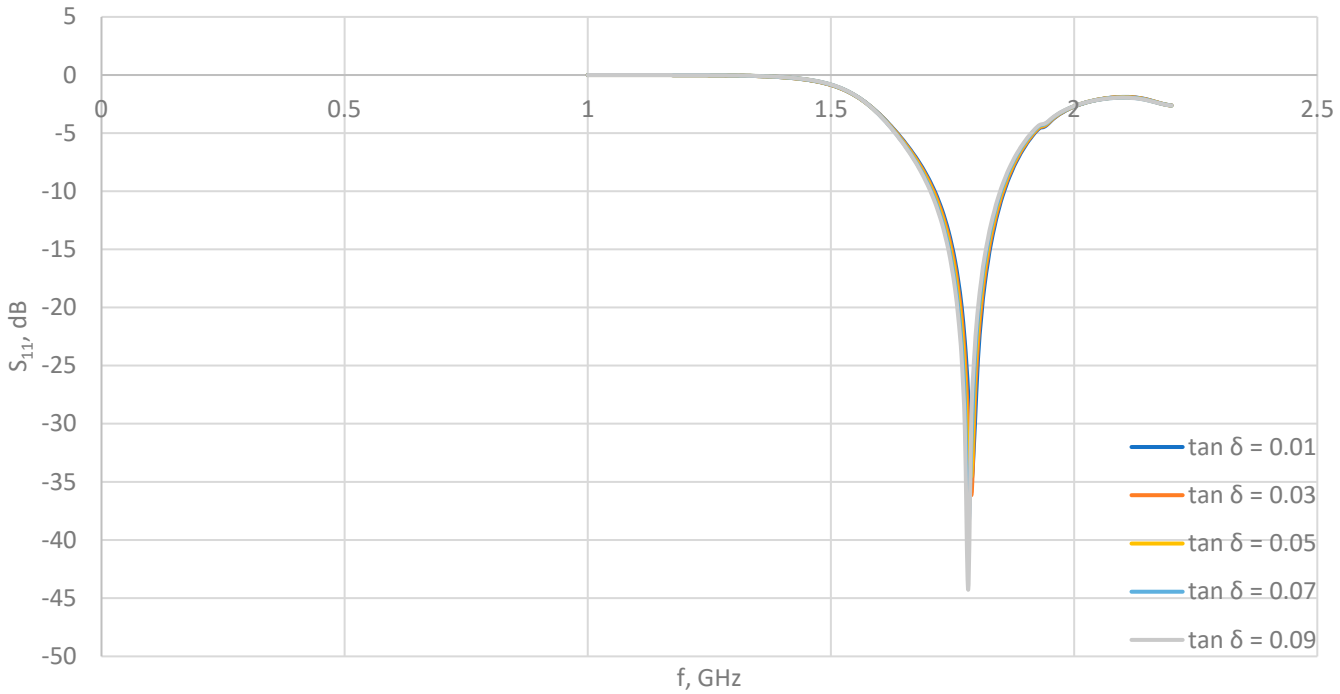


Figure 10. The simulated reflection coefficient S_{11} for an aperture antenna with dielectric plate tan $\delta \in [0.01, 0.09]$.

Table 5. Calculated values of S_{11} for different dielectric plate dielectric loss tg δ.

tg δ	f, GHz	S_{11}, dB
0.010	1.7887	−41.48
0.030	1.7887	−41.48
0.050	1.7887	−34.41
0.060	1.7820	−35.19
0.070	1.7820	−39.01
0.090	1.7820	−43.43
0.098	1.7820	−41.48

3.2.4. Influence of Dielectric Plate Relative Permeability μ_r and Magnetic Loss Tangent tan δ_μ on the Reflection Coefficient

Because only dielectrics are used as protective shields for antennas, the analysis includes materials with a value of relative permeability of approximately 1. Because the antenna is protected by dielectric materials (diamagnetic), all simulation calculations were performed for a material that has the complex permeability $\mu = \mu' - j\,\mu'' = \mu_0 1 - j\,0$ (relative permeability is equal to 1, and plate magnetic loss tangent tan $\delta_\mu = 0$).

Simulation calculations were performed for changes in the real and the imaginary part of permeability (μ_r ranging from 0.9 to 1.1, and tan δ_μ ranging from 0 to 2), and they showed that a deviation from the defined values $\mu_r = 1$ and tan $\delta_\mu = 0$ significantly degrades the value of the reflection coefficient S_{11}.

