

RESEARCH PAPER

Design of high-gain SIW and HMSIW *H*-plane horn antenna using metamaterial

VANDANA KUMARI, WRIDDHI BHOWMIK AND SHWETA SRIVASTAVA

*In this paper, a substrate-integrated waveguide (SIW) *H*-plane horn antenna has been designed for X-band applications. Metamaterial is incorporated for performance enhancement of the designed antenna. Capacitively loaded loop is used as the unit cell of metamaterial for achieving negative values of relative permittivity and relative permeability. A half-mode SIW *H*-plane horn antenna is also proposed in this paper which reduces the size of the antenna without much effect on its performance. Metamaterial is integrated on the half-mode horn as well for improvement in gain and radiation pattern. The antennas are fabricated and tested. Excellent agreement between the measured and simulated results was obtained.*

Keywords: Antenna design, Modeling and measurements, Meta-materials and photonic bandgap structures

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I. INTRODUCTION

A horn antenna is simple to design and provides good performance. Generally a three-dimensional horn is used, which is fed using a waveguide [1]. Waveguide feeding has the advantages of low spurious radiation and less leakage in comparison to the microstrip feed lines and the major disadvantage of these structures is their volume making it difficult to integrate them with Microwave integrated circuit (MIC) components. The substrate-integrated waveguide (SIW) horn is a planar configuration containing all the advantages of classical waveguide horn antenna.

In general, a metamaterial is synthesized by embedding specific metallic structures, which should be periodic, in a medium. So far, a rich variety of metamaterials have been invented and their applications on microwave structures have been studied. It has been proved experimentally and that metamaterials can enhance the gain and directivity when integrated with the antenna structures [2, 3].

In the present paper, a SIW *H*-plane horn antenna is designed and the metamaterial structures are embedded on it. The proposed structure combines the advantages of the waveguide horn with the metamaterial resulting in a compact antenna with good radiation performance. The structure is developed on the RT/Duroid substrate with the permittivity (ϵ_r) of 2.33, height (b) of 0.8 mm and loss tangent ($\tan\delta$) of 0.0012. The simulation is done using Ansoft HFSS software. In addition to the simulation, the antenna is fabricated and the radiation performance is validated through the measurements.

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II. DESIGN

A) Design of SIW

The SIW is a planar equivalent of a waveguide. The side walls of the waveguide are realized using metallic vias to avoid leakage. Initially, the SIW is realized to operate as a feed to the proposed horn antenna. The SIW is designed for a cutoff frequency of 9 GHz with the parameters such as width (a) = 13.6 mm, center-to-center distance between the metallic vias (p) = 2 mm and diameter of the metallic vias (d) = 0.5 mm using the following equations, where w_{eff} is the width of the waveguide [4, 5] (Fig. 1):

$$w_{eff} = a - 1.08 \frac{d^2}{p} + 0.1 \frac{d^2}{a}. \quad (1)$$

Figure 2 shows the simulated S-parameter characteristics of the designed SIW. The response is same as that of the classical waveguide. S_{11} is well below -10 dB and S_{21} is almost touching the 0 dB line. A satisfactory performance has been

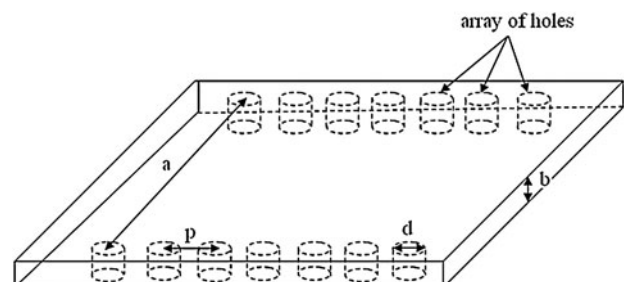


Fig. 1. Design of a SIW.

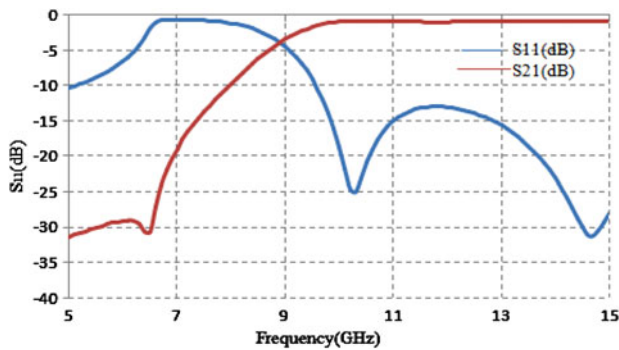


Fig. 2. Variation of S-parameter with frequency of SIW.

achieved by designed SIW for the complete X-band applications.

B) Design of horn antenna

The horn antenna is designed for a resonant frequency of 10.5 GHz. The design parameters are the antenna aperture length, $a_1 = 5.5\lambda_g$ and the waveguide aperture length = $0.5\lambda_g$.

