

PERFORMANCE IMPROVEMENT OF CONICAL HORN ANTENNA BY USING WIRE MEDIUM STRUCTURE AND DIELECTRIC LOAD

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Abstract

This paper proposes a technique for gain improvement of a conventional conical horn antenna for the X-band frequency by adjusting the principal planes of the radiation pattern to be symmetrical with a dielectric load and using a wire medium structure as a metamaterial applied on the aperture of the horn to enhance the directive gain without changing the antenna's dimensions. The main idea of this research is for the applications of the dielectric load, which is located inside the horn to improve the patterns before transferring the electromagnetic waves through the wire medium structure, to enhance the directivity and reduce the side lobe level so that the total gain is obtained. The results show that the dielectric load and wire medium structure can increase the gain of a conventional conical horn antenna by approximately 20.4 dBi at 10 GHz of the operating frequency. In order to validate the simulated results, a prototype antenna was fabricated. The fundamental parameters such as the reflection coefficients (S11), radiation patterns, and directive gain were measured and compared to the calculation results. Finally, we found that the simulation results show good agreement with the experimental results.

Keywords: Wire Medium, conical Horn Antenna, artificial material

Introduction

Metamaterials at microwave frequencies have become an extensive research area because of their special electromagnetic properties and potential applications. An important application of metamaterials is to reduce wave velocity, or even reverse it in some frequency regions to achieve an electrically small radio frequency structure. In addition, an interesting class of metamaterials with a low or near-zero index of refraction has been investigated by several groups because of their useful applications such

as for compact resonators, zero-phase delay lines, wavefront transformers, transparent coating, sub-wavelength tunneling, highly directive beams, and relaxed dimension tolerance in nanoscale fabrication (Zhou *et al.*, 2010). In recent research, the use of metamaterials in antenna applications has been widely investigated. They were utilized to control electromagnetic waves like artificial materials with permittivity levels close to zero. These were also known as epsilon-near-zero (ENZ) metamaterials (Jun *et al.*, 2013) and were

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used for controlling the directivity of radiation patterns of antennas (Burghignoli *et al.*, 2008b). In addition, they are also suitable for the development of lenses due to their ability to tailor the wavefronts to the desired shape by simply controlling the lens profile (Torres *et al.*, 2015).

At microwave frequencies, a wire medium is well known to implement the artificial plasma, and can be used to realize the ENZ condition (Forati *et al.*, 2015). The wire medium structures are considered to be a kind of electromagnetic band gap material or metamaterial structure, which is actually electrically anisotropic for arbitrarily polarized fields. These structures consist of a periodic arrangement of metallic wires that perfectly conduct cylinders (wires) in an infinitely long and parallel rectangular lattice, which is embedded inside a homogeneous host medium of a dielectric constant. However, the electromagnetic properties of this material can be described in terms of the effective permittivity that occurs with the advent of the metamaterials (Burghignoli *et al.*, 2008a; Tomaz *et al.*, 2013a).

The basic theory of a conical horn is that it is a truncated section of a right circular conical waveguide, and it is usually connected to a circular waveguide or a rectangular waveguide which is gradually transitioning into the circular waveguide (Al-Nuaimi *et al.*, 2014). The conical horn is a basic and popular microwave antenna for many practical applications due to its high gain, high power-handling capabilities, and simple feed. In addition, the physical dimensions of a conical horn which correspond to a maximum gain, for a given length, lead to optimum gain designs (Aboserwal *et al.*, 2013).

However, the conical horn antenna also has disadvantages, including its heavy weight and large size. Presently, there are many researchers who have investigated different designs for the conical horn antenna that are meant to improve its performance by facilitating higher directivity, decreasing the antenna's weight, and reducing the antenna's size for easier use with more applications.

In (Qiu *et al.*, 2008), a quad-ridged horn antenna was designed using a dielectric hemispheric lens placed on a ridged horn

antenna, which was done to minimize the phase variations of the radiated electromagnetic wave in the plane of the antenna's aperture. The dielectric lens can increase the gain and realize the dual polarization character of the quad-ridge horn antenna. Reyes-Ayala and Jardon-Aguilar (2014), reduced the length of the standard conical horn by the addition of a dielectric load at the antenna's aperture. Moreover, the synthesis of different beam patterns for far-field radiation has been accomplished by the insertion of a dielectric cylinder spiral phase plate at the aperture of the conical horn antenna (Doumanis *et al.*, 2013). Ramaccia *et al.*, (2013) designed the epsilon-positive and ENZ metamaterials flat lens to cover the aperture of the short horn antenna; the radiation performances of this antenna were similar to those of the conventional horn antenna. Tomaz *et al.*, (2008b), used a wire medium for the modifications on the radiation pattern of a standard X-band horn antenna, for which a wire medium structure consisting of 5 layers of Styrofoam plates hosted a periodic array of metallic wires. The loading wire medium exhibited a high directivity and reduced the side lobe level, while the gain of the proposed antenna was lower than that of the conventional horn. Furthermore, a high-directivity compact-size conical horn lens antenna was proposed to create a spherical wavefront similar to an electromagnetic wave by using a wire medium lens to cover the aperture of the conical horn and obtain a higher gain (Al-Nuaimi *et al.*, 2014).

