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Creating a Gain Enhancement Technique for a Conical Horn Antenna by Adding a Wire Medium Structure at the Aperture

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Abstract

This paper proposes a technique for improving the conventional conical horn antenna for the X-band frequency using metamaterial on a wire medium structure. The main idea of this research is the application of the wire medium metamaterial to the conical horn's aperture for the enhancement of the horn's gain; this is done without changing the antenna's dimensions. The results show that the wire medium structure can increase the gain of a conventional conical horn antenna from approximately 17.7 dB to 20.9 dB (an increase of approximately 3.2 dB). A prototype antenna was fabricated, and its fundamental parameters including its reflection coefficient (S_{11}), radiation patterns, and directive gain were measured. The simulated and measured results were very good. The wire medium structure of the proposed antenna improved the radiation pattern, enhanced the directivity, increased the gain, and reduced the side lobe level using a simple integrated wire medium structure.

Key Words: Conical Horn Antenna, Metamaterial, Wire Medium Structure.

I. INTRODUCTION

The conical horn antenna is often applied in a variety of applications due to its high gain and high power-handling capabilities. The advantages of the conical horn antenna are that it is simple to feed, it has a low back lobe, it can function with very good directivity, and it can gain properties. The physical dimensions of a conical horn directly increase as the horn gains power. The conical horn antenna also has disadvantages, including its heavy weight and large size. Still, the conical horn antenna achieves higher gain compared with other antenna types, especially at low frequencies [1]. There are many different conical horn antenna designs that are meant to improve performance by facilitating higher directivity, decreasing the antenna's weight, and reducing the antenna's size for easier use with more applications.

Generally, improvement of the conical horn antenna has been achieved by configuring the antenna's length and flare angle; however, this approach still sometimes results in phase errors within the horn. The conical horn can be improved with the use of a dielectric lens in the horn's aperture. This type of lens is produced in various shapes and with a range of materials. For example, 2D and 3D lenses are both made from different dielectric materials [1]. Dielectric lenses can also be used to improve the performance of a conical horn antenna. The dielectric lens is mounted to the antenna's aperture to facilitate concen-

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tration of the radiated energy into a narrow beam and to prevent that energy from spreading in undesired directions. Other advantages of this method include its good return loss, high gain, and low side lobe [2].

In recent research, the use of metamaterials in antenna technology applications has been widely investigated. Metamaterial can be defined as new technology used to control electromagnetic waves. Special attention has been paid to artificial materials with permittivity levels close to zero. These are also known as epsilon near zero (ENZ) metamaterials [3]. In recent studies, ENZ materials have attracted a great deal of attention for their highly unusual optical properties. Additionally, ENZ materials have been employed for perfect coupling through a narrow channel, optical switching and bistability, as well as for gaining directivity control of the radiation pattern of antennas [4]. These materials are also suitable for the development of lenses due to their ability to tailor the wave fronts to the desired shapes by simply controlling the lens profile [2]. In addition, the wire medium structures are considered to be a kind of electromagnetic band gap material or metamaterial [4]. 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 dielectric constant. The electromagnetic properties of this material can be described in terms of the effective permittivity that occurs with the advent of the metamaterials [5, 6].

In [7], 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 len canincreased the gain and realized the dual polarization character of the quad-ridge horn antenna. In [8], the length of the standard conical horn was reduced by the addition of a dielectric load at the antenna's aperture. Moreover, in [9], the synthesis of different beam patterns for far-field radiation was accomplished by the insertion of a dielectric cylinder spiral phase plate (SPP) at the aperture of the conical horn antenna. In [10], the epsilon positive (EPS) and ENZ metamaterials flat lens was designed to cover the aperture of the short horn antenna; the radiation performances of this antenna were similar to those of the conventional horn antenna. In [11], a wire medium of the modifications on the radiation pattern of a standard X-band horn antenna, which a wire medium structure consisting of five layers of Styrofoam plates hosting a periodic array of metallic wires. The loading wire medium exhibited a high directivity and reduced 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 wave front similar to an EM wave by using a wire medium lens to cover the aperture of the conical horn and obtain a higher gain [12].