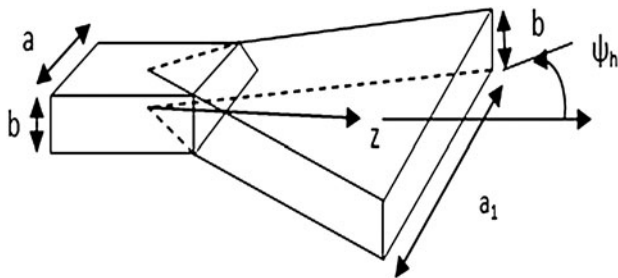


Fig. 3. H-plane waveguide horn antenna.

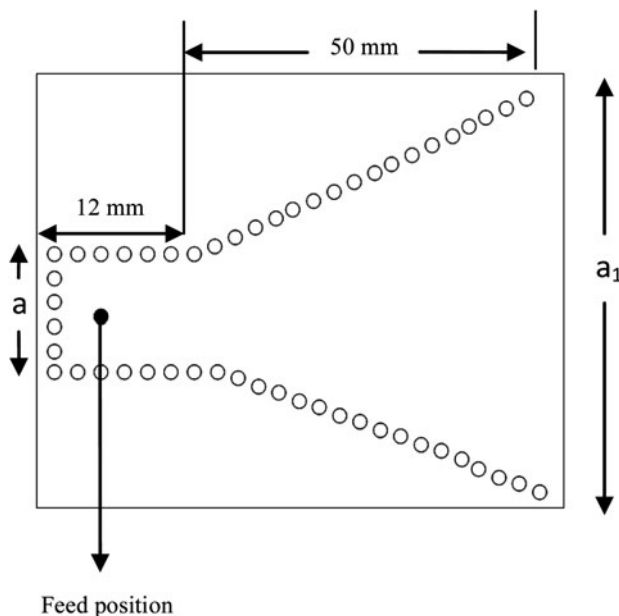


Fig. 4. Horn antenna designed using SIW, $a_1 = 60\text{ mm}$, $a = 10\text{ mm}$.

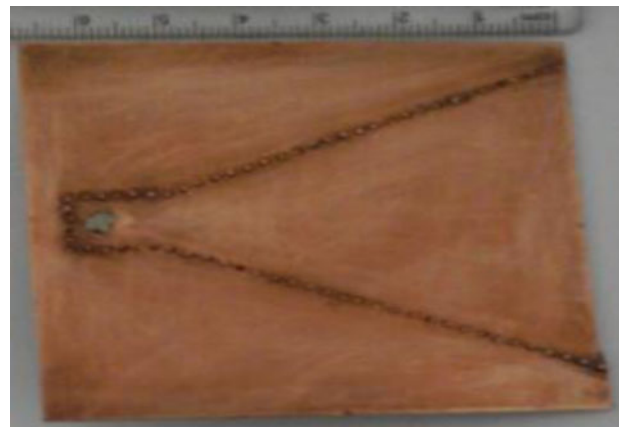


Fig. 5. Fabricated structure of H-plane SIW horn antenna.

Figure 3 shows the basic waveguide H-plane horn antenna and Fig. 4 shows its SIW equivalent. It is clearly visible that on converting a non-planar structure to a planar structure the design complexity reduces. The antenna is fed using coaxial feed at 4 mm distance from the short end. The position is optimized by several iterations to achieve the best results [6]. The fabricated SIW horn is shown in Fig. 5. The fabrication process is carried out using chemical photolithography and the vias are incorporated in the structure. The S_{11} is measured practically using Agilent N5230APNA-L Network Analyzer (Fig. 6). The simulated and experimental S_{11} response of the SIW horn antenna is given in Fig. 7. A little mismatch between simulated and measured reflection losses is observed, which may be attributed to fabrication errors. The antenna is resonating at 10.8 GHz both in simulations and measurements and the reflection loss of -18.2 dB (in simulation) and -15.9 dB (in measurement) has been achieved. The current distribution of the SIW H-plane horn antenna at 10.8 GHz is shown in Fig. 8.

The radiation pattern and gain of the fabricated antenna is measured using the X-band microwave test setup as shown in Fig. 9. The X-band waveguide horn is used as a transmitter and the designed antenna is used as a receiver.

Figure 10 shows the normalized radiation pattern of the horn antenna. The patterns show similar behavior with the experimental pattern showing a loss (1 dB) in comparison to the simulated one. The antenna gives a maximum gain of 5.8 dB at -10° .



Fig. 6. S-parameter measurement of horn antenna using VNA.

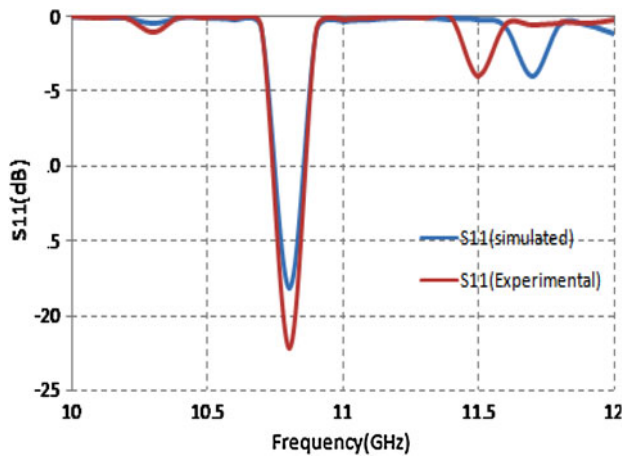


Fig. 7. Simulated and experimental S-parameter of horn antenna.

