High-gain narrow-band slotted antenna based on ENZ SIW structure

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Abstract—**The development of a Slotted Substrate Integrated Waveguide Antenna with Epsilon Near Zero material is presented. Here, Epsilon Near Zero (ENZ) waveguide structure is used in the design. The ENZ material used to realize unconventional tunneling of electromagnetic energy with ultra-thin subwavelength channels and it is considered to attain a highly directive narrow band antenna. The effect of the various parameters of the antenna is studied by simulation. A prototype is fabricated and the measurement results are compared with the simulated values.**

Keywords—Metamaterials, Epsilon Near Zero structures, Waveguides, Substrate Integrated Waveguide, Antennas, Micro strip.

1. Introduction

Antenna is an essential part of any communication system. Planar antennas with conventional geometries suffer from disadvantages like narrow bandwidth and low gain. Improved performance such as ultra-wide bandwidth or multiple band operation is achieved by modifying the radiating structure [1] or using defected ground plane [2, 3]. Haipeng Li *et al* has reported the use of a metasurface for designing thin single layer antennas with high gain [4, 5]. The development of a new class of electromagnetic materials: metamaterials, which owe their properties to subwavelength details of structure rather than to their chemical composition, have opened up a number of exciting applications due to their properties that are difficult or impossible to find in nature. The most important property of these artificially engineered structures is the negative values for permeability and permittivity. Negative refractive index allows the creation of super lenses [6]; that is, a lens that can see beyond the diffraction limit.

However, metamaterials do not always focus on the negative permittivity and permeability values. Materials with a permittivity values near zero or epsilon near zero (ENZ) materials can produce unconventional electromagnetic features. The possibility of using ENZ materials to drastically improve the transmission of electromagnetic energy through a narrow irregular channel with subwavelength transverse cross-section has been explored [7].

Recently, epsilon-near-zero (ENZ) metamaterial technology has received much attention because of its potential advantage in miniaturization and enhanced sensitivity, as energy can be tunneled through a narrow waveguide. At the cut off frequency of the waveguide the effective permittivity falls to zero. This is the effect used to create an effective ENZ material in an ENZ super tunneling narrow waveguide [7]. This phenomenon has led to several potential applications [8]-[13]. In this paper, a novel highly directive narrow band slotted substrate integrated waveguide epsilon near zero antenna is presented. The ENZ properties of metamaterial is utilized efficiently in the field of antenna design. The antenna is based on a slotted substrate integrated waveguide [14] operated near cut-off. This ensures a near constant field in the slot with increased gain over a conventional waveguide slot antenna. This paper is organized as follows. Section 2 describes the epsilon near zero waveguide. Section 3 presents epsilon near zero slot antenna design procedure. Section 4 describes the Slotted Substrate integrated waveguide epsilon near zero antenna Structure and design. Section 5 presents the fabricated slotted SIW ENZ antenna results and discussions.

2. Epsilon near zero waveguide

Early inspiration on current metamaterials can be attributed to Rotman [15]. Rotman produced design techniques to simulate plasmas by arranging arrays of rods. Further work on this phenomenon was carried out by Alu and Silveirinha, and Engheta [16]. Engheta et al. demonstrated that using two larger waveguides connected by an ultra-narrow waveguide channel produces a section that is effectively seen as an ENZ metamaterial [17]. The dispersion relation of rectangular waveguide was employed to realize an ENZ metamaterial at particular frequencies [18], because the effective permittivity is approaching zero when frequency is near waveguide cutoff. Super-tunneling occurs where the wave propagates through with little reflection. In this paper we use the ENZ properties of an appropriately dimensioned waveguide to form an antenna.