In this paper, the design of a wire medium structure designed for gain improvement of a standard conical horn at an operating frequency of 10 GHz is presented. The most suitable structure for the practical application of the wire medium will be investigated and designed. The wire medium must be mounted on the horn aperture without modifying the dimensions of the horn. The present study demonstrates the possibility of using a simple integrated wire medium structure to enhance the directivity, increase the gain, amd reduce the side lobe level of a conical horn antenna.

The theory and configuration of the wire medium structure are briefly mentioned in Section II. In Section III, the basic design of the conventional conical horn and the design procedure for the wire medium structure are presented using licensed Computer Simulation Technology (CST) software. Antenna prototyping and verification of simulated and measured results are discussed in Section IV, while Section V presents the conclusion of this research.

II. Theory and Configuration of the Wire Medium Structure

A rectangular wire medium structure lattice is ideally made by conducting parallel thin wires, as shown in Fig. 1 [13]. The wire medium shown in Fig. 1 is an isotropic for electromagnetic waves with an arbitrary polarization, and as such, it requires the use of an 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 [5]. Additionally, the wire medium structure consists of a finite

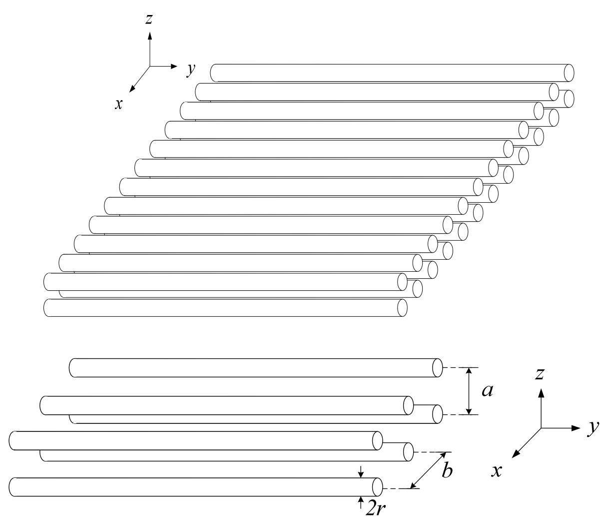


Fig. 1. The dimension of the wire medium.

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 [14, 15]. 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

$$\varepsilon_{WM} = \varepsilon_0 \varepsilon_{rh} \left(1 - \frac{k_p^2}{\varepsilon_{rh} k_0^2 - k_y^2} \right) \tag{1}$$

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 wavenumber, and k_y represents the wavenumber along the wire axis. However, the plasma wavenumber usually depends on the geometrical and physical parameters of the structure, which can be expressed as [5]

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

where

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

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.

III. Simulated Results and Discussion

1. Design of the Conical Horn Antenna

The structure of a conventional conical horn antenna is shown in Fig. 2. The dimensions of such a conical horn can be theoretically calculated to achieve the desired absolutegain, which that the gain was mentioned in [16]. The calculated results for the present study's horn dimensions are length (L_1) = 120 mm, aperture diameter (d_m) = 112 mm, and circular waveguide diameter (R_1) = 26 mm. These dimensions are calculated at an operating frequency of 10 GHz and result in a gain of 17.7 dB, as shown in the 3D radiation pattern in Fig. 3. Furthermore, the simulated results of the conventional conical horn antenna illustrate the reflection coefficient (S_{11}), the normalized radiation patterns, and the 2D radiation patterns, as shown in Figs. 4 and 5.

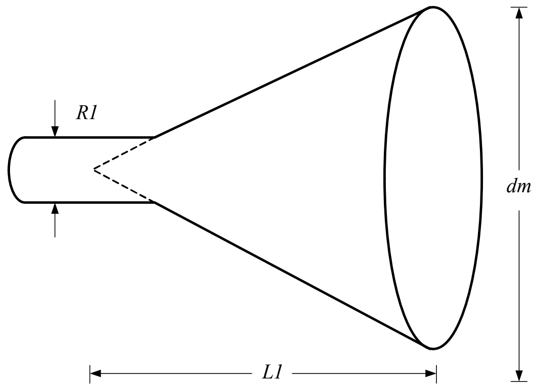


Fig. 2. The structure of a conventional conical horn antenna.