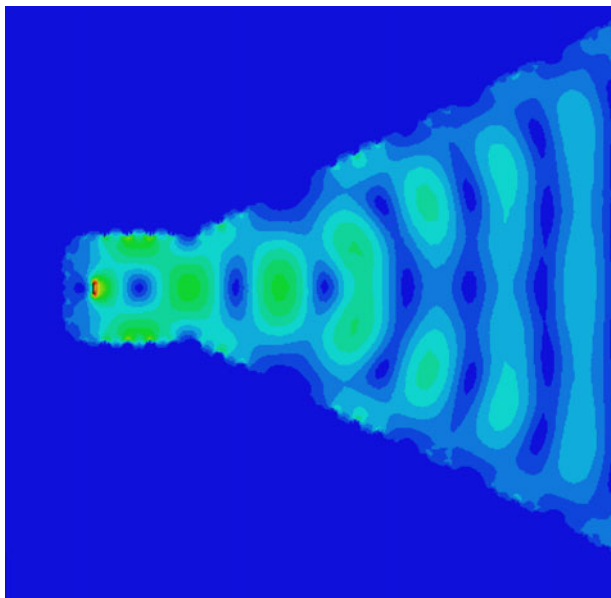


Fig. 8. Current distribution of SIW H-plane horn antenna.



Fig. 9. Testing of radiation pattern of horn antenna on X-band microwave test bench.

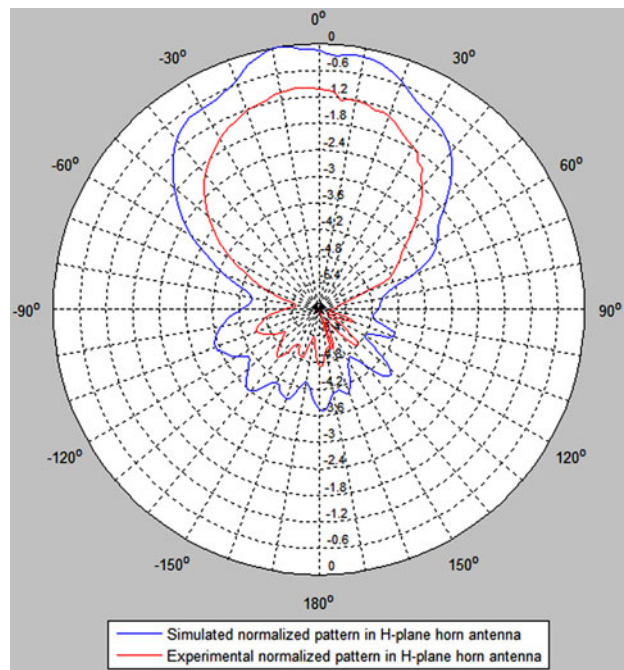


Fig. 10. Normalized radiation pattern of horn antenna.

C) Design of metamaterial

Metamaterials are materials that carry unique properties that are not found in natural materials. One such property is the negative value of refractive index, permittivity (ϵ_r), and permeability (μ_r). Such materials are called as left-handed materials (LHM). This increases the gain when introduced in an antenna by reducing the losses due to dielectric and increasing the radiation efficiency.

Several structures for metamaterial have been designed in previous years [7]. In particular, some that are capable to provide artificial magnetic responses and electric walls, the capacitively loaded loop (CLL) cells, proposed by Erentok et al. [8], which allows the creation of an artificial magnetic conductor – AMC, and an artificial electric conductor – AEC. The main aim is to improve of the electric and magnetic fields. The AMC is obtained when a plane wave focuses on the capacitive gap, while the AEC is obtained through the opposite way (Fig. 11).

The CLL structure is placed inside a waveguide with ports assigned to two of its ends. The response of the waveguide is shown in Fig. 12. This shows acceptable performance at the frequency of interest (10.7 GHz). The value of permittivity

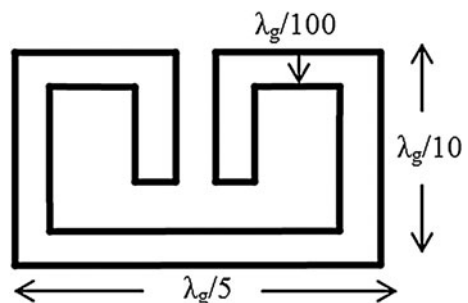


Fig. 11. Geometry of the designed metamaterial.