In this paper, the design of a wire medium structure designed for gain improvement and reduction of the side lobe level of a standard conical horn at an operating frequency of 10 GHz is presented. Furthermore, in order to increase the directivity and decrease the beamwidth, we added a circular dielectric load inside the horn to adjust its radiation pattern to be symmetrical both in E- and H-planes before transferring energy through a wire medium. The most suitable structure for the practical application of the wire medium and dielectric load will be investigated and designed. The wire medium must be mounted on the horn aperture, while the dielectric load will be properly placed into the horn structure without modifying the dimensions of the horn.

The structure of the conventional horn antenna with and without a dielectric load will be briefly mentioned in section II. After that, the theory and design procedure for the wire medium structure are presented and simulated using licensed Computer Simulation Technology (CST) software in section III. Next, the antenna prototyping and verification of simulated and measured results are discussed in section IV. Finally, section V presents the conclusion of this research.

Theory and Configuration

Design of the Conical Horn Antenna

The structure of a conventional conical horn antenna is shown in Figure 1. The dimensions of such a conical horn can be theoretically calculated to achieve the desired absolute gain and are mentioned in King (1950). The calculated dimensions for the proposed horn antenna are:

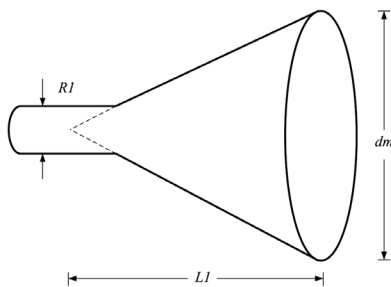


Figure 1. The structure of a conventional conical horn antenna

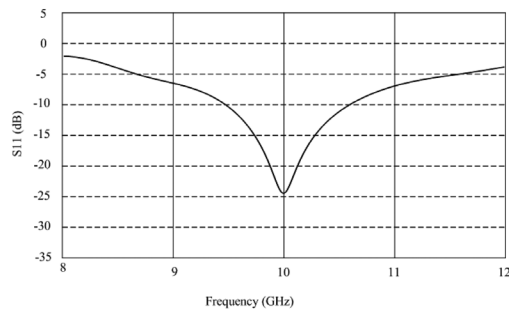


Figure 2. The simulated reflection coefficient of a conventional conical horn antenna

length ($L1$) = 120 mm, aperture diameter (dm) = 112 mm, and circular waveguide diameter ($R1$) = 26 mm. These dimensions are calculated at an operating frequency of 10 GHz. The simulated results of the conventional conical horn antenna illustrate the reflection coefficient ($S11$) and the normalized radiation patterns, as shown in Figure 2 and Figure 3, respectively. In Figure 3, it is observed that the simulated radiation patterns both in the E-plane and H-plane at 10 GHz providing the peak gain are approximately 17.7 dB. Meanwhile its beamwidths in both plane are close to being symmetrical, whereas the side lobe levels of both planes are rather different (29.4 dB in E- plane and -22.7 dB in H-plane).

Design of the Dielectric Load for Horn Antenna

In order to adjust the radiation pattern of the conventional conical horn antenna in the both planes to be a symmetrical shape and provide the narrower beamwidth, dielectric loading is

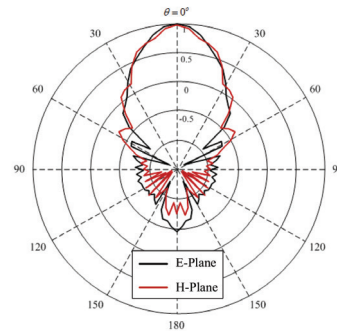


Figure 3. The simulated 2D radiation patterns of a conventional conical horn antenna

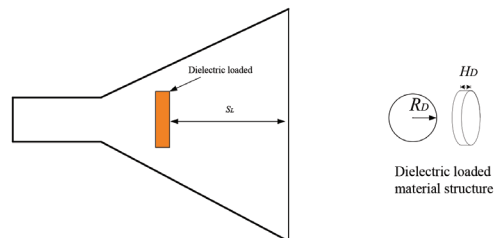


Figure 4. The structure of the dielectric loaded material structure of conical horn antenna

an alternative approach to improve the horn's radiation characteristics. The important parameters of the dielectric loaded material, which cause the radiation pattern characteristics of the horn antenna, are improved with regard to its dimension and its location inside the horn was investigated (Clenet and Shafai, 1998; Tan and selsen, 2009). However, we firstly specified the dielectric loaded material by using polyamide ($\epsilon_r = 3.5$) with $H_D = 7.5$ mm of thickness. After that, we used the CST simulation software to calculate the most proper radius (RD) of the dielectric load and the optimized distance (SD) between such load and the horn aperture, which provides the minimum reflection and resonance at 10 GHz of frequency. From the simulation results, Figure 4 shows the geometry of a dielectric loaded material which is inside the conical horn. The comparison of the reflection coefficients with different radii of the circular dielectric load is shown in Figure 5. We found that the radius = 15 mm causing the horn antenna to

be at maximum optimization at the desired resonant frequency. Whereas the different distances between the horn's aperture and dielectric's location will also affect the reflection coefficients, as shown in Figure 6. It is found that the optimized distance (SD = 30 mm) caused a better matching than the other distances at 10 GHz of operating frequency. In order to compare the simulation results of S11 of the conventional horn antenna with and without the dielectric loaded material, in Figure 7 it is observed that both cases still maintain the operating frequency at 10 GHz and the bandwidth at S11 = -10 dB. However, if we consider the bandwidth at S11 = -15 dB, then the bandwidth of the horn's antenna with dielectric load is narrower than the one without the dielectric load.