For a wave to propagate through a waveguide, it is required to be above the cut-off frequency and is calculated by

$$f_c = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\frac{m^2}{a^2}+\frac{n^2}{b^2}} \qquad (1)$$

Where *a* and *b* are respectively the width and height of the waveguide, *c* is the speed of light in vacuum and the integers *n, m* > 0 are mode numbers; ε_r is the relative permittivity of the material filling the waveguide. The ENZ effect can be obtained inside a rectangular waveguide channel that operates near the cut-off frequency of its dominant mode. The cut-off frequency of a rectangular waveguide in its dominant mode TE_{10} is obtained by

$$f_{c_{10}} = \frac{c}{2a\sqrt{\varepsilon_r}} \tag{2}$$

From (2), the waveguide width can be written as,

$$a = \frac{c}{2f_c\sqrt{\varepsilon_r}} \tag{3}$$

The ENZ effect can be realized in the waveguide due to the dispersive behaviour of the effective permittivity in the waveguide. The ENZ metamaterial can be realized using the effective permittivity value in the waveguide for TE_{10} mode, calculated by [8]

$$\varepsilon_{eff} = \varepsilon_r\left(1 - \frac{\lambda^2}{4a^2}\right) \tag{4}$$

As seen from (4), the effective permittivity is near zero when λ approaches $2a$. Therefore, ENZ metamaterial can be realized by waveguides operating near the cut-off. At the cut-off frequency, the propagation constant is zero, which leads to an infinite phase velocity and infinite guided wavelength [15] [18]. This results in a uniform and strong electric field along the channel.

3. Epsilon near zero slot antenna design

To enable the waveguide to radiate a longitudinal slot is added to the top surface of the waveguide. This slot runs parallel along the waveguide as shown in figure 1. In a SIW implementation, with small b, the slot greatly perturbs the nominal TE_{10} mode changing its nature to a quasi $TE_{1/2,0}$ mode [19]. This changes the cut-off frequency of the waveguide with the cut-off now predominantly set by the W dimension [14].

$$f_c \approx= \frac{c}{4W\sqrt{\varepsilon_r}} \tag{5}$$

W is the width of the wider section of the waveguide wall. Rearranging equation (5) we get as

$$W = \frac{c}{4f_c\sqrt{\varepsilon_r}} \tag{6}$$

A more accurate figure can be calculated using the transverse resonance technique and the effective capacitance of the slot [14].

It is important that the slot should not be in the exact center of the waveguides, but instead be offset. This is because radiation is caused from the slot by currents travelling around it and the current density at the center of the waveguide *(a/2)* is zero. One end of the waveguide is fed by a microstrip line with the other end left open. The waveguide therefore acts as a resonant structure. However, since the waveguide is operated near cut-off the slot resonates as a zero order resonance with a near uniform field along the length of the slot. The microstrip feed line is offset to enable a good match to the antenna.

4. Slotted substrate integrated waveguide epsilon near zero antenna design

Schematic of the ENZ Antenna designed using Substrate Integrated Waveguide technology is shown in figure 1. In the earlier design there are effectively two waveguides. Here the design change is that one of the waveguide at the end of the structure would was deleted. This is specifically a dielectric filled waveguide that connects the top of the substrate to the bottom by via-holes packed tightly together along the sides. At these wavelengths they are effectively seen as walls to the wave travelling along. The characteristic impedance of the micro strip feed line is 50Ω. This design is simulated and optimized using the CST Studio Suite.

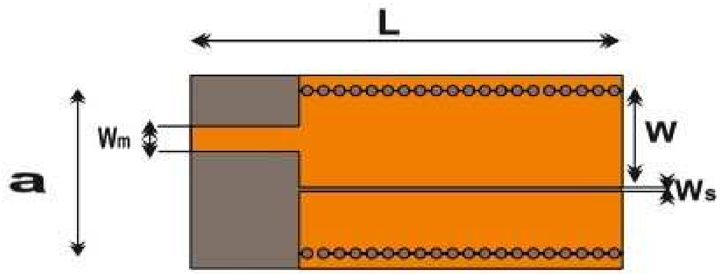


Figure 1. Single SIW ENZ antenna

The comparison of the properties of the antenna of our present work with previous work [20] is given in Table 1. The fractional bandwidth of the proposed antenna increased by increasing the substrate thickness of the antenna is shown in table 1.