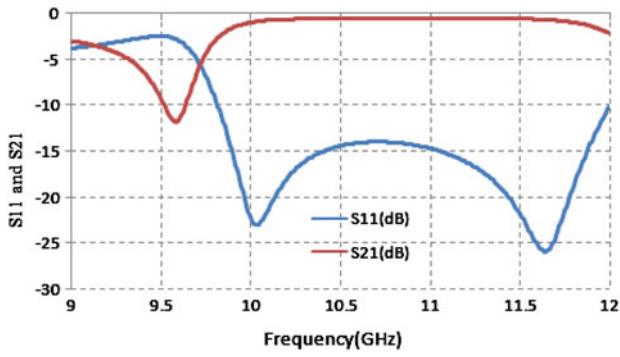


Fig. 12. S-parameter response of waveguide with CLL.

(ϵ) and permeability (μ) can be calculated using following equations (2-5) [9, 10]:

$$z = \sqrt{\frac{(1 + S_{11})^2 - (S_{21})^2}{(1 - S_{11})^2 - (S_{21})^2}} \quad (2)$$

$$n = \frac{1}{k_0 d} \cos^{-1} \left[\frac{1}{2S_{21}} (1 - S_{11}^2 + S_{21}^2) \right], \quad (3)$$

$$\epsilon = \frac{n}{z}, \quad (4)$$

$$\mu = \frac{n}{z}, \quad (5)$$

where z is the impedance, n represents the refractive index, d is the thickness of the substrate and wave number, $k_0 = (2\pi/\lambda_0)$, where λ_0 is the free-space wavelength.

Figure 13 shows the variation of relative permittivity and relative permeability with frequency of the proposed metamaterial structure. The response shows that the structure is providing a metamaterial behavior in the frequency range of 8.1–11.4 GHz.

III. DESCRIPTION OF ANTENNA USING METAMATERIAL

The metamaterial is incorporated as an array of six elements in the flared region of H -plane SIW horn antenna as shown in

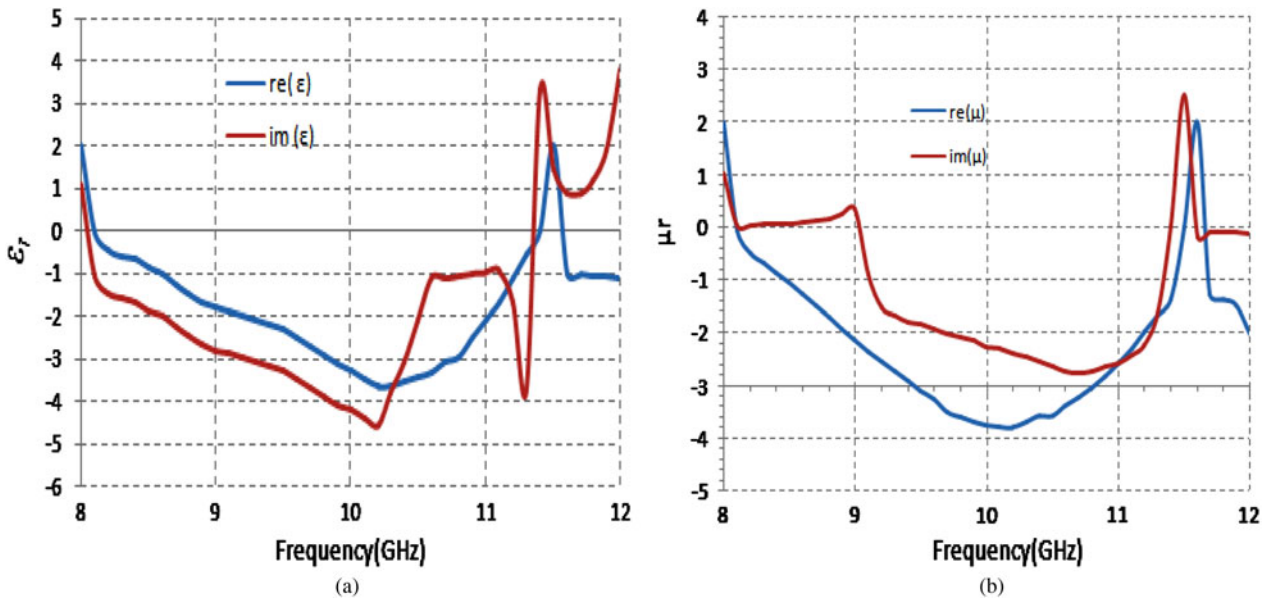


Fig. 13. Real and imaginary parts of (a) permittivity and (b) permeability as a function of frequency of the proposed metamaterial.