3.3. Simulation Calculation of the Radiation Pattern of a Circular Aperture Antenna with a Dielectric Plate

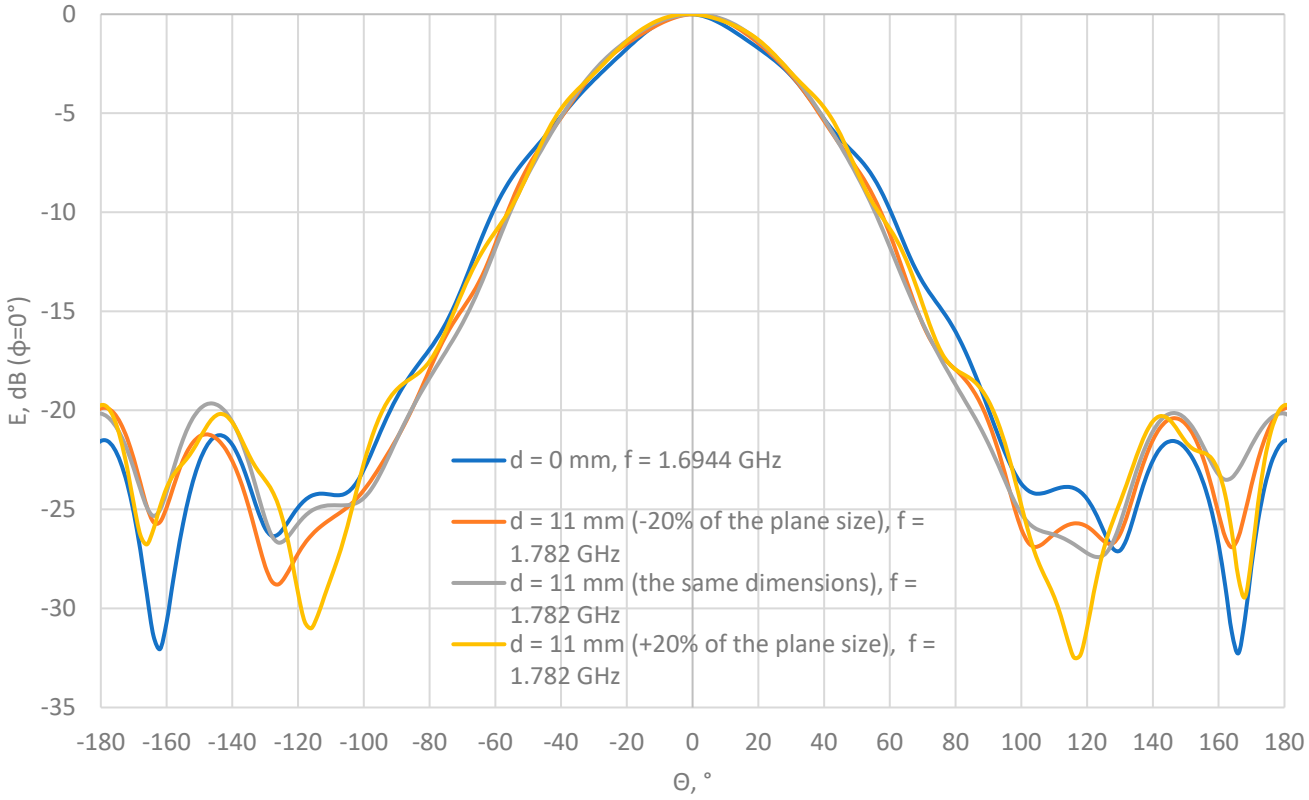
The effects of changes in the structural and electromagnetic parameters of the plate on the reflection coefficient of the aperture antenna with dielectric plate have been analyzed in previous subsections. It is necessary to determine whether changing the parameters of the dielectric plate while improving the reflection coefficient of the antenna distorts the radiation pattern of the antenna. Therefore, the simulation calculation results of the

influence of the change in the dielectric plate parameters on the radiation pattern of the aperture antenna are analyzed in this subsection.

If we compare the radiation patterns of the aperture antenna with and without the dielectric plate (d = 0 and d = 11 mm for the same dimension of the dielectric material and the plane in Figure 11) with the previously defined best values of the dielectric plate parameters (i.e., the thickness d = 11 mm, $\varepsilon_r = 2.5$, $\mu_r = 1$, $\sigma = 0$ S/m, tg $\delta = 0.09$, tg $\delta_\mu = 0$, $h_1 \times h_2 = 423 \times 450$ mm^2, $\rho = 1200$ kg·m^{-3}), it can be concluded that there are some changes in the radiation diagram. The largest deviations of -2.5 dB at $\pm 25^\circ$ (side lobes) and +5.0 dB at 158° (back lobe) can be seen in the *H* plane and +9.0 dB at 165° (back lobes) in the *E* plane, whereas deviations are negligible in the rest of the range of angles in both planes (*E* and *H* planes).

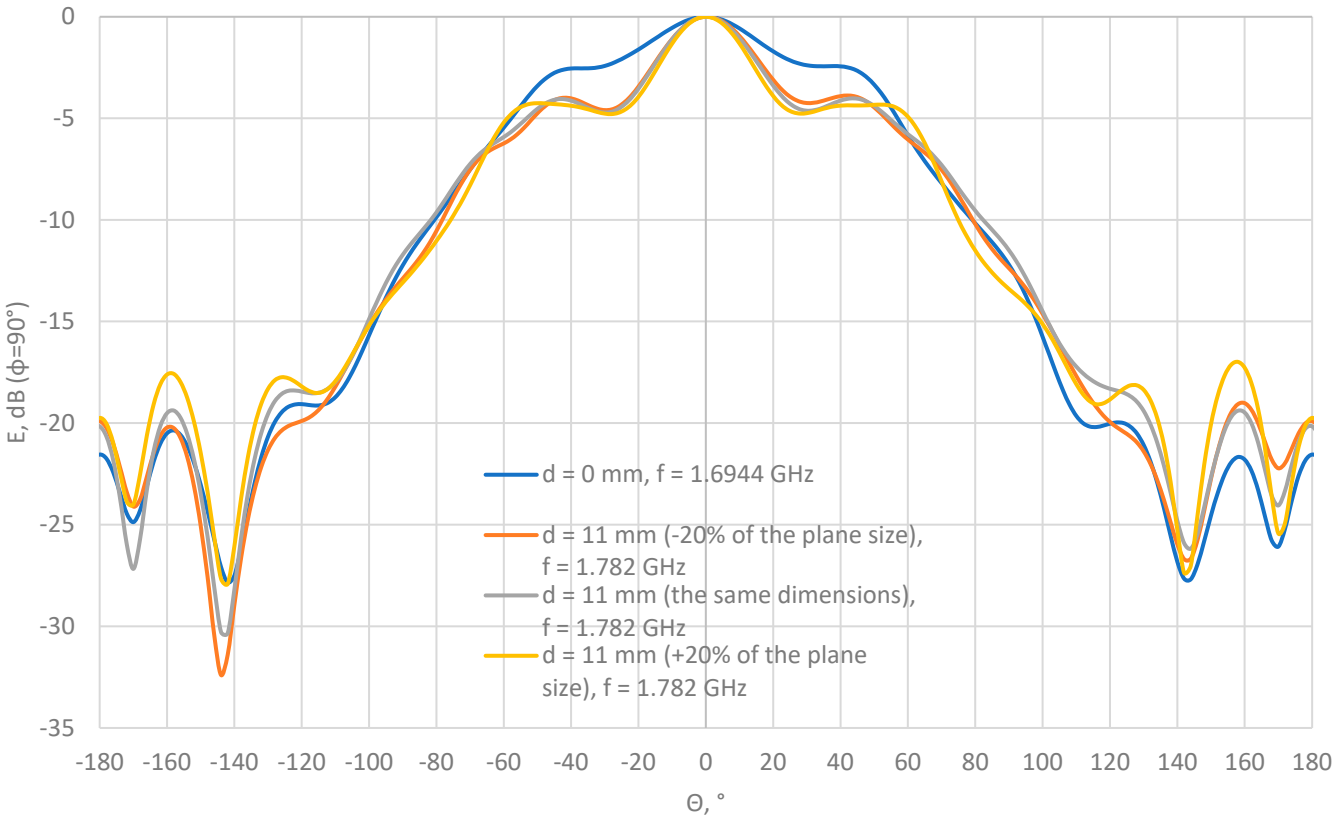
Furthermore, a variation in the width and length of the dielectric plate, which ranges from $\pm 20\%$ of the full size of the grounded plane (dimensions of the grounded plane are $h_1 \times h_2 = 423 \times 450$ mm^2), does not result in significant changes in the radiation pattern compared to the dielectric plate with dimension $h_1 \times h_2 = 423 \times 450$ mm^2 (Figure 11). The largest deviations of +4.5 dB at $\pm 158^\circ$ (back lobes) can be seen in the *H* plane, and +6.0 dB at 117 and 168° (back lobe) in the *E* plane, whereas deviations are negligible in the rest of the range of angles in both planes (*E* and *H* planes).