The radiation pattern in both planes of the horn's antenna with dielectric loading is calculated and illustrated in Figure 8. We found that, when dielectric loaded material is located in the optimized position, the radiation patterns

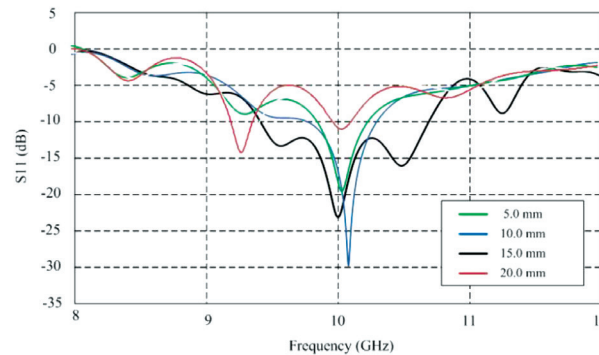


Figure 5. The simulated reflection coefficient of the different radii of the dielectric loaded material structure

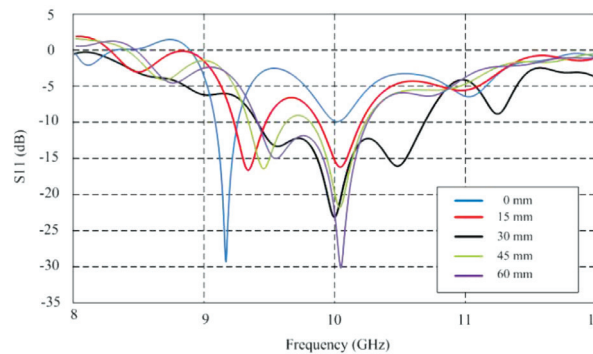


Figure 6. The simulated reflection coefficient of the different distances of the dielectric loaded material structure

are very satisfactory because the obtained beamwidths are almost identical and the side lobe levels are still low both in the E-and H-planes (lower than -24 dB). Furthermore, the half power beamwidths (HPBW) of both planes are controlled so as to be identical when dielectric load is inserted inside the horn, so its gain can be increased from 17.7 dB to 18.4 dB automatically. Finally, the radiation characteristics of the conical horn's antenna with/without the dielectric loading are comparatively summarized, as shown in Table 1.

Design of the Wire Medium Structure

In Figure 9, the wire medium is an artificial material formed by a regular lattice of ideally conducting wire. The radius of the wires is assumed to be very small when compared to the lattice periods and the wavelength. Generally, the wire medium structure has been known for a long time as an artificial dielectric with plasma-like frequency-dependent permittivity, but it was only recently that it was shown that this dielectric is non-local and possesses also strong spatial

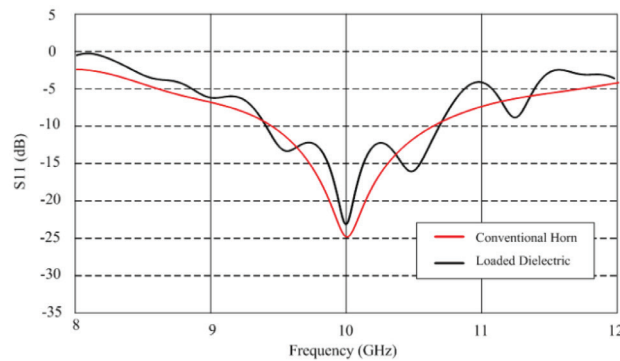


Figure 7. The simulated reflection coefficient of the loaded dielectric material structure

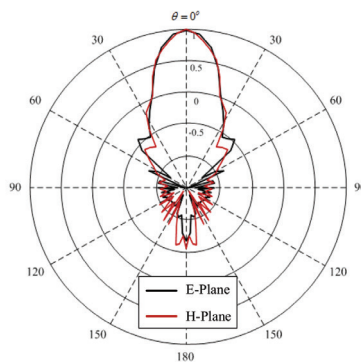


Figure 8. The simulated 2D radiation patterns of the dielectric loaded material structure