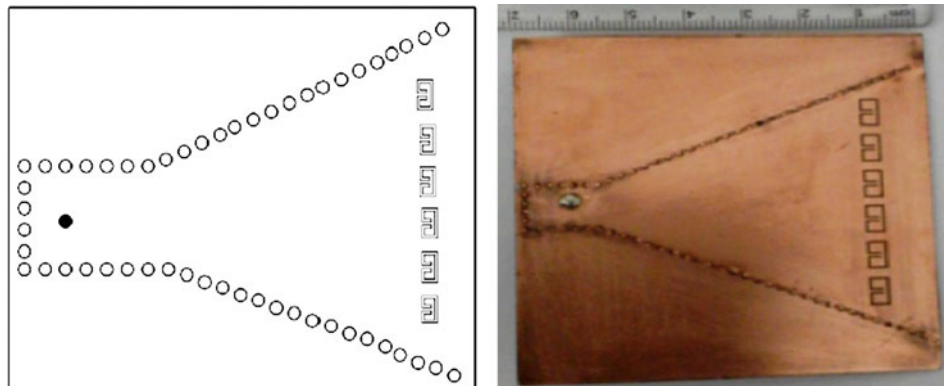


Fig. 14. Layout and fabricated SIW horn antenna using metamaterial.

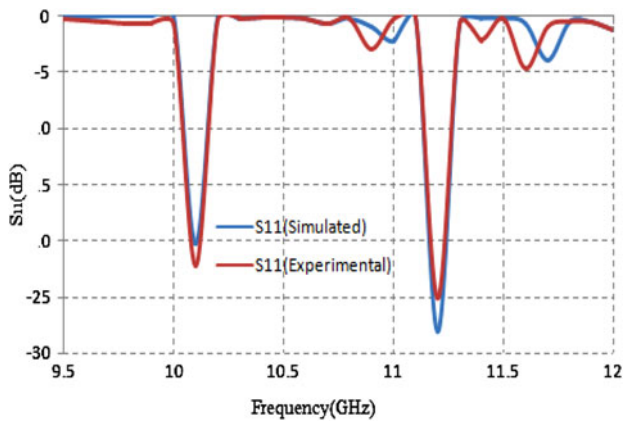


Fig. 15. Simulated and experimental S-parameter of SIW horn antenna using metamaterial.

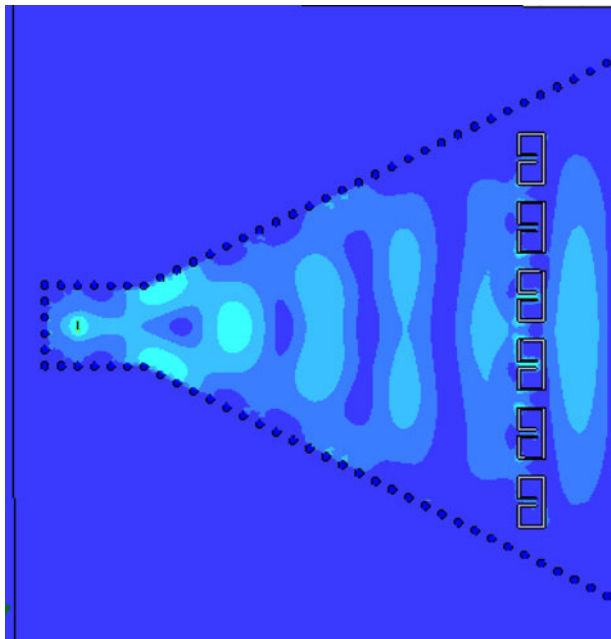


Fig. 16. Current distribution of modified SIW *H*-plane horn antenna.

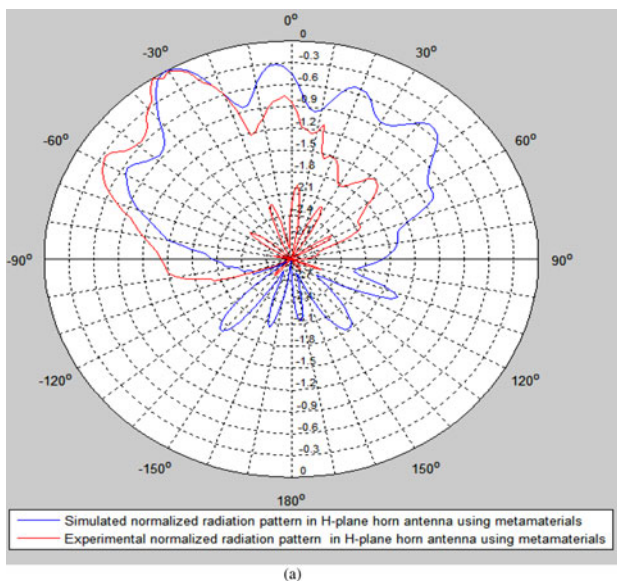


Fig. 14. Addition of the metamaterial structures to the basic horn antenna, changes the characteristics of substrate material, reducing the losses and by increasing the radiation efficiency.