Therefore, it can be concluded that the scattering at the edges of the grounded plane of such a circular aperture antenna (with an opening radius of 61 mm (0.36 λ)) with a grounded plane of dimensions 423 × 450 mm^2 (2.51 × 2.67 λ) has an effect on the side and back lobes, but there is no main lobe and, therefore, it does not significantly affect the operation of this antenna. Lowering the side lobe in the *H* plane further slightly improves the radiation pattern.



(**a**)

Figure 11. *Cont.*



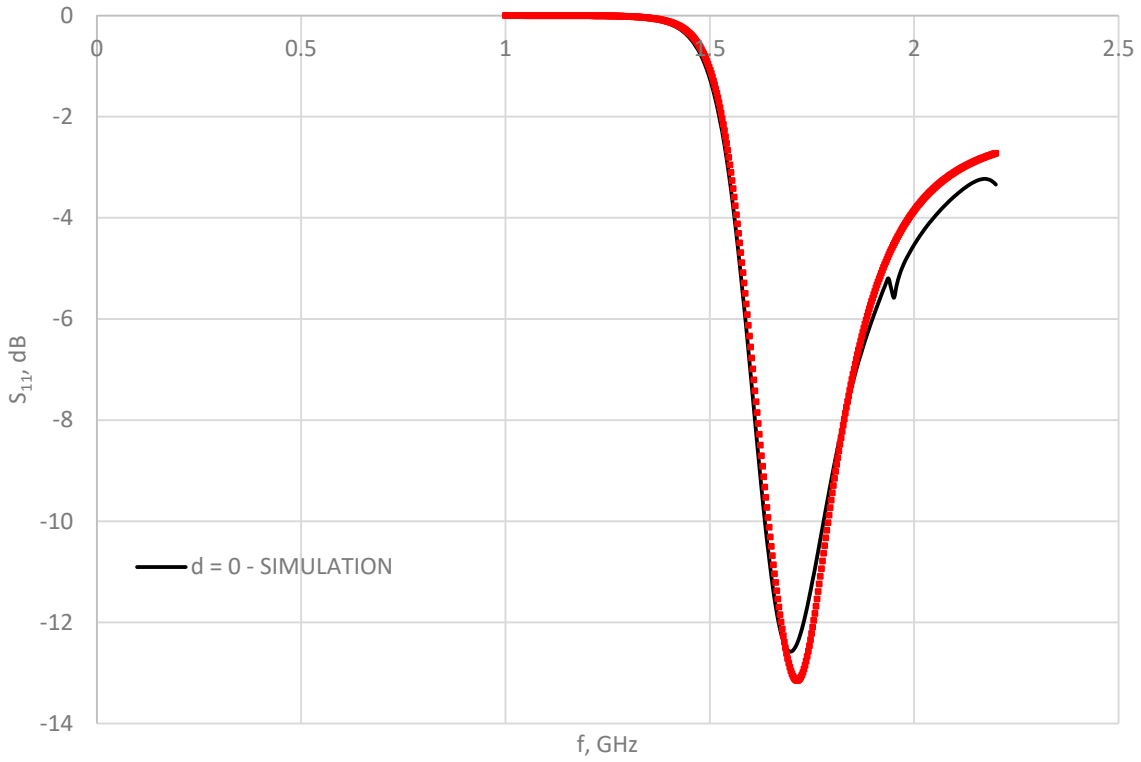
(**b**)

Figure 11. Radiation pattern of an aperture antenna with a dielectric plate: (**a**) *E* plane; (**b**) *H* plane.