Table 1. Radiation characteristic of the conical horn antennas at 10 GHz

Type	Gain [dB]	Side lobe Level [dB]		Half-power beamwidth	
		E-Plane	H-Plane	E-Plane	H-Plane
Conventional Conical Horn Antenna	17.7	-29.4	-22.7	18.4°	17.6°
Conventional Conical Horn Antenna with loaded dielectric Material	18.4	-24.5	-25.9	17.9°	17.9°

dispersion even at very low frequencies (Zhao *et al.*, 2007). This wire medium structure, as shown in Figure 9, is an isotropic for electromagnetic waves with an arbitrary polarization and, as such, it requires the use of a uniaxial permittivity with an optical axis parallel to the wire (y) axis. When the wire medium structure is homogenized, the wavelengths become sufficiently larger than the wire spacing. Additionally, the wire medium structure consists of a finite number N of periodic layers of thin conducting cylinders embedded in a dielectric sheet with relative permittivity (ϵ_{rh}). Furthermore, in cases with long wavelength limits, the wire medium structures act as homogeneous materials (Belov *et al.*, 2003; Maslovski *et al.*, 2002). However, if the wires of the structure are perfect conductors for electrical polarized plane waves, then effective relative permittivity (ϵ_{WM}) occurs. This is a frequency-dependent scalar quantity that can be expressed as

$$\epsilon_{WM} = \epsilon_0 \epsilon_{rh} \left(1 - \frac{k_p^2}{\epsilon_{rh} k_0^2 - k_y^2} \right) \quad (1)$$

where ϵ_{rh} is the relative permittivity of the medium host with the wire, ϵ_0 represents the permittivity of free-space, k_p is the plasma wave-number, k_0 is the free-space wave number, and k_y represents the wave number along the wire axis. However, the plasma wave number usually depends on the geometrical and physical parameters of the structure, which can be expressed as (Burghignoli *et al.*, 2008a).

$$k_p^2 = \frac{2\pi}{ab \left[\ln \left(\frac{\sqrt{ab}}{2\pi r} \right) + F(a/b) \right]} \quad (2)$$

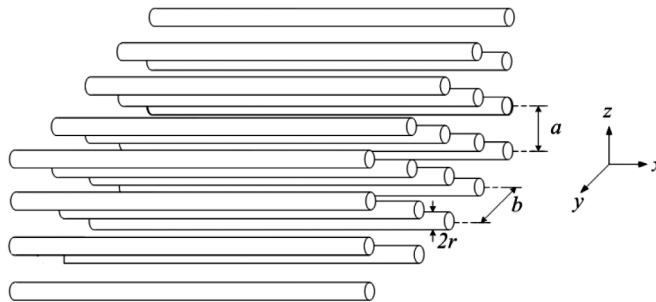


Figure 9. The dimension of the wire medium

where

$$F(a/b) = -\frac{1}{2} \ln(a/b) + \sum_{n=1}^{+\infty} \frac{1}{n} \left[\coth \left(\frac{\pi n a}{b} \right) - 1 \right] + \frac{\pi}{6} (a/b) \quad (3)$$

where a, b, and n represent the spatial period along the z-direction, the spatial period along the x-direction, and the number of wire layers along the z-direction, respectively. For the commonly used case of the square grid (a=b), $F(a/b) = 0.5275$.

An important assumption of Equation (1) is the wires are very thin, so that the plasma frequency corresponds to a free space wavelength much greater than the lattice spacing, and therefore the Bragg diffraction effect can be ignored (Zhou *et al.*, 2010). The Graph in Figure 10 illustrates the result of the calculated effective permittivity of the wire medium with $r = 1.25$ mm, $a = 3.5$ mm, $b = 3.5$ mm and $n = 2$ using Equation (1). It shows that the plasma theory is self-consistent and a metallic wire array may be used as an effective medium with special properties such as a very small or near-zero permittivity. Furthermore, the near-zero permittivity of a wire array medium can be realized in any microwave frequency by adjusting the wire array spacing and the wire radius according to Equation (1).

As in the theory of the wire medium detailed in section II, the dimensional structure of the wire medium in the present study has been designed and optimized for the most appropriate efficiency, as shown in Figure 11. The design consists of a 2-layered rectangular lattice of thin wire in parallel operation. This

lattice is embedded on both sides of the polyamide ($\epsilon_r = 3.5$) dielectric sheet. Furthermore, the effective relative permittivity of a wire medium structure can be realized in operating frequency 10 GHz by adjusting the wire array spacing and the wire radius according to Equation (1). We found that the most appropriate dimensions for the wire medium structure, which provided the desired performance, were: wire radius (r) = 1.25 mm, wire array spacing ($s1$) = 3.5 mm, and polyamide thickness ($h1$) = 3.5 mm. When this wire medium structure is modeled, it can be explained as an effective medium model with an equivalent lumped resonant (LC) element, as shown in Figure 12.

Optimization of the Wire Medium Structure for the Conical Horn Antenna

There are several important parameters that may influence the behavior of a wire medium structure. For the initial approach to the design process of the conical horn antenna, the dimensions of the wire medium structure are chosen according to the frequency range of interest. The configurations of the wire medium structure are designed and optimized by the performance of various parametric simulations using electromagnetic simulation software. In Figure 13, 4 models of the proposed conical horn are shown. The comparative geometries of the