Table 1.Comparison between the reference and proposed antennas

Antenna Type	Resonant Frequency (GHz)	ε_r	Size (W*L) (mm)	Substrate Thickness (mm)	Gain (dB)	Fractional Bandwidth (%)
Reference Antenna	5.8	2.17	0.77λ *0.87λ	0.03λ	-2	3.8
Proposed Antenna	5.97	2.2	0.38λ*1.79λ	0.005λ	7.6	1.4

The effective epsilon curve of the proposed structure is shown in figure 2. The figure depicts the real value of permittivity. The negative peak for permittivity is found between 2 GHz to 5.60 GHz and a positive peak from 5.64 to 10 GHz. However this curve also have a near zero region between the frequency of 5.12 GHz to 6.18 GHz. The epsilon near zero region has appealing applications in the field of antenna and cloak design [21]. This property can be applied in designing an ENZ SIW antenna because materials with this feature create uniform phase distribution.

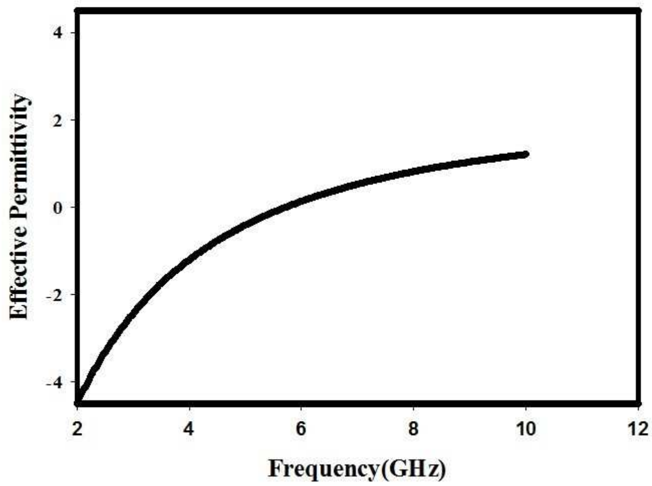


Figure 2. Effective permittivity curve

To understand the epsilon near zero operation, consider the dispersion diagram of the relevant mode [22-23]. The unit cell used to obtain the dispersion characteristics by solving an eigen mode problem is shown in figure 3. The waveguide width (a), width (w), slot width (w_s) are same as in the final design. The length of the unit cell (L_u) is same as p i.e. the center to center distance between two adjacent vias is 1.5mm. Figure 4 shows the dispersion diagram of the unit cell obtained using the CST EM Eigenmode solver. The periodicity of the unit cell is in ±y-directions. At ±y-direction periodic boundaries, a variable phase shift has been applied. By running a parameter sweep on the phase shift and plotting the calculated eigenmodes as a function of the phase shift, the propagation constant has been extracted. The variations of β with frequency shows the epsilon near zero behavior at the resonance frequency.