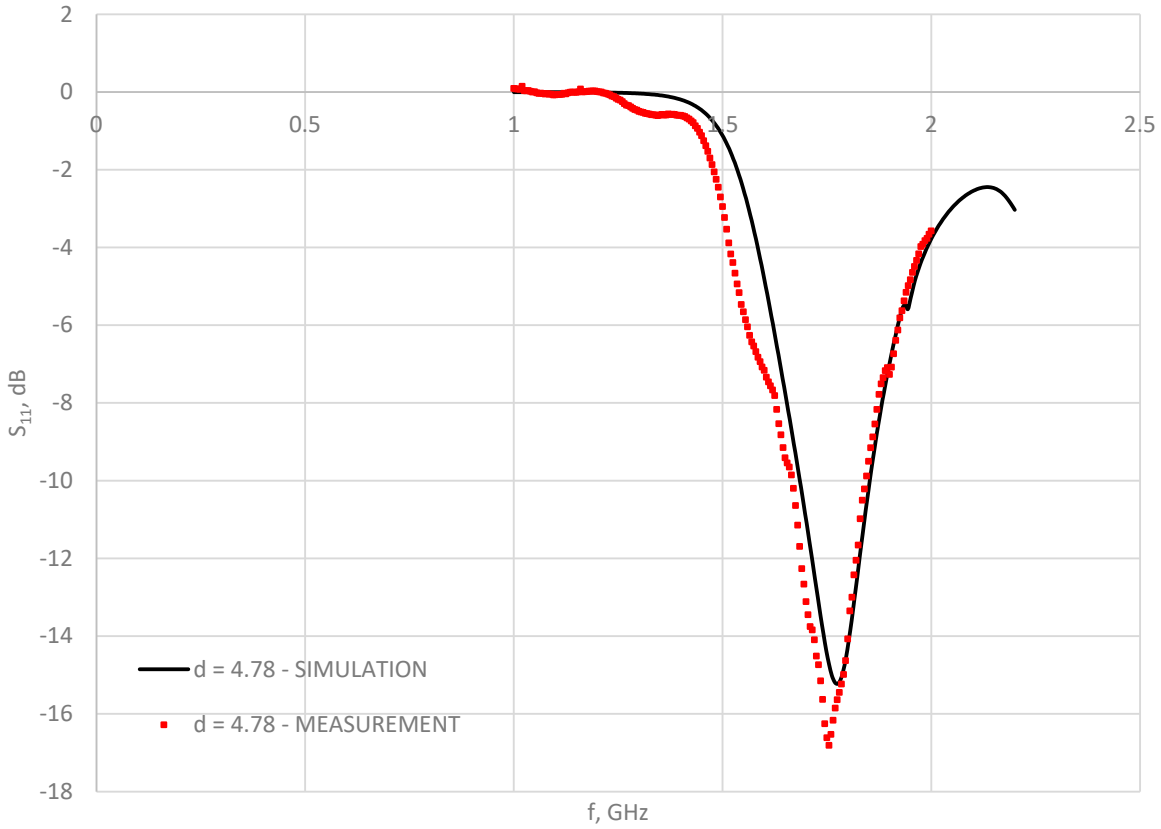
4. Measurement Results

For long-term research to be meaningful, simulation, i.e., the simulated values of the reflection coefficient S_{11}, must be validated via laboratory measurements. What can be measured with certainty is S_{11} for a given thickness d of the dielectric plate on the antenna. Laboratory measurements of S_{11} at the waveguide–free space boundary and the waveguide–dielectric boundary were performed for d = 0 mm, d = 4.78 mm, d = 7.08 mm, d = 9.26 mm, and d = 11.08 mm. Simulation calculation precedes the measurements for these dielectric plate thickness values by using paper as a dielectric. Comparison results of the simulated and measured values of S_{11} are shown in Figure 12a–e. Table 6 shows the comparative values of the reflection coefficients (simulated and measured) for different values of dielectric thickness.

It can be seen that there are some differences between the simulated and the measured curves. The measured curves show a small shift towards lower frequencies. This can be explained by the fact that when the sheets of paper are stacked on top of each other to achieve the specified thickness of the dielectric plate, there is obviously an unwanted amount of air between the two sheets. This can be explained by the fact that simulation models do not take into account a number of factors that are present in the laboratory models on which the measurements were carried out. The measured results are affected by the calibration of the measuring device, the conditions under which the measurement is performed (a laboratory with an EM echo), the performance (errors) of the measurement model, and the lack of knowledge of the exact structural–geometric and electromagnetic parameters of the measured model.

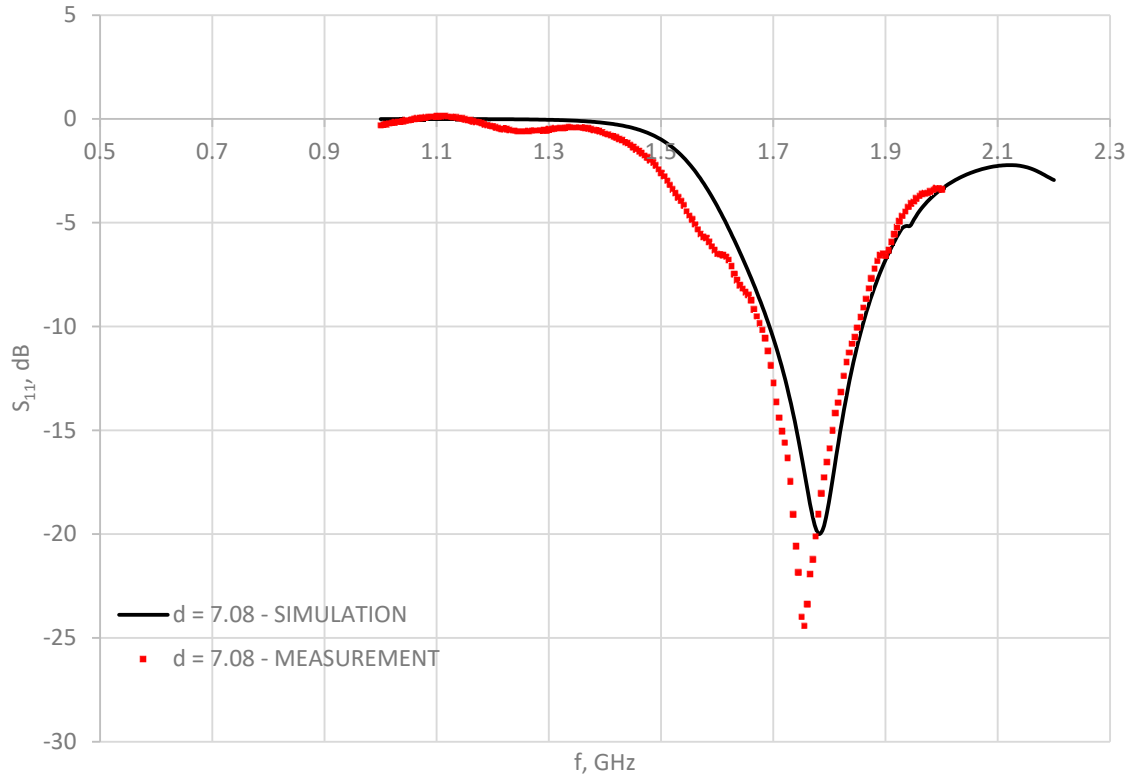


(**a**)