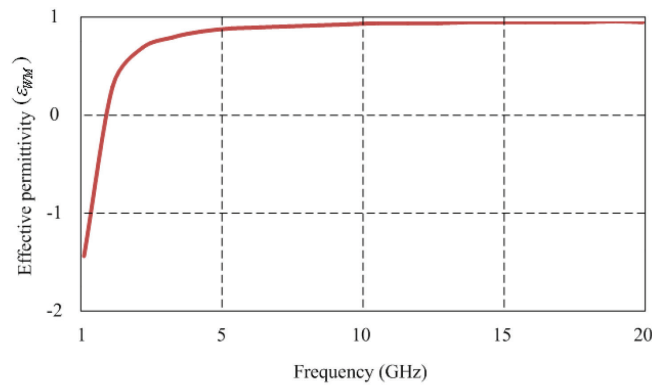


Figure 10. Calculated effective relative permittivity of wire medium using the plasma theory

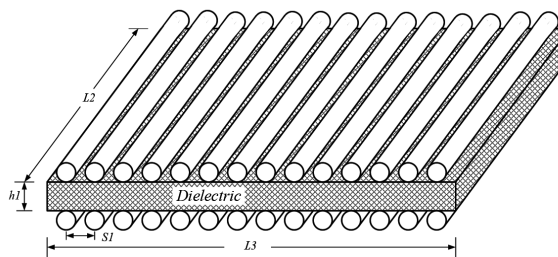


Figure 11. The proposed wire medium structure

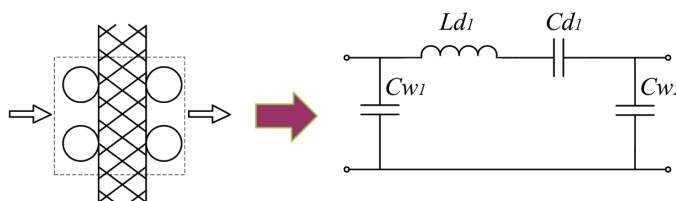


Figure 12. The equivalent resonance circuit of the wire medium structure

4 different models are evaluated to establish the most appropriate performance. The simulated reflection coefficients of each model from the simulated results have been compared, as shown in Figure 14. We found that after they were tuned until the parameters met the same resonant frequency at 10GHz, the frequency bandwidths of all models examined at the reflection coefficient around -10 dB are rather similar.

However, the reflection coefficients of all structures are narrower than the conventional horn due to the effect of the wire medium. Moreover, in Figure 15, we present a comparison of the radiation patterns of all models in both the E-and H-plane. It is found that the conical horn with the wire medium structure of model D provides the better pattern symmetry and fewer numbers of minor lobes when compared to the

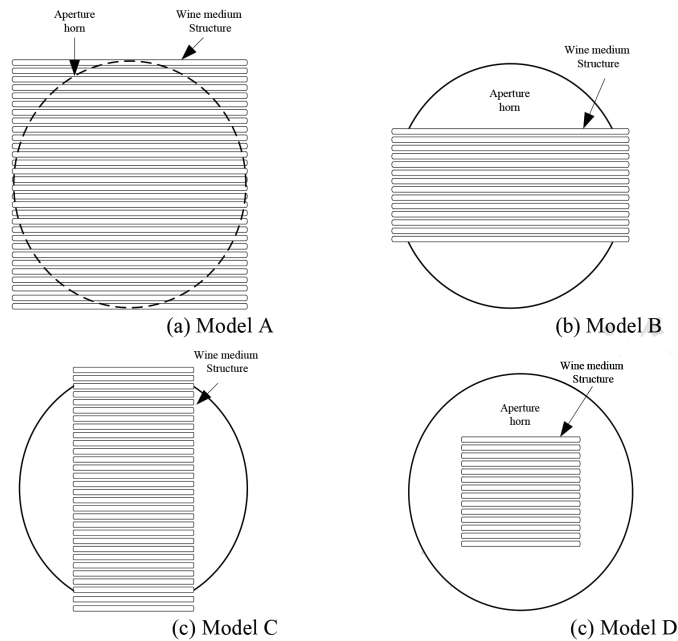


Figure 13. Different configurations of the wire medium structure placed on the horn's aperture

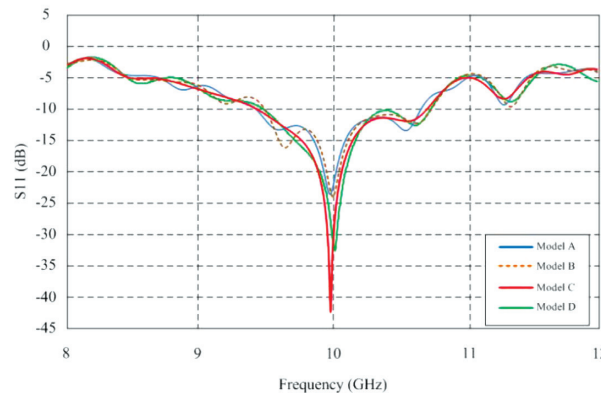


Figure 14. The simulated reflection coefficient versus frequency of each model of the wire medium structure on the horn's aperture

other models.

Figure 16 presents a comparison of the simulated gains of the conical horn when placed each model on its aperture. The gains of the conical horn with the model D structure were improved by substantially more than the other models. In terms of the simulated results for the conical horn from the 4 models, the reflection coefficient, directivity, and gain performances of the model D structure are the most suitable for optimization.