The S_{11} response for the horn antenna with metamaterial is shown in Fig. 15. It is observed that the antenna exhibits dual-band behavior. The initial resonant frequency of the simple horn antenna shifts to the lower side (10.1 GHz) and another resonance is seen at a higher frequency (11.2 GHz). The LHM is incorporated in the SIW *H*-plane horn antenna by cutting slots in the flaring region. Due to these slots the behavior of current flow on the metallic layer changes resulting in dual-frequency resonance of the antenna. Because of the shifting of first resonance to the lower side, we can say that the size of antenna is reduced. Getting an additional resonance can be useful if the antenna is used for two different applications. Fig. 16 shows the current distribution of the modified SIW *H*-plane horn antenna. Fig. 17 shows the normalized radiation pattern at two different frequencies. The direction of the maximum radiation at 10.1 GHz is tilted by -30° . The antenna structure is completely symmetrical, but this could be due to some higher mode excitation at such high frequency. A control can be made on the direction of the electromagnetic radiation by the inherent property of the LHM. The current is more directed (Fig. 16) in the modified horn antenna than the conventional one (Fig. 8). So the LHM acts as a focusing device and hence the gain of the antenna is increased. Also the relative permittivity of the substrate has significant effect on the gain of the antenna. If it is high, then high dielectric loss is encountered and it degrades the antenna gain. So lower the permittivity would minimize the dielectric loss and hence improves the gain of antenna. By making use of the extraordinary property of the metamaterial, the relative permittivity of the substrate is less than unity or negative.

IV. HALF-MODE SIW (HMSIW) HORN ANTENNA

When a SIW operates in the dominant mode, the electric field becomes maximum at the vertical center plane along the

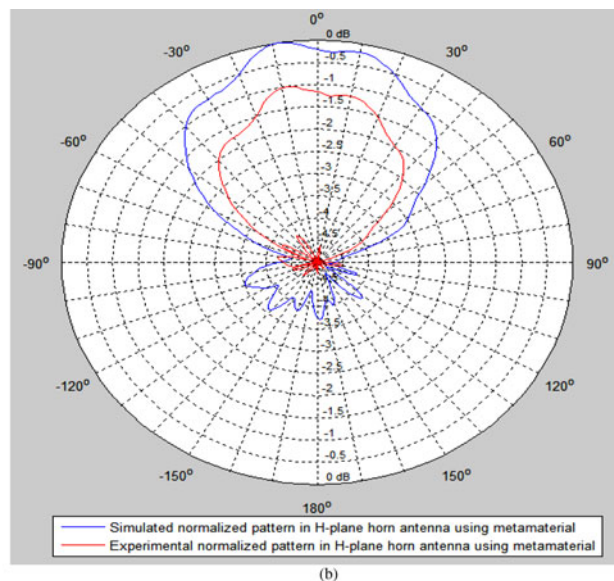


Fig. 17. Normalized radiation pattern of horn antenna using metamaterial. (a) At 10.1 GHz and (b) at 11.2 GHz.

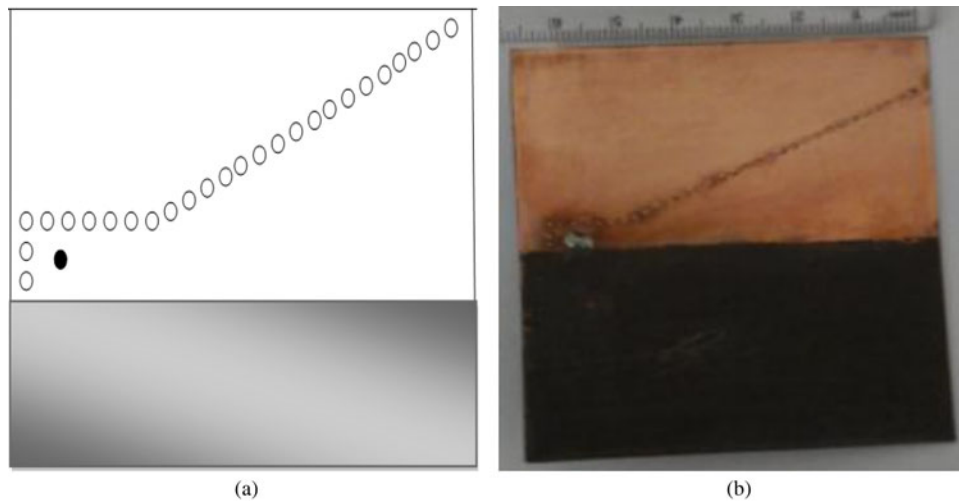


Fig. 18. Layout and fabricated HMSIW horn antenna. (a) Layout and (b) fabricated structures.

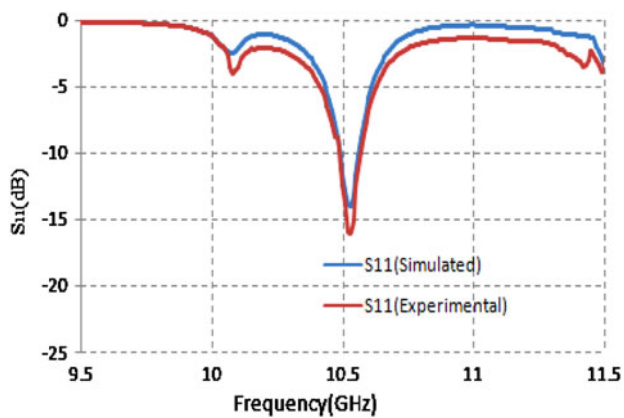


Fig. 19. Simulated and experimental S-parameter of HMSIW horn antenna.