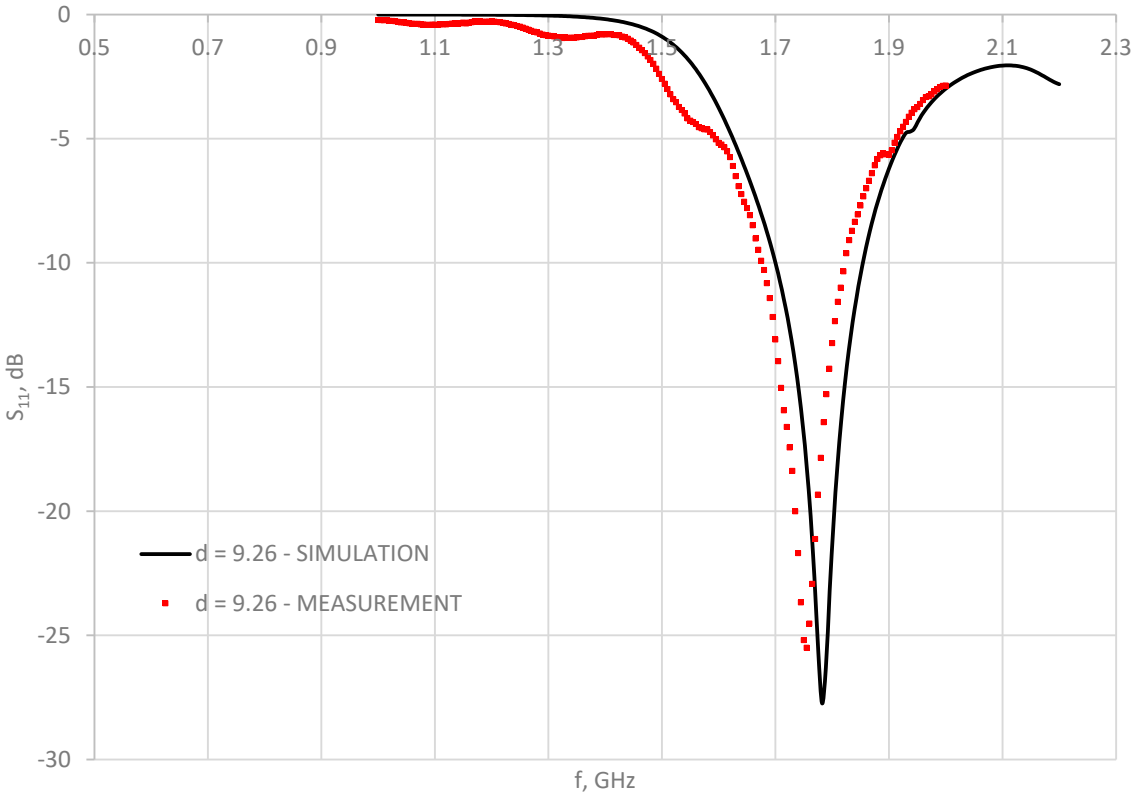


(**b**)

Figure 12. *Cont.*

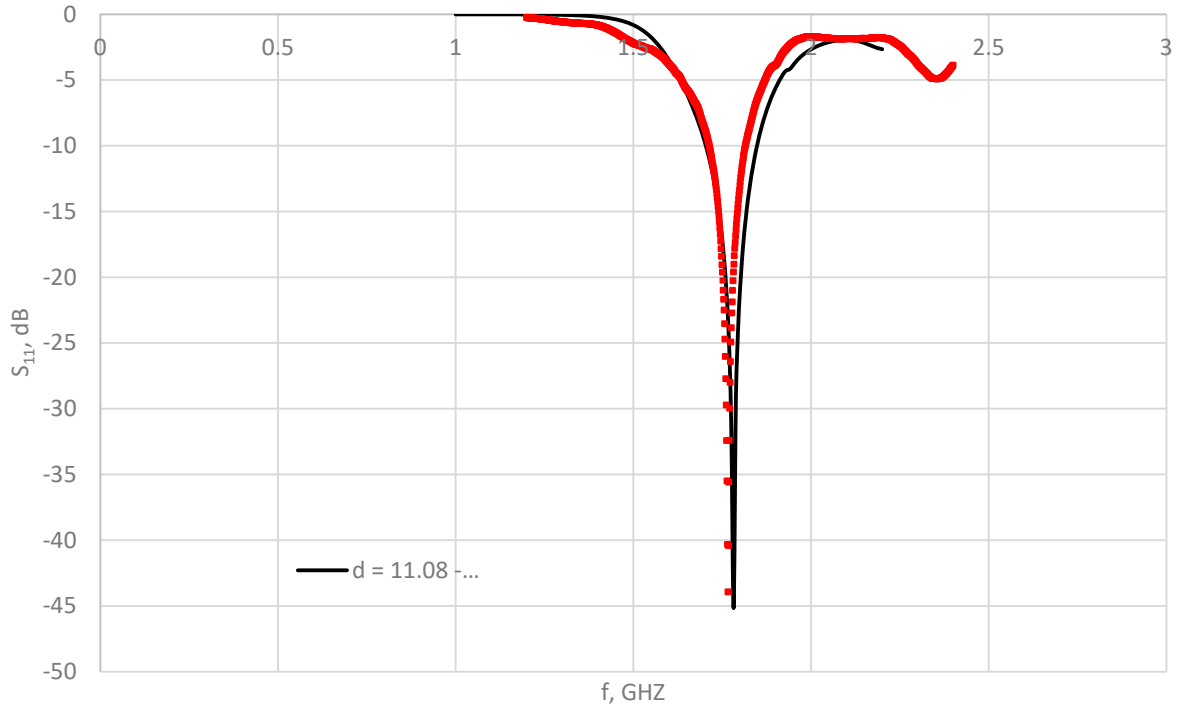


(**c**)



(**d**)

Figure 12. *Cont.*



(**e**)

Figure 12. Simulated and measured reflection coefficient S_{11} for an aperture antenna: (**a**) without dielectric plate (d = 0 mm) and with dielectric plate thickness: (**b**) d = 4.78 mm, (**c**) d = 7.08 mm, (**d**) d = 9.26 mm, and (**e**) d = 11.08 mm.

Table 6. Comparative values of the reflection coefficient S_{11} for an antenna with and without dielectric plate at the antenna aperture.

d, mm	f_{sim}, GHz	S_{11sim}, dB	f_{meas}, GHz	S_{11meas}, dB
0	1.6944	−12.57	1.7147	−13.15
4.78	1.7753	−15.23	1.7550	−16.81
7.08	1.7820	−19.99	1.7550	−24.41
9.26	1.7820	−27.73	1.7600	−25.49
11.08	1.7820	−45.17	1.7550	−43.93

To conclude this section, the measurement of S_{11} at the boundary between a waveguide-dielectric and a dielectric-free space was carried out by using an N9914A FieldFox Handheld RF spectrum analyzer, the operating range of which extends up to 6.5 GHz. The laboratory in which the reflection coefficient measurement was performed is not a chamber without an electromagnetic echo (Figure 13).