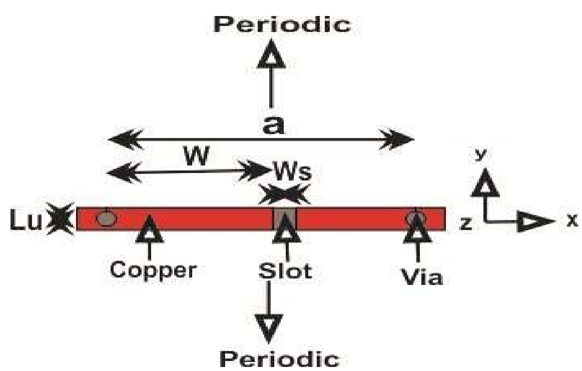


Figure 3. Unit cell

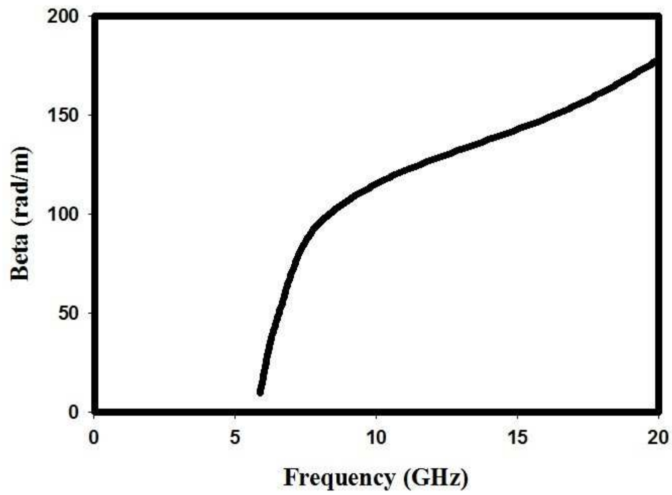


Figure 4. Dispersion diagram

The operating theory of the SIW structure of the antenna is explained using the equivalent circuit [24] given in figure 5. The two parallel LC circuit (L_1&C_1, L_2&C_2) Represents the vias in the SIW structure. The inductor L_4 represent micro strip feed line and the inductors L_3 and L_5 represent the SIW coupling sections. The capacitor C_3 indicates the radiating slot in the proposed structure. The values of L_3, C_3 and L_5 determines the frequency at which the antenna is matched, that is on the width of the sections and the gap.

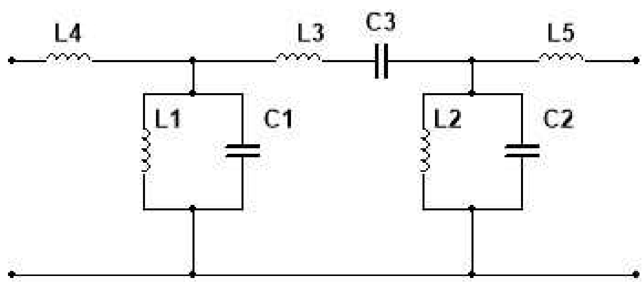


Figure 5. Equivalent circuit model

To better understand the antenna's behavior the effect of various parameters on the performance of the antenna is studied and given in the next section.

4.1. Effect of substrate thickness

Here we studied the properties of the proposed antenna with varying substrate material thickness without changing the other parameters. The substrate chosen for the design is RT/Duroid 5880 with relative permittivity of 2.2 and loss tangent of 0.0009. The width of the feed line W_m is changed according to the substrate thickness to have a characteristics impedance of 50Ω. Figure 6 shows the variations of the operating frequency with substrate thickness using standard substrate thicknesses.

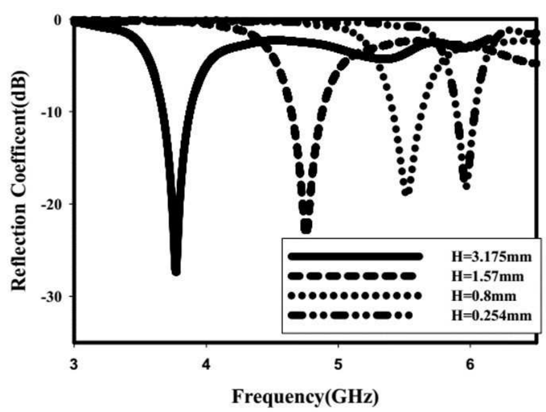


Figure 6. Reflection characteristics verses substrate height
(L=40mm, a=16mm, W=8.613mm, W_S=1.2mm)

The E-field distribution of the antenna with different substrate thickness is shown in figure 7.