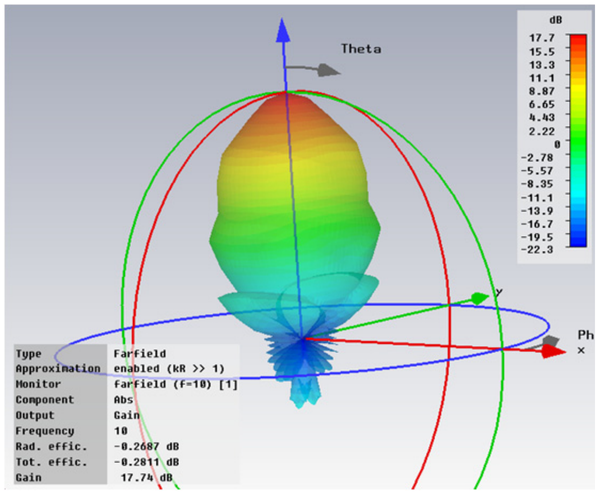


Fig. 3. The directive gain from the simulated 3D radiation pattern of a conventional conical horn antenna.

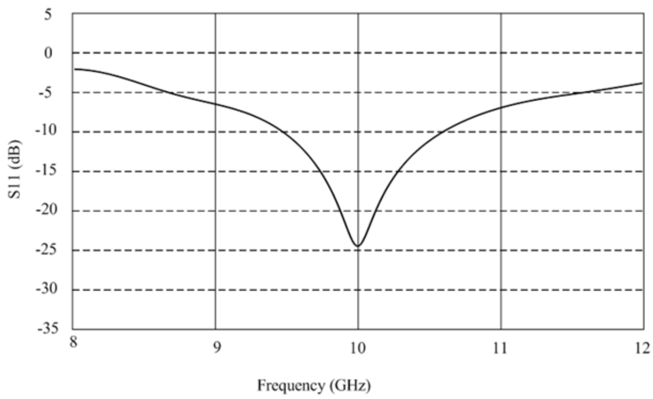
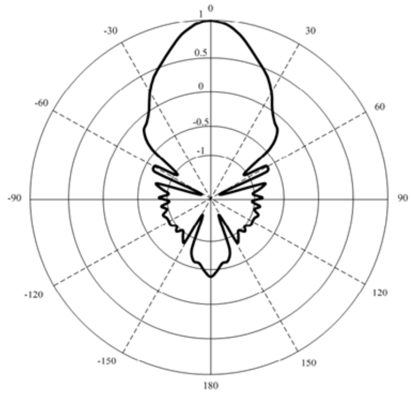


Fig. 4. The simulated reflection coefficient of a conventional conical horn antenna.

2. Design of the Wire Medium Structure

As in the theory of 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 efficient, as shown in Fig. 6. The design consists of a two-layered rectangular lattice of thin wire in parallel operation. This lattice is embedded on both sides of the polyamide (ε_r = 3.5) dielectric



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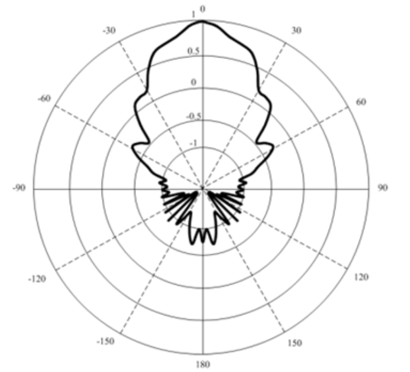

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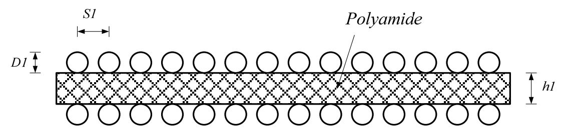
Fig. 5. The simulated 2D radiation patterns of a conventional conical horn antenna. (a) E-plane, (b) H-plane.



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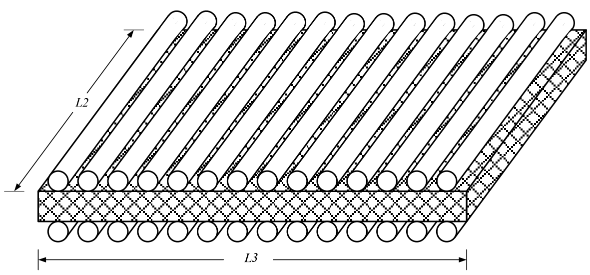


(b)

Fig. 6. The proposed wire medium structure: (a) side view, (b) perspective view.