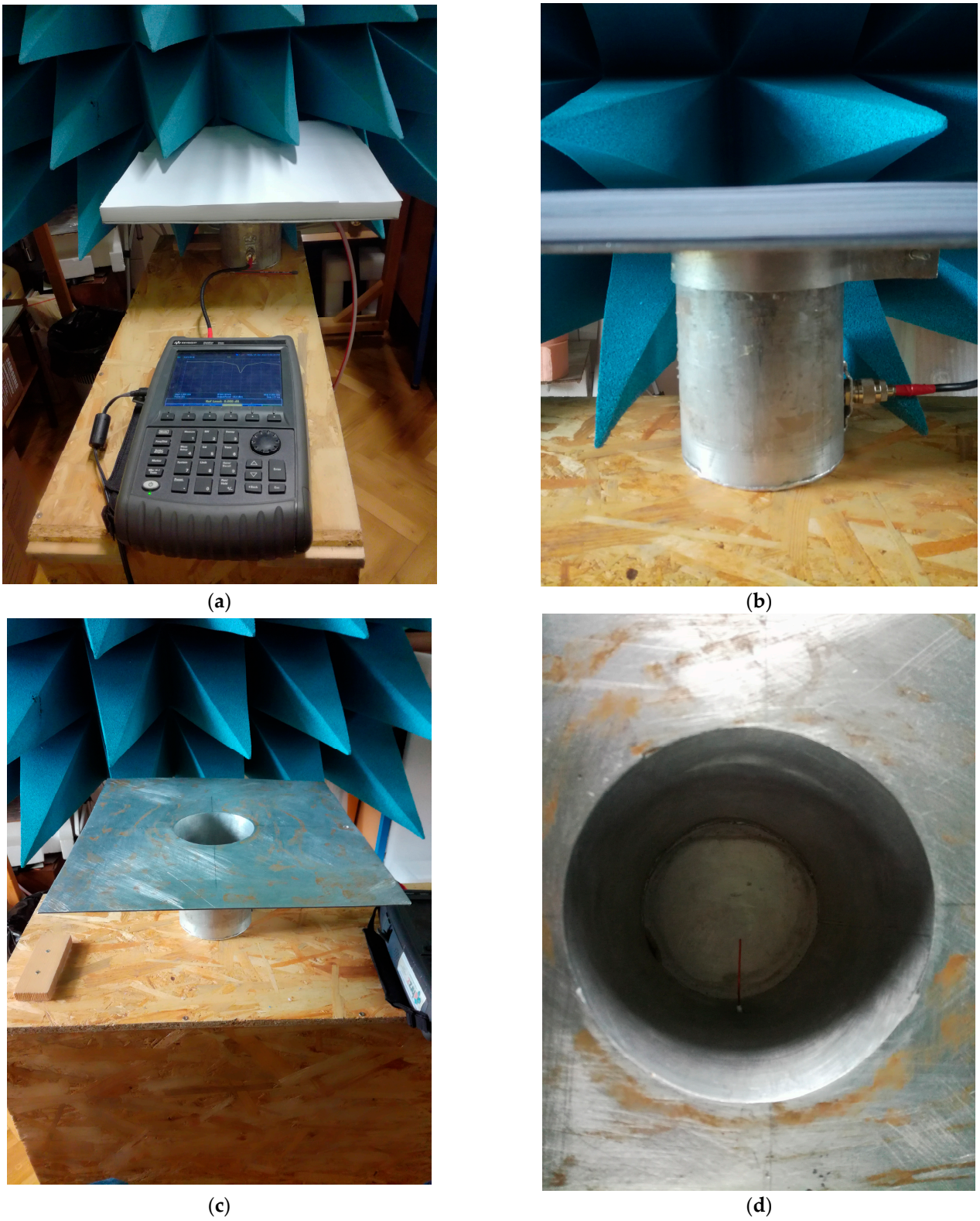


Figure 13. (**a**) Measurement of the S_{11} coefficient of the aperture antenna fed by a circular waveguide (covered with dielectric material) with an N9914A FieldFox Handheld RF Analyzer (6.5 GHz); (**b**) side view; (**c**) aperture antenna without radome; (**d**) space inside the waveguide.

5. Discussion

The radome placed on the antenna serves several purposes. It protects the antenna and constituent parts from external disturbances (e.g., snow, rain, wind, etc.), but research has

shown that the exact choice of the material covering the antenna can significantly affect its properties and performance. The investigated materials that can constitute certain radomes are polycarbonate, Teflon, and polystyrene–dielectrics, because they are able to maintain good antenna performance and a satisfactory reflection coefficient, i.e., materials with the lowest possible dielectric constant and tangent loss.

This article analyzes the influence of all parameters (whether geometric or electromagnetic) on the change in the reflection coefficient at the aperture of the antenna covered with a dielectric. It can be concluded that by placing a dielectric plate on the antenna, the reduction in the reflection coefficient S_{11} can be significantly affected, and with the proper selection of all dielectric parameters, this coefficient value can be brought to the minimum value. Figure 14 clearly shows the situations in which no dielectric plate is placed on the antenna and in which a dielectric plate with the best parameter values achieved (d = 11 mm, $\varepsilon_r = 2.5$, $\mu_r = 1$, $\rho = 1200$ kg·m^{-3}, $\sigma = 0$ S/m, tan $\delta = 0.09$, tan $\delta_\mu = 0$) is placed on the antenna.