To demonstrate the advantage of using a wire medium structure with the conical horn antenna, the performance of the structure was tested at different distances between its structure and horn's aperture. For the sake of comparison,

the same dimension of model D structure are given and simulated again to determine the effect of the spacing. From the simulation result in Figure 17, it is seen that the wire medium structure of model D provides the best matching at 10 GHz of the resonant frequency when the wire medium is placed on the aperture plane (0 mm).

Furthermore, we also studied the effect of the different types of dielectric (air, FR4, Teflon, and polyamide) that are a part of the wire medium structure. From the study, it is found that each type of dielectric provides the different reflection coefficient as shown in Figure 18. However, in our work we found that the polyamide dielectric provides the lowest reflection at the resonant

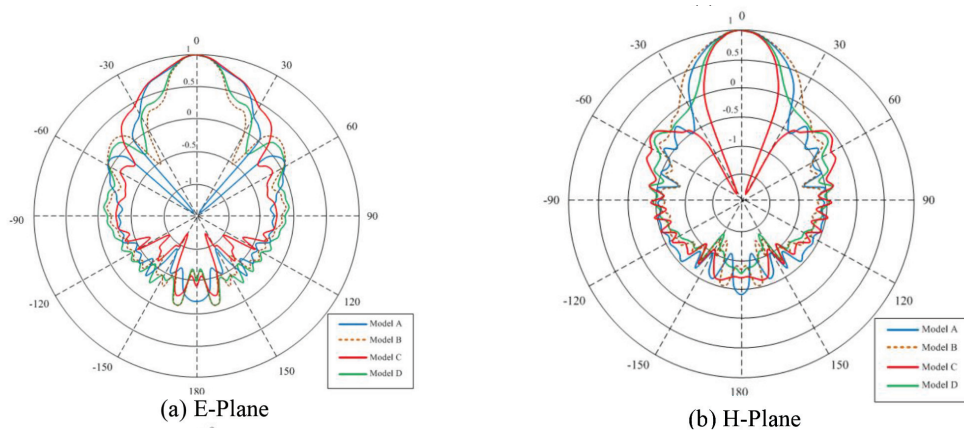


Figure 15. The simulated radiation patterns of each model of the wire medium structure placed on the horn's aperture

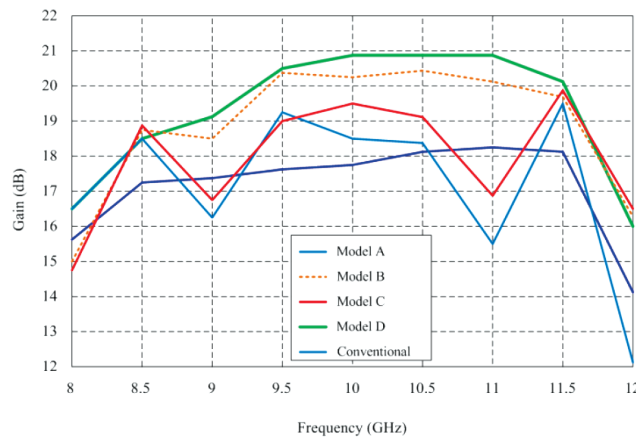


Figure 16. The simulated gains of each model of the wire medium structure on the horn's aperture

frequency of 10 GHz.

After that, we continued to study the effect of the number of layers of the wire medium structure placed on the aperture. We found that the different number of layers affected the frequency response of the horn antenna, especially

the resonant frequency, as shown in Figure 19. Since the desired resonant frequency of the proposed horn antenna is 10 GHz, 2 layers of wire medium were selected.

For the next step, the perspective view of the proposed horn antenna comprised of the

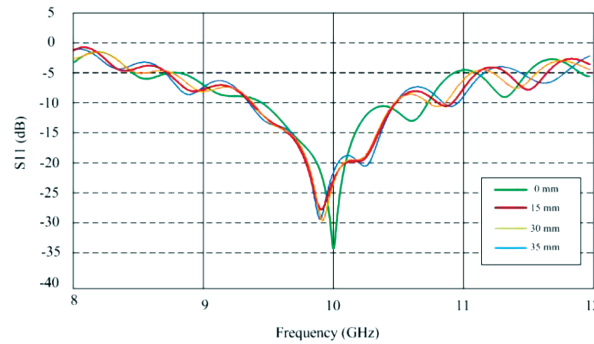


Figure 17. The simulated reflection coefficient versus frequency when the distance between the wire medium and horn's aperture is different

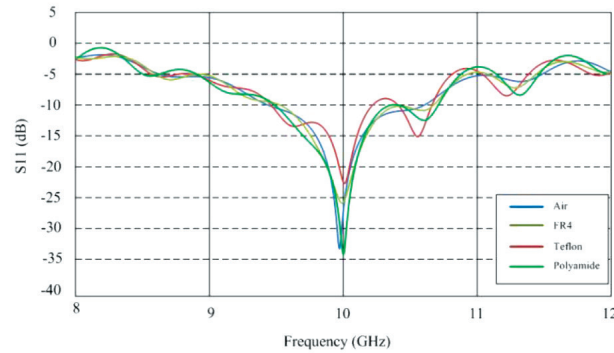


Figure 18. The simulated reflection coefficient when the types of dielectric of wire medium structure are different