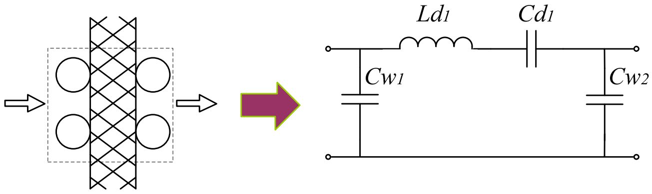
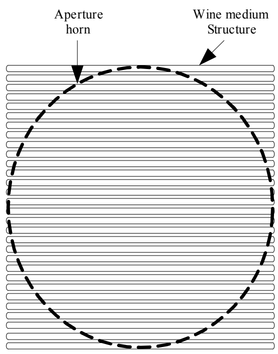


Fig. 7. The equivalent resonance circuit of the wire medium structure.

sheet. Furthermore, the effective relative permittivity of a wire medium structure can berealized in operating frequency 10 GHz by adjusting the wire array spacing and the wire radius according to (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 (s_1) = 3.5 mm, and polyamide thickness (h_1) = 3.5 mm. When this wire medium structure is modeled, it can be explainedan effective medium model with equivalent lumped LC element, as shown in Fig. 7.

3. 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 Fig. 8, four models of the proposed conical horn are shown. The comparative geometries of the four 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 Fig. 9. The four models have been tuned to resonate at the same



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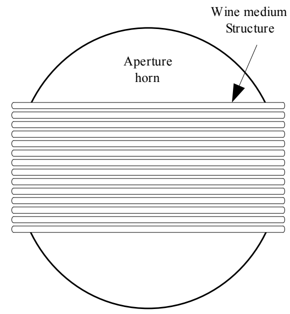

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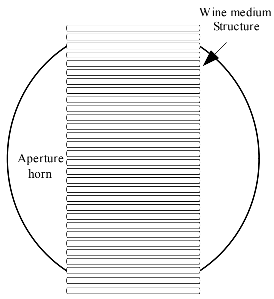

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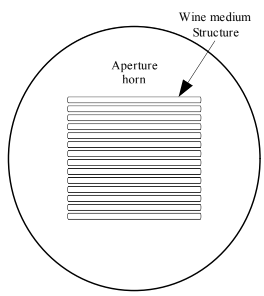


(d)

Fig. 8. Different configurations of the wire medium structure. (a) Model A, (b) model B, (c) model C, and (d) model D.

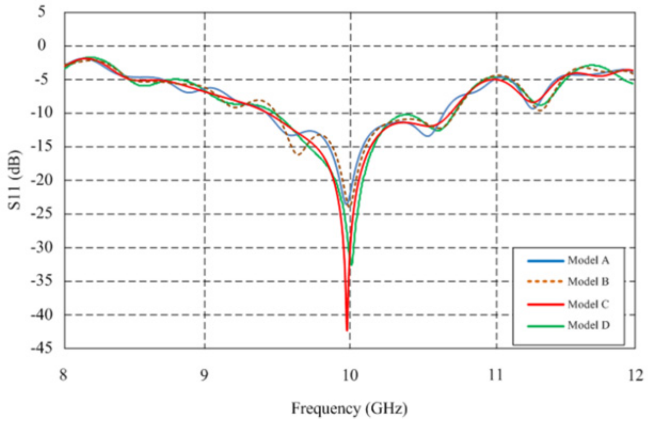


Fig. 9. The simulated reflection coefficient of the four models of the wire medium structure.

frequency (10 GHz). All models examined show reflection coefficients of higher than −10 dB, and the models all have similar bandwidths. However, the reflection coefficients of the models' structures are narrower than the conventional horn due to the effect of the wire medium structure. Fig. 10 presents a