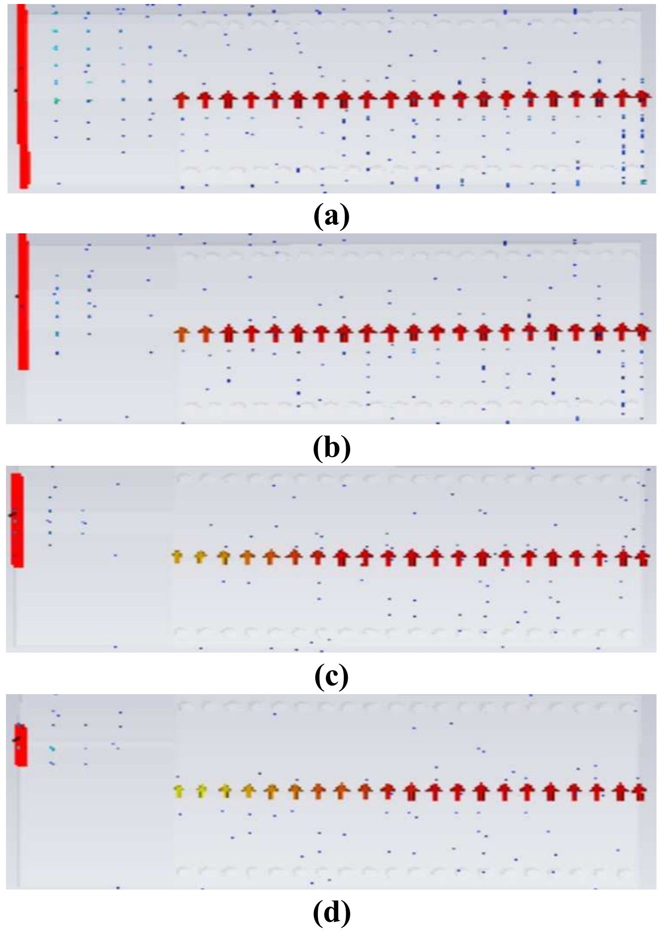


Figure 7. E-field distribution (a) H=3.175mm (b) H=1.575mm (c) H=0.8mm (d) H=0.254mm (L=40mm, a=16mm, W=8.613mm, W_S=1.2mm)

The E-field shows a fairly uniform field across the slot for all substrate thickness. It means that the radiation from the slot will be in the same phase. The result of this study is summarized in table 2.

Table 2. Effect of substrate thickness study

Substrate Thickness (H) (mm)	Bandwidth (MHz)	Frequency (GHz)	Gain (dB)	Fractional Bandwidth (%)
3.175	135.5	3.77	2.420	3.6
1.575	114.5	4.75	4.378	2.4
0.8	105.2	5.52	5.062	1.9
0.254	82.7	5.97	5.290	1.4

4.2. Effect of width W

The frequency of the ENZ SIW antenna depends on the value of W (width of the wider section) as can be observed in figure 8. As W decreases frequency increases, as is expected from equation (5). This parameter can be used to tune the resonant frequency of the antenna.

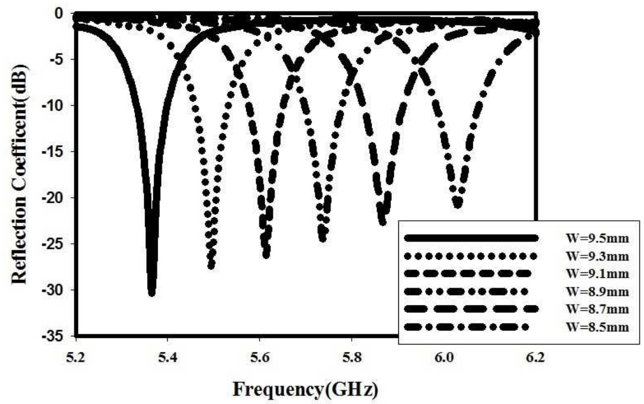


Figure 8. Reflection characteristics verses W (L=40mm, a=16mm, H=0.254mm, W_S=1.2mm)

4.3. Effect of slot width W_s

Figure 9 shows the variation of the width of the slot (W_s). Here increasing slot width slightly decreases the frequency and improve the matching.