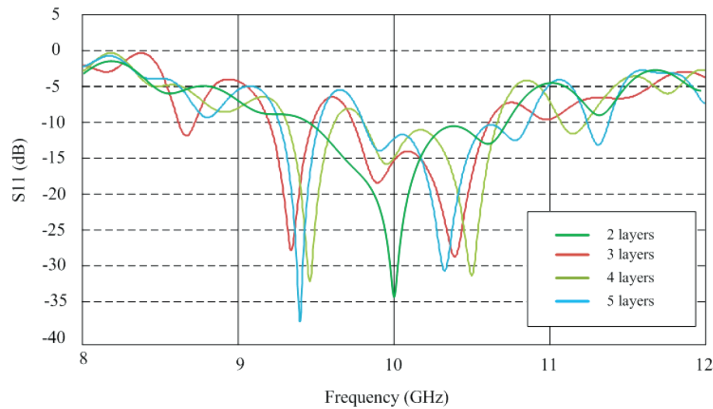


Figure 19. The frequency response of horn antenna when the wire medium structure has the different number of layers

dielectric loaded material and the optimized wire medium structure are shown in Figure 20. Here, the optimized dimensions of the wire medium structure are: height of the polyamide ($L2$) = 60 mm, wire radius (r) = 1.25 mm, wire spacing ($s1$) = 3.5 mm, number of wires (n) = 21, and polyamide thickness ($h1$) = 3.5 mm. The optimized parameters of the circular dielectric load are: thickness of load (H_D) = 7.5 mm, dielectric radius (R_D) = 15 mm, and the distance

between the dielectric load and the horn's aperture (S_D) = 30 mm. The simulation results of the proposed horn antenna with these parameters are shown in Figure 21 and 22. We found that the simulated reflection coefficient versus the given frequency of the proposed conical horn antenna shows much better impedance matching and narrower bandwidth when compared to the conventional one, as illustrated in Figure 21. For the HPBW, the normalized radiation

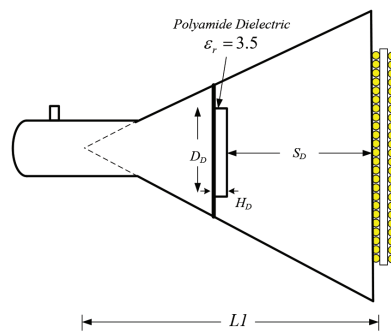


Figure 20. The conical horn antenna with a wire medium structure

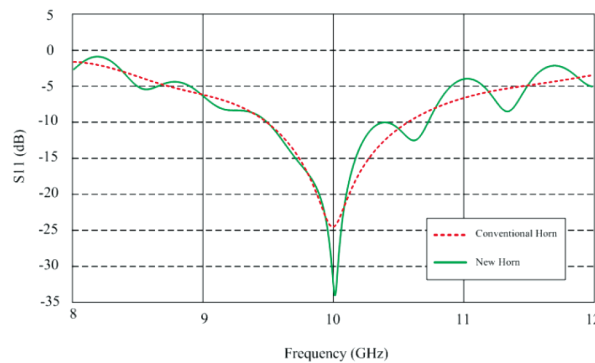


Figure 21. The simulated reflection coefficients of the proposed Antenna

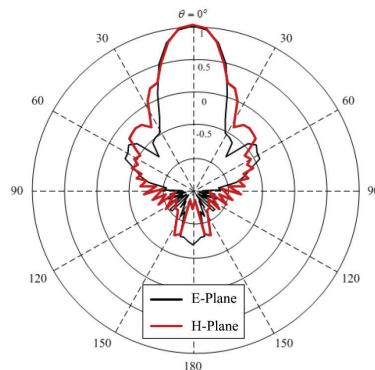


Figure 22. The simulated radiation patterns of the proposed antenna

patterns in both planes are shown in Figure 22. It is found that the HPBW's in both planes of the proposed horn are narrower than those of the conventional horn. While the conventional horn provides an asymmetric pattern, our horn antenna provides more symmetry and lower side lobe levels (-32.2 dB in E – plane, -32.4 dB in H-plane).

However, in order to provide a comparative illustration, we report the differences of the simulated radiation patterns at 10 GHz of the different types of the conical horn antennas which we studied: (a) conventional conical horn, (b) with dielectric load, (c) with wire medium, and (d) with dielectric load and wire medium (the proposed antenna), as illustrated in Figure 23. It is noted that the HPBW of the proposed horn antenna provides the narrowest beam and lowest side-lobe level causing it to provide the highest gain, as noted in Table 2.

Antenna Prototyping and Measurement

A prototype of the proposed antenna is shown in Figure 24. The simulated and

measured reflection coefficients of this antenna are compared in Figure 25. We found that 2 results of S11 from simulation and measurement are in good agreement. Furthermore, in Figure 26, the measured E- plane and H-plane normalization radiation patterns of the antenna prototype show good agreement when compared to the simulation. However, the maximum gain of the simulated results at 10 GHz is around 20.9 dB, while the difference between the simulation and experimentation is inferior at only 0.2 dB.