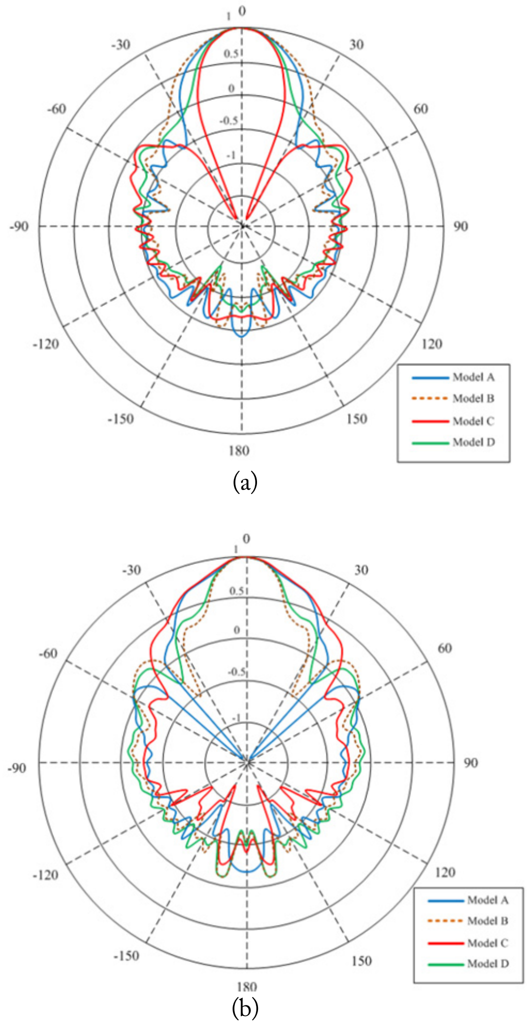


Fig. 10. The simulated radiation patterns of the four models of the wire medium structure. (a) E-plane, (b) H-plane.

comparison of radiation patterns between these models in both the E-plane and the H-plane. The conical horn with the model D structure was found to offer better pattern symmetry and lower side-lobes compared to the other models.

Fig. 11 presents a comparison of the simulated gains of the conical horn between the four models. The gains of the conical horn with the model D structure improve the gain by substantially more than the other models. In terms of the simulated results for the conical horn with the four models, the reflection coefficient, directivity, and gain performances of the model D structure (Fig. 8(d)) were most suitable for optimization.

To demonstrate the advantage of using a wire medium st-

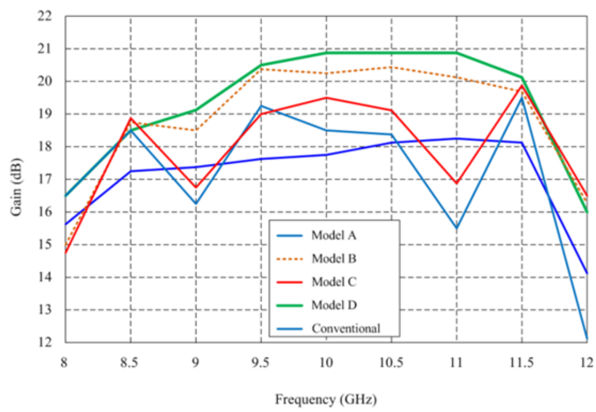


Fig. 11. The simulated gains of the four models of the wire medium structure.

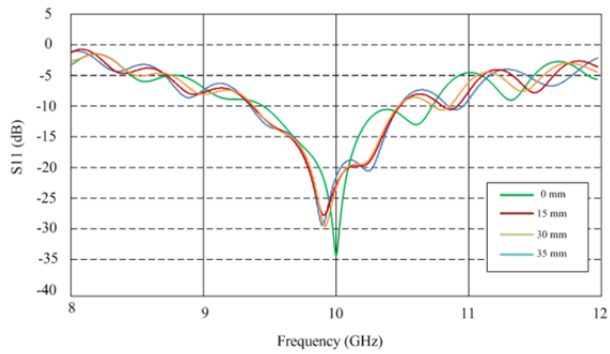


Fig. 12. The simulated reflection coefficient of the different distances of the wire medium structure.

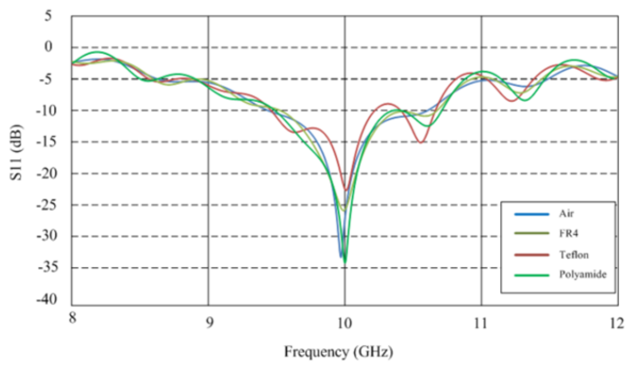


Fig. 13. The simulated reflection coefficient of different dielectrics.

ructure with the conical horn antenna, the performance of the structure was tested at different distances. For the sake of comparison, the model D structure was also simulated, as this model has the same dimensions as the geometries in Fig. 8(d). The findings showed agreement when the wire medium structure was placed on the aperture (0 mm), as shown in Fig. 12.