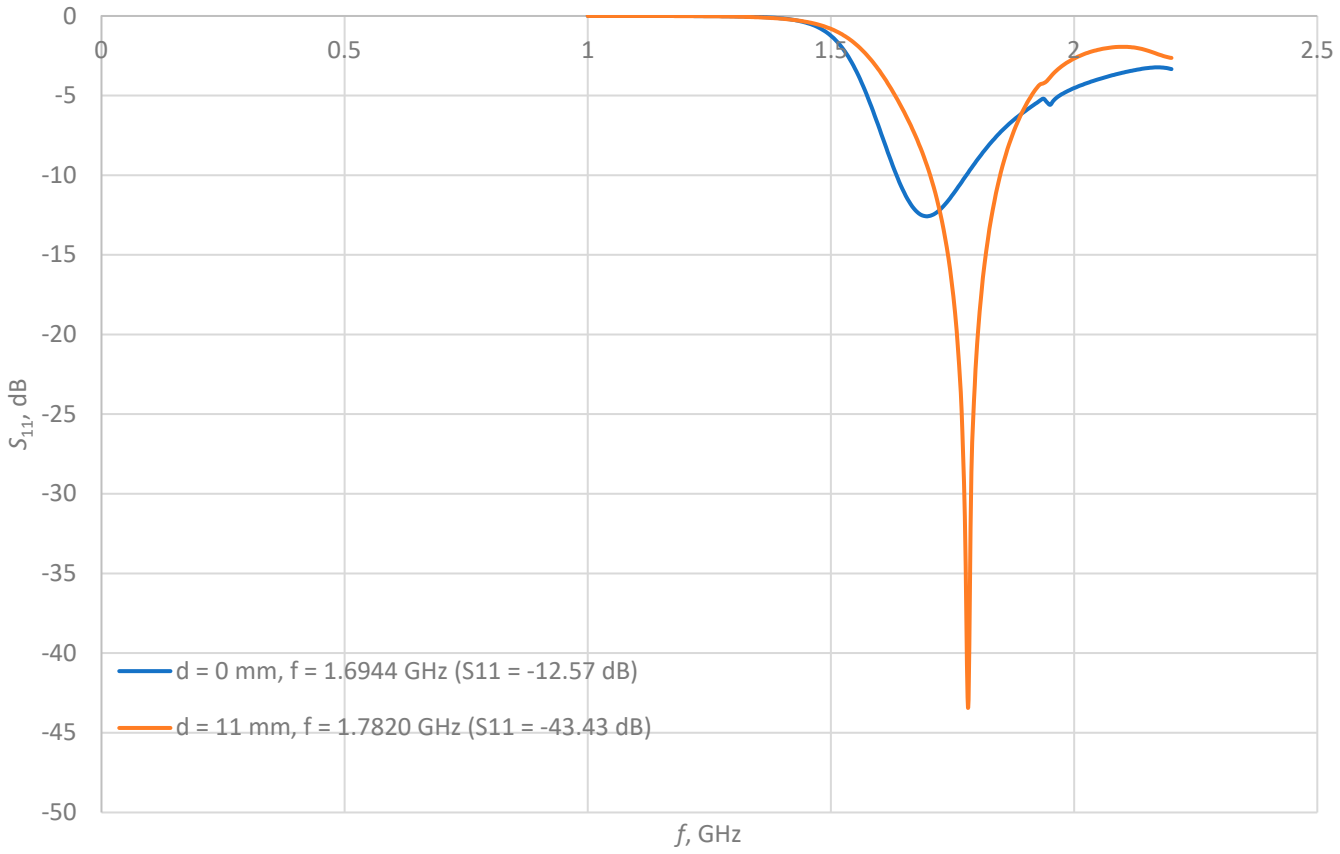


Figure 14. Simulated reflection coefficient S_{11} for an aperture antenna with a dielectric plate of thickness d = 11 mm and without dielectric plate (d = 0 mm).

However, a systematic analysis of the known dielectric parameters (geometric and electromagnetic) and their influence on the reflection coefficient and, thus, on impedance matching, as well as the choice of the frequency range of the antenna itself, was carried out as a part of this study. The present article is intended as a detailed extension of previous studies on the influence of just two parameters (thickness and permittivity) on impedance matching or the reflection coefficient [10,12]. This article analyzes the influence of all parameters of the dielectric plate. The geometrical parameters taken in this analysis are the thickness d and width/length h_1/h_2 of the dielectric plate. The electromagnetic parameters used in this analysis are the real and the imaginary part of permittivity (ε_r, tan δ) and electrical conductivity of the dielectric plate (σ). Simulation calculation and analysis included other structural and electromagnetic parameters of the dielectric plate

(density of the dielectric material, relative permeability, and magnetic loss tangent (ρ, μ_r, and tan δ_μ)), but the results showed that in the range of real values of dielectric parameters for the materials used for the dielectric plate, those three parameters had no significant influence on the reflection coefficient. Finally, simulation is validated with measured values. The aim of the study was to achieve the lowest possible reflection coefficient of the circular aperture antenna in order to accomplish the best impedance matching of the antenna itself.

The first part of the study involved simulation of the reflection coefficient of the antenna aperture fed by a circular waveguide using Ansys HFSS simulation software. The parameter analyzed, which significantly affects the performance of the antenna, is the thickness of the dielectric plate on the aperture. The thickness d ranges from 1 to 13 mm, and studies have shown that the best value of $S_{11} = -43.43$ dB is obtained for d = 11 mm.

A very significant contribution to the properties of the antenna is made by the change in the permittivity of the dielectric plate because it is basically the measure of the energy stored in the dielectric. In the simulations, the permittivity ε_r ranges from 1 to 10, and the best result of S_{11} is obtained for $\varepsilon_r = 2.5$. This ε_r value corresponds to the relative permittivity of the paper used as a dielectric material in the measurements, but such permittivity has some other materials suitable to be used for the antenna radome.

The total permittivity also consists of an imaginary component, the size of which provides information on how dissipative the dielectric material is in relation to the applied electric field. This component, in proportion to the aforementioned real part of the dielectric constant, forms loss tangent tan δ. The loss tangent tan δ ranges from 0.01 to 0.098, and the simulations showed the minimal value for tan $\delta = 0.09$.

Electrical conductivity of the dielectric plate σ takes values from 0 to 10 S/m in the simulations, and, as expected, it showed the minimal value for $\sigma = 0$ S/m.

At the very end of the study of antenna behavior with and without a dielectric plate on the aperture, laboratory measurements of the reflection coefficient were obtained by using an N9914A FieldFox Handheld RF spectrum analyzer. The chamber in which laboratory measurements were obtained is a chamber with an electromagnetic echo. Because the laboratory is not isolated from electromagnetic interference and the dielectric plate can never be arranged as in the simulations (in practice, homogeneity of the dielectric plate is not perfect: there is an undesirable amount of air between the layers of paper), there is some variation in the values obtained for the reflection coefficients S_{11}. This statement is also evident in Figure 12a–e, in which the graphs of the measured values show a frequency shift to the left, i.e., to lower frequency values. Another circumstance favors the difference between the simulated and the measured values; in practice, it is very difficult to adjust dielectric parameters to the value used by the simulation. The only parameter value that can be measured very accurately is the dielectric thickness d.

The focus of this article is not on the effects of edge scattering of the grounded plane of the aperture antenna. However, because the effects of edge scattering are visible on the side and back lobes, it is evident from this article that the effect of the finite edge must be included in the calculation in order to obtain more accurate results of the radiation patterns.