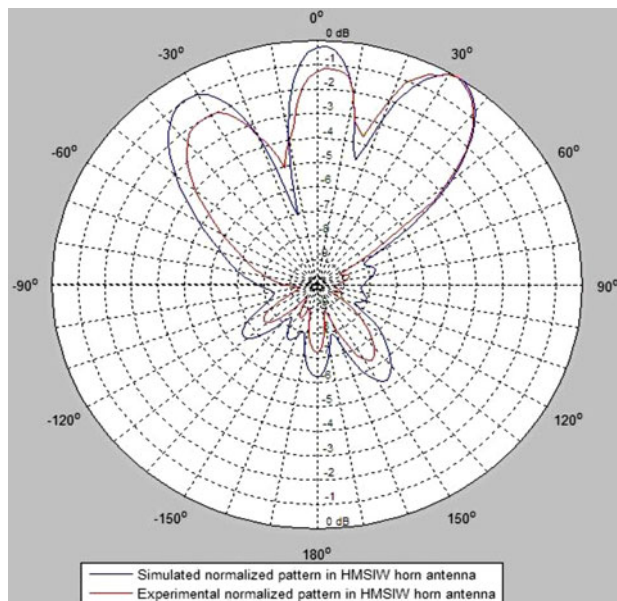


Fig. 20. Normalized radiation pattern of HMSIW horn antenna.

direction of propagation; so the center plane can be considered as an equivalent magnetic wall. Based on this idea, SIW can be bisected with a fictitious magnetic wall and each half of SIW becomes an HMSIW [11, 12]. So, HMSIW can be simply designed by dividing the SIW into two equal parts. In this paper, an HMSIW horn antenna [13] is introduced. The proposed antenna is fed by a coaxial feed line unlike the previous works on HMSIW components which are fed using microstrip line. The microstrip feeding suffers from parasitic radiation (which may degrade the radiation pattern of the horn antenna in the H -plane) and high conductor loss at higher frequencies, and so a coaxial line is used as the feed in order to avoid these imperfections. The aperture length of the SIW H -plane horn antenna is 60 mm and width of the waveguide portion is 10 mm. The implementation of HMSIW technique will reduce the aperture length to 30 mm and the width of the waveguide portion to 5 mm. Size of the rectangular unused portion of HMSIW antenna is 68 mm \times 40 mm. This region does not have any metallic layer and so it does not affect the radiation performance of the antenna and also reduces the conductor loss. The proposed antenna is simulated with HFSS software and its radiation properties are investigated.

The antenna structures (layout and fabricated) are shown in Fig. 18. It is clearly visible that the antenna size is reduced by half. This also reduces the complexity of the design. Fig. 19 shows the S-parameter characteristics of the proposed horn antenna. The resonant frequency of the antenna slightly shifts to the lower side at about 10.6 GHz in both simulation and measurement. The radiation pattern is shown in Fig. 20. The aperture length of HMSIW H -plane horn antenna is exactly half of the conventional SIW horn antenna. The reduced aperture length of the HMSIW horn antenna might be the reason of spreading of the radiation pattern.

V. HMSIW WITH METAMATERIAL

Metamaterial is incorporated on the HMSIW as well. Array of three structures is placed along the radiating aperture

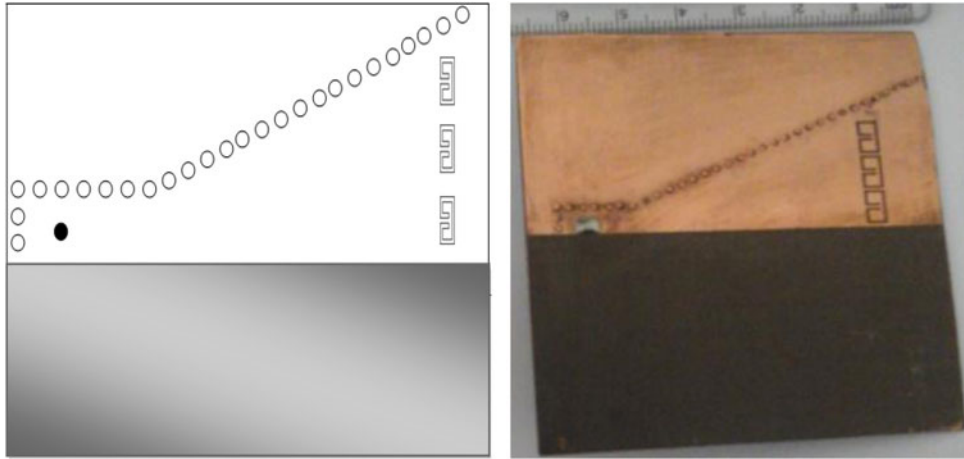


Fig. 21. Layout and fabricated HMSIW horn antenna using metamaterial. (a) Layout and (b) fabricated structure.