Fig. 13 shows the simulated reflection coefficient of the four dielectric sheets (air, FR4, Teflon, and polyamide). The simulated reflection coefficient of polyamide dielectric was found to be a better match than the other sheets at operating frequency 10 GHz.

The number of layers of the wire medium structure placed on the aperture was also considered. The comparison of the reflection coefficient with the layers of the wire medium structure is shown in Fig. 14. The resonant frequency of the two layers was found to be in good agreement, while the multi-layer designs were found to have lower resonant frequencies than the two layers.

In this section, the simulated results of the proposed horn antenna with the optimized wire medium structure are shown. The perspective view of the proposed conical horn is shown in Fig. 15. All parameters of the metamatrial technique of the wire medium structure, in which the conical horn is placed on the aperture, have been optimized using the simulation software. The most appropriate dimensions of the wire medium structure were found to be: polyamide height (L_2) = 60 mm, wire radius (r) = 1.25 mm, wire spacing (s_1) = 3.5 mm, number of wires (n) = 21, and polyamide thickness (h_1) = 3.5 mm.

Fig. 16 shows the maximum gain of the antenna, which is approximately 20.9 dB. The calculated results are presented in the simulated 3D radiation pattern.

Additionally, the reflection coefficient and radiation patterns of the E-plane and H-planes of the proposed conical horn with the wire medium structure are compared to the conventional horn and illustrated in Figs. 17 and 18. In Fig. 17, the simulated reflection coefficient of the proposed antenna shows excellent

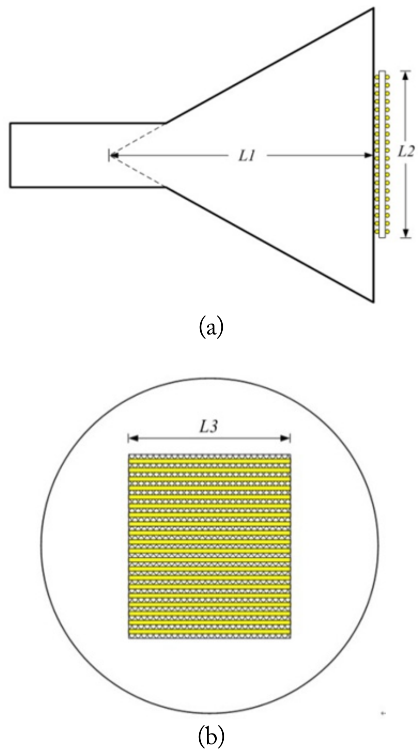


Fig. 15. The new conical horn antenna with a wire medium structure. (a) Side view, (b) front view.

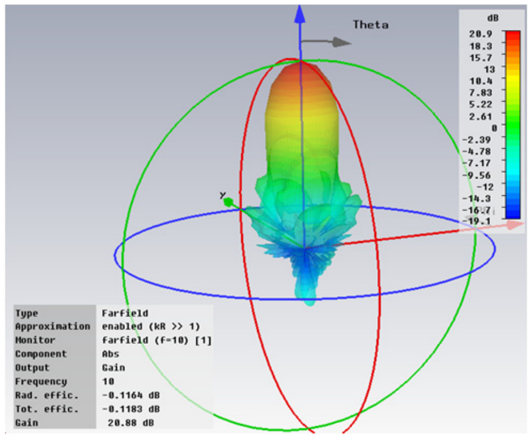


Fig. 16. The simulated 3D radiation pattern of the proposed antenna.