The measurement was possible for a larger number of dielectric thicknesses, and it was found that for the given aperture antenna, a dielectric plate thickness of 11.08 mm gives the minimum value of the reflection coefficient S_{11} of -43.93 dB at the frequency of 1.7550 GHz. The minimum reflection coefficient obtained by additional simulation for d = 11.08 mm is -45.17 dB at the frequency of 1.7820 GHz. Apart from d, which is variable, other parameters are set within the limits given in [17,20].

Despite the differences mentioned between the measured and simulated values, it can be stated that the curves of the reflection coefficients match very well. Furthermore, the assumption was confirmed that by adjusting the value of the geometric and electromagnetic parameters of the dielectric plate placed on the antenna, the reflection coefficient can be significantly improved (minimized), which ultimately results in good impedance matching of the antenna opening.

In the context of this investigation (simulations and measurements), it was assumed that a dielectric is a linear, homogeneous, and isotropic material.

Future work will include investigations of the performance of an aperture antenna with multi-layer dielectric plates, dielectric plates composed of nonlinear materials and materials of different shapes, and dielectric plates of different positioning on the antenna aperture. Possible different excitation modes will also be analyzed in future work.

Author Contributions: Conceptualization, V.M. and S.R.; methodology, V.M. and S.R.; software, V.M.; validation, V.M., S.R., S.R.-D. and I.B.; formal analysis, V.M.; investigation, V.M. and S.R.; resources, V.M.; data curation, V.M.; writing—original draft preparation, V.M.; writing—review and editing, V.M. and S.R.; visualization, V.M. and S.R.; supervision, S.R. and S.R.-D.; project administration, S.R.-D. and I.B.; funding acquisition, S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chang, K.C.; Smolski, A.P. The effect of impedance-matched radomes on SSR antenna systems. Radar-87. In Proceedings of the International Conference, London, UK, 19–21 October 1987; (A88-33301 13-32). Institution of Electrical Engineers: London, UK; New York, NY, USA, 1987; pp. 155–159.
2. Frazita, R.F.; Lopez, A.R. *Radome Having Integral Heating and Impedance Matching Elements*; Hazeltime Corporation: Greenlawn, NY, USA, 1989.
3. Vesselin, N.; Peshlov, V.N.; Dankov, P.I.; Hadjistamov, B. Models of multilayer antenna radomes with Anisotropic Materials. In Proceedings of the First European Conference on Antennas and Propagation, Nice, France, 6–10 November 2006.
4. Griffiths, L. A Fundamental and Technical Review of Radomes, MFG Galileo Composites. *Feature Article*, May 2008.
5. Frech, M.; Lange, B.; Mammen, T. Influence of a Radome on Antenna Performance. *J. Atmos. Ocean. Technol. Am. Meteorol. Soc.* **2013**, *30*, 313–324. [CrossRef]
6. Wahab, M. Radar Radome and Its Design Considerations. Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME). In Proceedings of the 2009 International Conference, Bandung, Indonesia, 23–25 November 2009.
7. Kumar, C.; Mohammed, H.U.R.; Peake, G. *mmWave Radar Radome Design Guide*; Application Report; Texas Instruments Incorporated: Dallas, TX, USA, 2021; pp. 1–21.
8. Bhowmik, S. *Investigation of Wide Band mm-Wave Radome*; Degree Project in Electrical Engineering, Second Cycle, 30 Credits; School of Electrical Engineering, KTH Royal Institute of Technology: Stockholm, Sweden, 2017.
9. Fitzek, F.; Rasshofer, R.H.; Biebl, E.M. Comparison of matching layers for automotive radome design. *Adv. Radio Sci.* **2010**, *8*, 49–54. [CrossRef]
10. Rupcic, S.; Sipus, Z.; Mandric, V. Input Admitance of Circular Waveguide Opening Mounted on Dielectric-Covered Grounded Spherical Surface. In Proceedings of the 51th international Symposium ELMAR 2009, Zadar, Croatia, 28–30 September 2009.
11. Mandrić Radivojević, V.; Rupcic, S.; Nesic, N.; Lisnjic, A. Reflection Coefficient of Circular Waveguide Aperture Antenna Covered by Dielectric Radome. In Proceedings of the 4th International Conference on Smart Systems and Technologies Osijek–SST, Osijek, Croatia, 14–16 October 2020.
12. Mandrić Radivojević, V.; Rupcic, S.; Srnović, M.; Bensic, G. Measuring the Dielectric Constant of Paper Using a Parallel Plate Capacitor. *Int. J. Electr. Comput. Eng. Syst.* **2018**, *9*, 1–10. [CrossRef]
13. Meyer, G.J. *Polyurethane Foam: Dielectric Materials for Use in Radomes and Other Applications*; General Plastics, Manufacturing Company: Tacoma, WA, USA, 2015.
14. Radon, A.; Włodarczyk, P. Influence of water on the dielectric properties, electrical conductivity and microwave absorption properties of amorphous yellow dextrin. *Cellulose* **2019**, *26*, 2987–2998. [CrossRef]
15. Balanis, C.A. *Antenna Theory, Analysis and Design*, 3rd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2005.
16. Amiet, A. Free Space Permittivity and Permeability Measurements at Microwave Frequencies. Ph.D. Thesis, Monash University, Clayton, Australia, 2003.
17. Relative Permittivity–Dielectric Constant. Available online: https://www.engineeringtoolbox.com/relative-permittivity-d_1660.html (accessed on 27 December 2022).

18. Density of Paper, Standard (Material). Available online: https://www.aqua-calc.com/page/density-table/substance/paper-coma-and-blank-standard (accessed on 27 December 2022).
19. Yang, L.; Rida, A.; Vyas, R.; Tentzeris, M.M. RFID Tag and RF Structures on a Paper Substrate Using Inkjet-Printing Technology. *IEEE Trans. Microw. Theory Tech.* **2007**, *55*, 2894–2901. [CrossRef]
20. Aboserwal, N.A.; Balanis, C.A.; Birtcher, C.R. Amplitude Patterns of Aperture Antennas Mounted on Circular and Square Ground Planes. In Proceedings of the 2013 IEEE Antennas and Propagation Society International Symposium (APSURSI), Orlando, FL, USA, 7–13 July 2013. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.