Conclusions

In this work, a new approach for gain enhancement of the conventional conical horn antenna was proposed. The metamaterial technique based on a wire medium structure was applied to the conical horn to enhance the gain characteristics without changing the antenna sizes, which are designed to work with 10 GHz of X-band frequency for radar applications. Moreover, we utilized a technique for adjusting the radiation patterns in the E- and H-planes symmetrically,

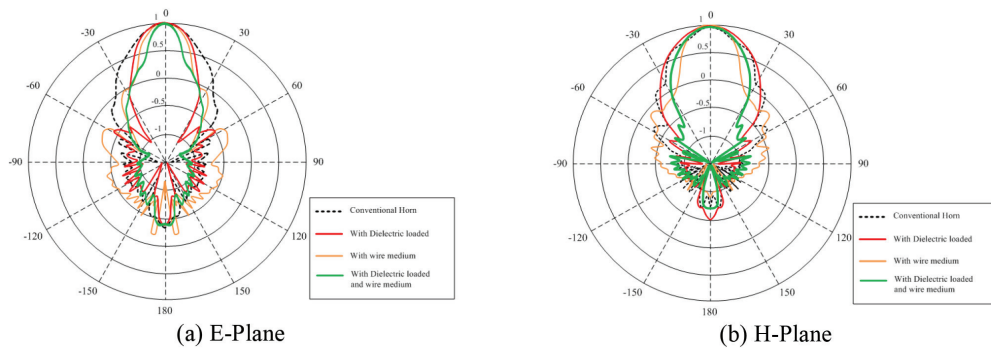


Figure 23. The of the normalized patterns of 4 studied cases. (a) conventional conical horn antennas (b) dielectric load (c) wire medium, and (d) dielectric load and wire medium

Table 2. Radiation characteristic of the 4 conical horn antennas at 10 GHz

Type	Gain [dB]	Side lobe Level [dB]	
		E-Plane	H-Plane
Conventional Conical Horn Antenna	17.7	-29.4	-22.7
Conventional Conical Horn Antenna with loaded dielectric Material	18.4	-24.5	-25.9
Conventional Conical Horn Antenna with wire medium	20.9	-23.8	-20.9
Proposed Antenna	20.9	-26.6	-26.8

with the dielectric loaded material placed inside the horn. The comparison results, including the reflected coefficient (S11) and radiation patterns of the proposed antenna and the conventional horn were simulated using the CST simulation software. Very good agreement between the simulations and measurements was reported in the findings. The proposed antenna provides

higher gain (20.9 dB) when compared to the gain of the conventional horn (17.7 dB). The gain of the conical horn antenna is around 3.2 dB. As for the pattern, the HPBW of the proposed antenna was narrower than that of the conventional horn causing the higher gain. To summarize, the wire medium structure of the proposed antenna improved the radiation pattern, enhanced the directivity, increased the gain, and reduced the side lobe level by using a simple integrated wire medium structure and circular dielectric loaded material. Additionally, the reflection coefficient decreased by more than -10 dB when compared to the conventional horn.



Figure 24. A photograph of the fabricated proposed antenna

Acknowledgment

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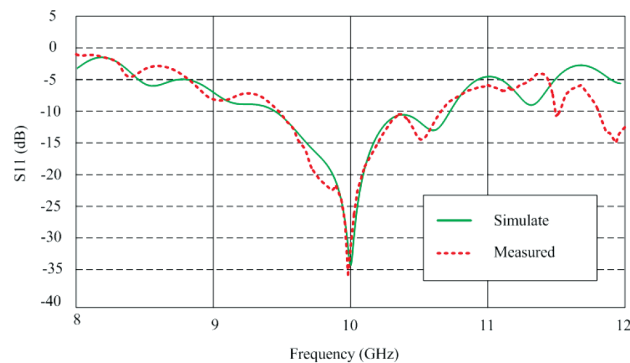


Figure 25. The simulated and measured results of the reflection coefficient of the proposed antenna

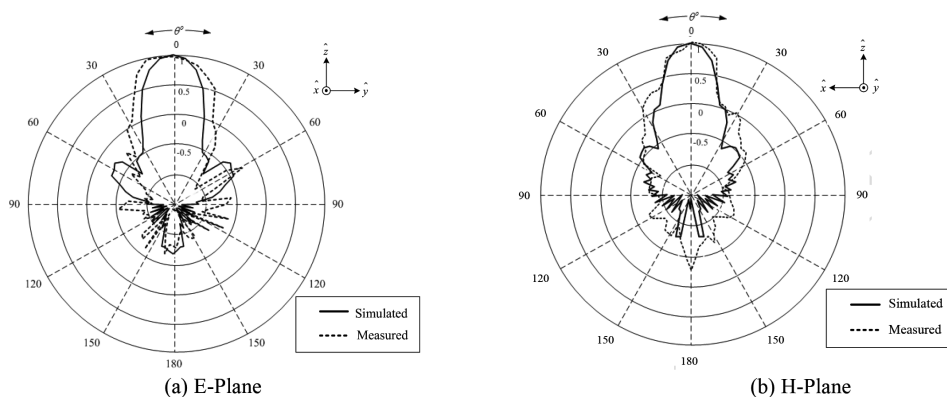


Figure 26. Comparison between the simulated radiation patterns of the conventional and proposed antennas

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