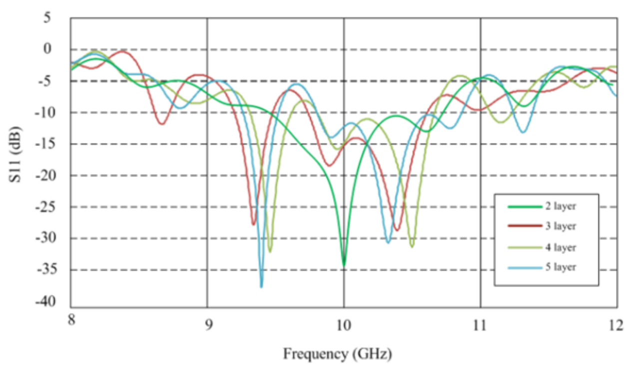


Fig. 14. The simulated reflection coefficient of a number of layers of the wire medium structure.

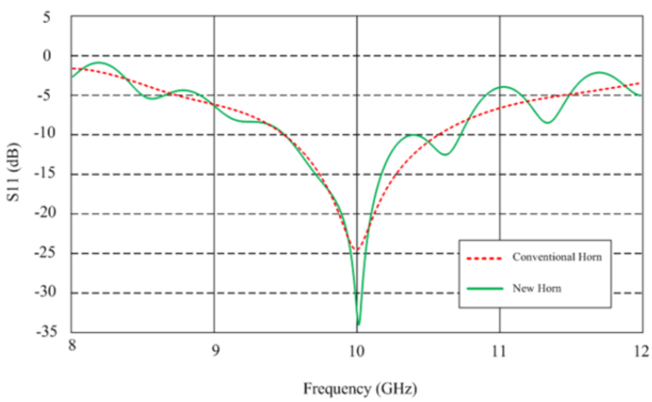
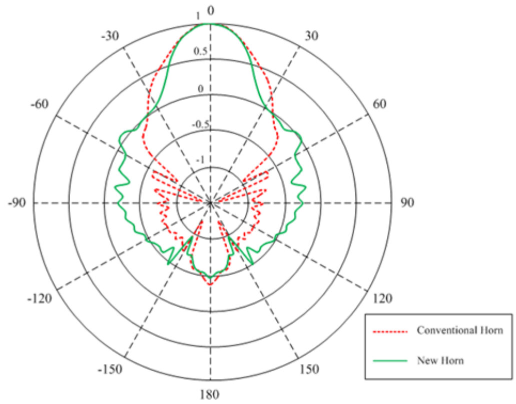


Fig. 17. Comparison between the simulated reflection coefficients of the conventional and proposed antennas.



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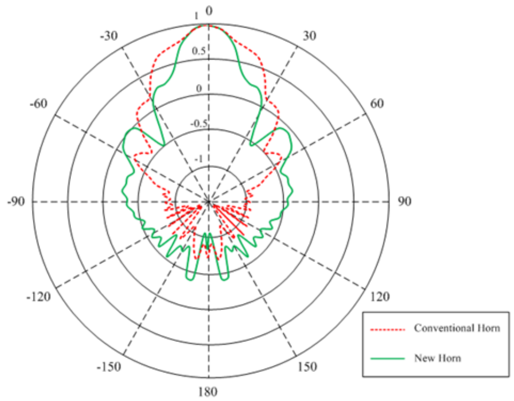


(b)

Fig. 18. Comparison between the simulated radiation patterns of the conventional and proposed antennas. (a) E-plane, (b) H-plane.

characteristics of impedance which match better than those of the conventional conical horn, in which the bandwidth is narrower. Fig. 18 shows the comparison between the radiation patterns of two such different horn antennas. The half-power beamwidth (HPBW) of the radiation patterns of the proposed antenna is narrower than that of the conventional antenna, but its gain is increased to around 3.2 dB, as noted in Table 1.

Table 1. Comparison of the gain results at 10 GHz

Type	Gain (dB)
Conventional conical horn antenna	17.7
New conical horn antenna	20.9

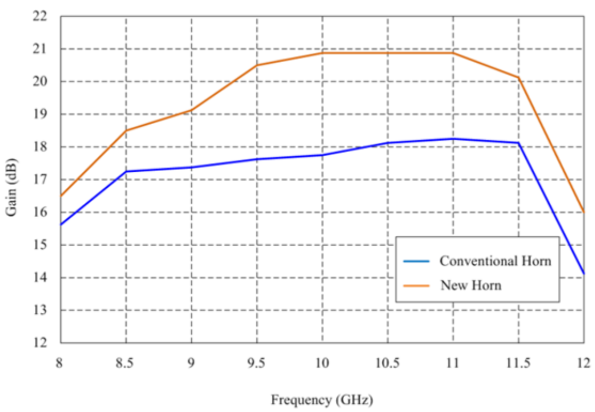


Fig. 19. Comparison between the simulated gain of the conventional and proposed antennas.