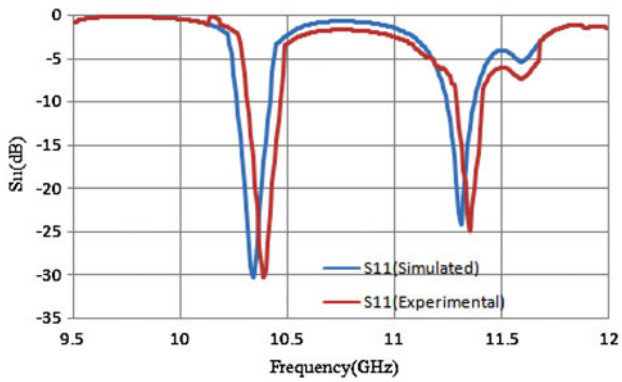


Fig. 22. Simulated and experimental *S*-parameter of HMSIW horn antenna using metamaterial.

(Fig. 21). *S*-parameter response of the HMSIW is shown in Fig. 22. Dual-band performance is achieved similar to the full-mode structure. Two resonances at 10.4 and 11.3 GHz are achieved. The normalized radiation pattern at these two frequencies is shown in Fig. 23. It is clearly evident that the pattern has improved and no prominent side lobes are visible in comparison to the pattern of the antenna without metamaterial.

The presence of the side lobes in the radiation pattern of HMSIW *H*-plane horn antenna is due to the reduction in the aperture length as mentioned in Section IV. Using the extraordinary property of LHM the current flow is more directed in the modified HMSIW *H*-plane horn antenna compared to the conventional HMSIW horn antenna. More directionality in the current flow might suppress the spreading or side-lobe levels and hence improve the gain (Table 1).

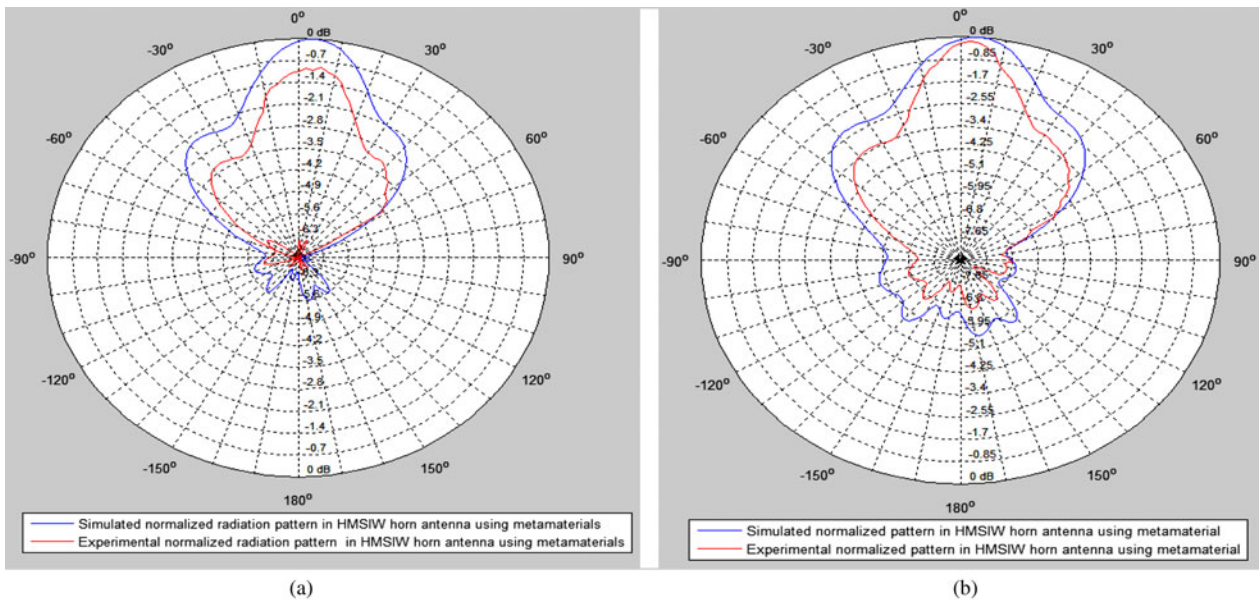


Fig. 23. Normalized radiation pattern of HMSIW horn antenna using metamaterial. (a) At 10.4GHz and (b) at 11.3GHz.

Table 1. Calculated and simulated values of gain of different types of antennas

Types of antennas	Gain in dB	
	Calculated	Measured
SIW horn antenna without metamaterial	4	3.82
SIW horn antenna with metamaterial	9	7.20
HMSIW horn antenna without metamaterial	4	3.82
HMSIW horn antenna with metamaterial	6.5	5.57

VI. CONCLUSION

From the discussions above, it can be concluded that a high-gain small-sized horn antenna is designed on SIW using metamaterial. In the application where high gain is required and size is not a constraint, the SIW *H*-plane horn antenna with metamaterial can be used. In places where compactness is a requirement, the half-mode horn antenna with metamaterial can be used with slightly lower gain.

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