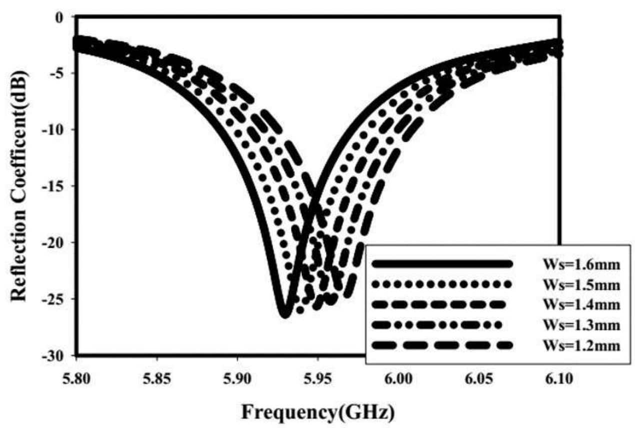


Figure 9. Reflection characteristics verses W_s (L=40mm, a=16mm, W=8.613mm, H=0.254mm)

4.4. Effect of waveguide width a

Figure 10 shows the antenna properties with variations in the overall width of the waveguide. The width of the waveguide causes slight changes in the operating frequency. The gain of the antenna is found to improve with increase in *a*. The value of *a* is less than or equal to the double of the width of the wider section of the antenna.

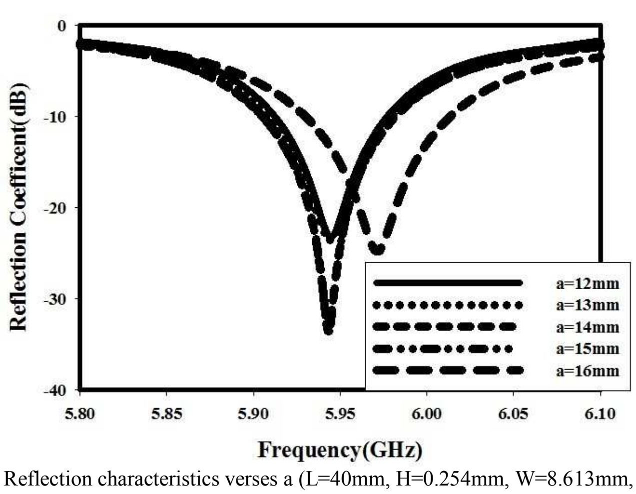


Figure 10. Reflection characteristics verses a (L=40mm, H=0.254mm, W=8.613mm, W_S=1.2mm)

4.5. Effect of waveguide length L

The variations cut off frequency and the gain of the antenna with length of the waveguide. Increasing the length increases the gain without changing the cut off frequency of the antenna as shown in figure 11 and table 3. This is as expected since near cut-off the guided wavelength becomes very large and therefore there is little phase change along the length of the guide. This results in a zero-order resonance which is un-effected by length. However, the larger effective aperture of the antenna results in an increased gain.

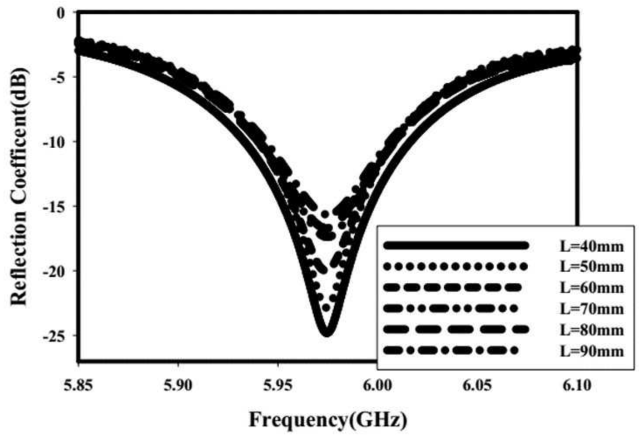


Figure 11. Reflection characteristics verses L (H=0.254mm, a=16mm, W=8.613mm, W_S=1.2mm)

Table 3.Gain versus waveguide length

Waveguide Length(L) (mm)	Gain (dB)
40	5.290
50	6.202
60	6.894
70	7.014
80	7.457
90	7.710

5. Result and discussions

The 3-D view of the presented Structure is shown in figure 12 and the fabricated prototype of the proposed Antenna is shown in figure 13. The substrate thickness chosen for the fabrication is 0.254mm. The vias are put in the holes to form an effective wall. The length L is taken as 90mm to have a better gain. A micro strip feed line, which is used to match the antenna. The micro strip should feed the widest section the slot separates. This is the section largely responsible for the cut off frequency. The advantages of this are it is simple and the transition has low losses. This is caused by a well matched field distribution in the SIW and electromagnetic field in the micro strip.