The comparison of the simulated gains between the conventional horn and the proposed antenna are shown in Fig. 19. The proposed antenna displays increased gain behavior that is greater than that of the conventional horn.

IV. Antenna Prototyping and Measurement

A prototype of the proposed antenna is shown in Fig. 20. The simulated and measured reflection coefficients of this antenna are compared in Fig. 21; the two performances are in good agreement. Furthermore, Fig. 22 shows the E-plane and H-plane normalization radiation patterns of the antenna prototype compared to the simulated results; good agreement between the simulation and measurement is also shown here. 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.

Fig. 20. A photograph of the fabricated proposed antenna.

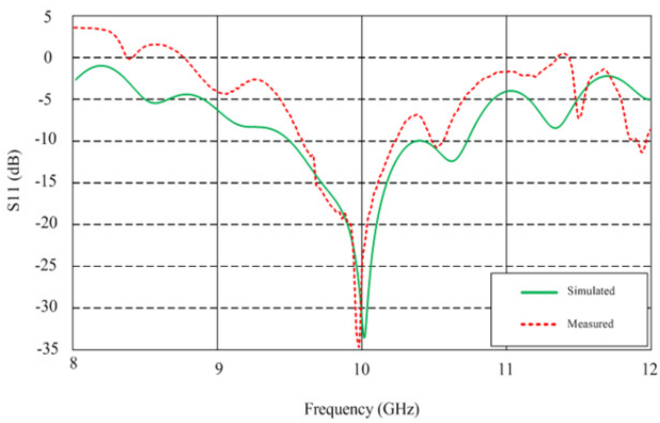
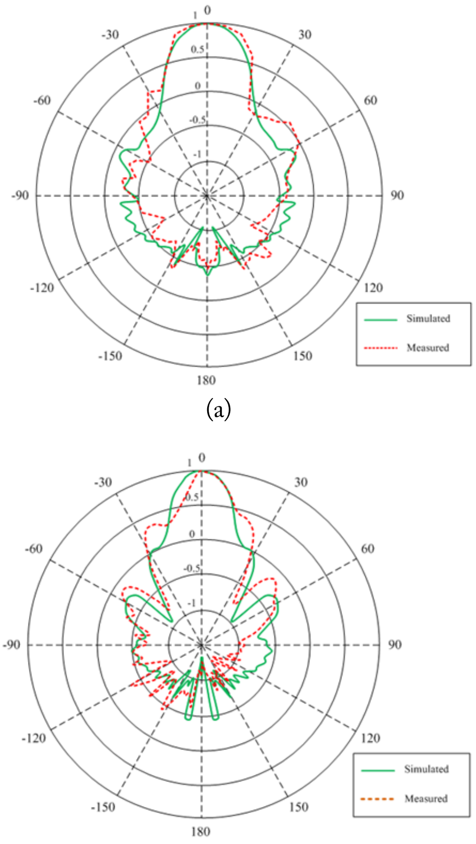


Fig. 21. The simulated and measured results of the reflection coefficient of the proposed antenna.



(a)

(b)

Fig. 22. Comparison between the simulated radiation patterns of the conventional and proposed antennas. (a) E-plane, (b) H-plane.

V. CONCLUSION

In this work, a new approach for gain enhancement of the conventional conical horn antenna was proposed. The wire medium of the metamaterial technique with 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. The comparison results, including the reflected coefficient (S_{11}) and radiation patterns of the proposed antenna and the conventional horn, were simulated using 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 can be increased to around 3.2 dB. As for the pattern, the beamwidth of the proposed antenna was narrower than that of the conventional horn. The wire medium structure of the proposed antenna improved the radiation pattern, enhanced the directivity, increased the gain, and reduced the side lobe level using a simple integrated wire medium structure. Additionally, the reflection coefficient decreased by more than –10 dB when compared to the conventional horn.

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