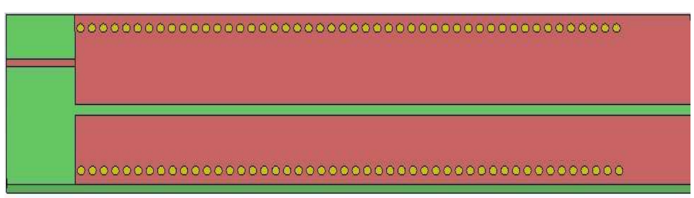


Figure 12. 3-D view of the presented Structure

Figure 13. Fabricated Antenna Structure

Figure 14 shows the measured and simulated S-parameter values of the antenna. The antenna has a cut off frequency of 5.97GHz with a return loss value of near 14.17dB. S-parameter figure shows a slight difference between the bandwidth such a small difference could be caused by the manufacturing errors caused by the structure being manmade. The maximum gain obtained is approximately 7.6 dBi over the operating band as shown in figure 15.

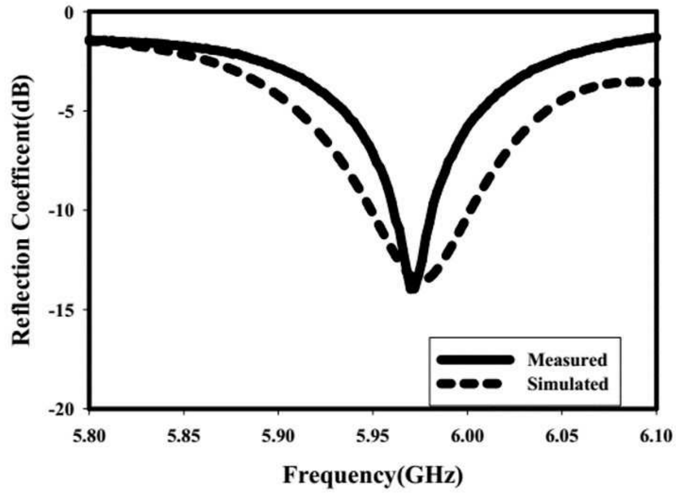


Figure 14. Reflection Characteristics

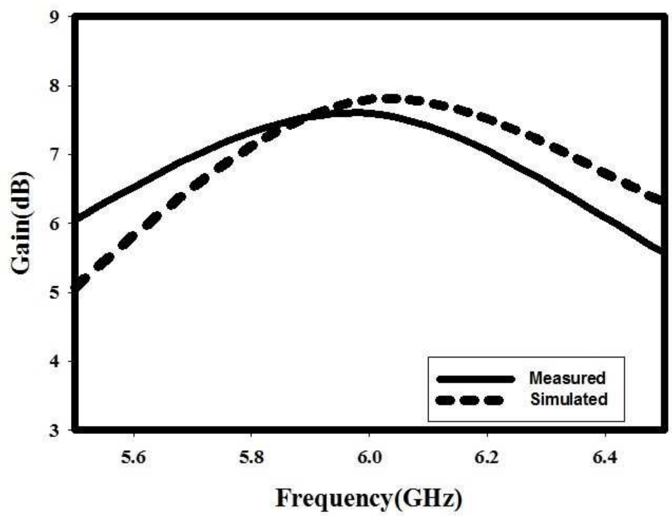
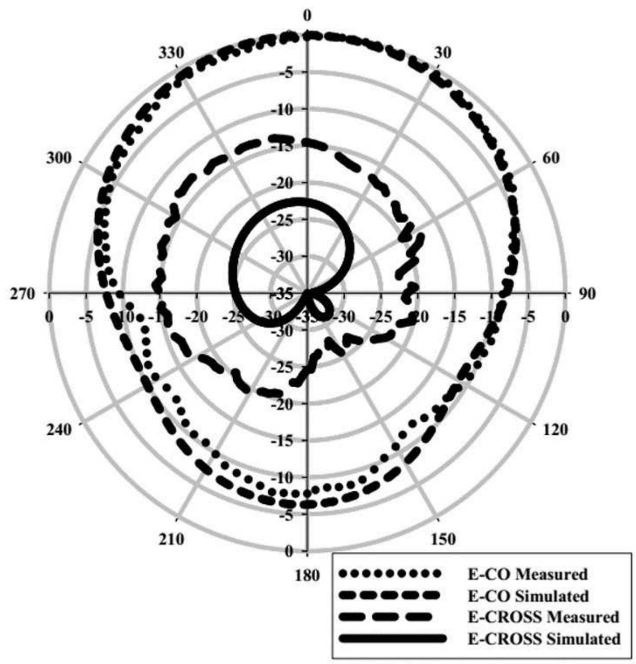
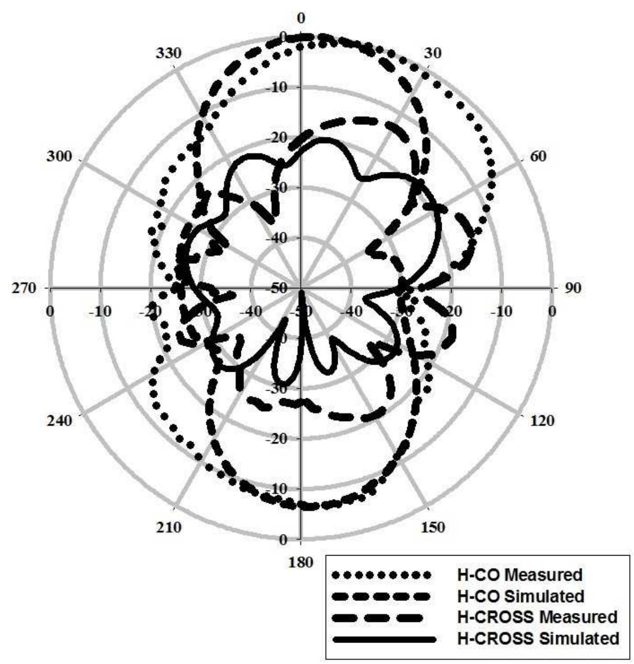


Figure 15. Measured and Simulated Gain

The measured and simulated radiation patterns of the proposed antenna at the operating frequency 5.97 GHz with E-plane and H-Plane is shown in figure 16. It shows a slight skewed radiation pattern towards the top of the antenna. The sharp peak response of a narrow band signal requires to avoid attenuation. In narrow band the smaller channel bandwidth have lower thermal noise. Narrow band provide better power consumption than the wide band. The lower power consumption of narrow band systems will lead to a lower cost for remote applications. Many applications such as wireless communications, military radios, Smart metering, oil/gas monitoring and public safety have historically used narrow band communications for their increased range and reliability.



(a)



(b)

Figure 16. Measured and Simulated Radiation pattern (a) E-Plane (b) H-Plane

6. Conclusion

This work started by looking at ways in which metamaterials being researched to enhance and progress various different fields. An effective ENZ material was designed using the relationship between the cut off frequency in a waveguide and permittivity. This formed an effective ENZ slotted substrate integrated waveguide. Use of ENZ waveguide structure for antenna design is presented in this paper. This finds applications in millimeter wave frequencies, where conventional patch antennas we difficult to fabricate. The proposed antenna can be easily fabricated by a printed circuit board process. The specific benefit of the antenna is to attain high gain or highly directive radiation pattern with low loss because of lower power consumption and low cost.

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