Design of Compact Annular Ring Antenna on Metamaterials for Improved Radiation Pattern and Gain

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Abstract - Simulated and experimental investigations have been carried out on annular ring antenna designed on metamaterial substrate. Different configurations of S-shaped metal structure are designed on RT-Duroid substrate to achieve metamaterial behavior at the frequency of 10.5 GHz. Annular ring antenna is designed for TM$_{31}$ mode on the metamaterial configurations. The antenna provides a huge size reduction of 87.58% when designed on metamaterial. The gain is improved from 1.0 dB for a simple ring to 6.22 dB on the ring antenna on metamaterial. Improvement is also clearly visible in the radiation pattern.

Index Terms - Annular ring antenna, Higher order mode, High gain, Metamaterial

I. INTRODUCTION

The word ‘meta’ means ‘beyond’ in Greek, and hence the word ‘metamaterials’ means ‘beyond conventional materials’. Metamaterials are artificially created materials that exhibit electromagnetic properties which are not otherwise exhibited in nature. Due to Maxwell equations’ macroscopic property, small particles made of typically metal and dielectric can be considered molecules when put together. The variation of shape and alignment of these molecules make macroscopically single negative, double negative or double positive materials.

Metamaterials are developed using the concept of negative refractive index. Refractive index is a measure of a factor by which phase velocity of light decreases in a medium as compared to vacuum. Light has two field components, electric and magnetic. When light is incident on a material only electric field component efficiently probes the atoms of the material. Magnetic field component of light has weak effect on atoms, hence light is considered as ‘one handed’. Metamaterials with their properties are capable of coupling both electric and magnetic field components, and therefore are said to give ‘two-handed’ light. Left Handed Metamaterial (LHM) is a material whose permittivity and permeability are simultaneously negative. These materials are termed as Left handed because due to negative refractive index the wave vector and electric and magnetic field vectors form a left-handed system [1-3]. With their unconventional properties, metamaterials exhibit several advantages over conventional materials such as compactness of microwave circuits, control over the electrical properties of the material such as characteristic impedance, surface wave propagation, dispersion characteristics etc., ease of multilayer design and enhancement in gain.

Several investigations have been done to synthesize metamaterial structure using many shapes of metal embedded in the dielectric [4-5]. Isolated triangle gaps and crossed strip-line gaps etched on the metal patch and ground plane, respectively used as planar metamaterial concept to design a broadband high gain antenna [6]. Planar metamaterial concept emphasizes bandwidth enhancement of rectangular patch antenna and the proposed research presents enhanced gain annular ring antenna with considerable size reduction antenna using double S and arrays of 8 S as metamaterial.
II. ANALYSIS AND METAMATERIAL DESIGN

In this paper a double S structure, placed one above the other separated by a dielectric forming a shape of 8 is selected. Single S on the dielectric forms metamaterial providing negative permittivity and permeability simultaneously. An annular ring antenna operating in TM$_{31}$ mode is designed on the metamaterial formed by double S forming an 8, and an array of four 8’s. The annular ring antenna is designed on the metamaterial for TM$_{31}$ mode. The annular ring antenna has the advantage of high radiation efficiency as compared to other patch antennas because of two radiating edges. The selection of an higher order mode is done to obtain good impedance matching of the annular ring with the coaxial feed [7].

Two layers of dielectric substrate RT Duroid having relative permittivity, $\varepsilon_r = 2.33$, tan $\delta = 0.0012$ and thickness of 0.8128 mm are stacked one over the other. Using chemical photoetching, S shaped copper patches as shown in Fig. 1 are designed on two of the opposite faces of upper dielectric substrate in order to synthesize the 8 shaped metamaterial structure. For verification of the metamaterial property of the designed structure, the following simulation procedure is carried out on Ansoft HFSSS software.

- A rectangular waveguide for TM$_{31}$ mode is designed.
- A complementary S shaped structure, on two opposite faces of upper dielectric host material with a dielectric substrate in the lower layer is loaded into a metallic rectangular waveguide excited in TM$_{31}$ mode for investigation as shown in Fig. 2.
- Using the transmission and reflection coefficients calculated for a wave incident on a finite slab of metamaterial, Impedance and refractive index of the metamaterial is calculated.

Using these parameters, dielectric permittivity and permeability of the medium is calculated. For an isotropic homogeneous slab in vacuum, the transmission coefficient ‘t’ and reflection coefficient ‘r’ have the following relations with the refractive index ‘n’, and the impedance ‘z’ of the slab [8,9]

$$ t^{-1} = \left[ \cos(nkd) - \frac{i}{z} \left( z + \frac{1}{z} \right) \sin(nkd) \right] $$ (1)

$$ r = \left[ (-1) \left( z - \frac{1}{z} \right) \sin(nkd) \right] $$ (2)

Where, k and d are wave vector and thickness of the slab respectively. Using eqs (1) and (2)

$$ z = \pm \sqrt{\frac{(1+r)^2 - r^2}{(1-r)^2 - r^2}} $$ (3)

$$ o (nkd) = \frac{1}{2t} (1 + t^2 - r^2) $$ (4)

Using S parameters, n and z are given as follows:

$$ z = \pm \sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} $$ (5)

Let

$$ e^{jnk_0d} = \frac{S_{21}}{[1-(S_{11})^2](\frac{z-1}{z+1})]} $$ (6)

Then

$$ n = \frac{1}{k_0} \left[ \text{Im} \left[ (e^{jnk_0d}) + 2\pi m \right] - j \text{Re} \left[ \text{ln}(e^{jnk_0d}) \right] \right] $$ (7)

Where k is the wave number and d is the thickness. The permittivity and permeability are given by

$$ \varepsilon = \frac{n}{z} $$ (8)

$$ \mu = nz $$ (9)

Fig. 1. Geometry of S Structure
Rectangular metallic waveguide loaded with metamaterial structure is simulated in HFSS software. Simulation is carried out in the range of 8 GHz to 12.5 GHz. Simulated S parameters show that waveguide is operating without any significant loss in the complete band. Using, S-parameter values in equations eq (5), eq (6) and eq (7), values of impedance and refractive index are calculated for the complete range. Using calculated values of refractive index and impedance, permittivity and permeability of the medium is obtained (eq (8) and eq (9)).

This graph indicates that for the frequency range between 10 GHz to 12.2 GHz, all the three parameters, permeability, permittivity and refractive index are negative. The negative band for the refractive index indicates the frequency range, where both the permittivity and permeability are simultaneously negative. It illustrates that the structure is a metamaterial for the frequencies between 10 GHz to 12.2 GHz.

An annular ring microstrip antenna to be used as a reference is designed for a resonant frequency of 10.5 GHz on RT Duroid having relative permittivity, \( \varepsilon_r = 2.33 \), tan \( \delta=0.0012 \) and thickness of 1.625 mm. The dimensions of the ARMSA on the metamaterial are varied to resonate at the same frequency as the reference antenna which clearly indicates the size reduction.

**III. REFERENCE ANTENNA DESIGN**

An annular ring microstrip antenna is designed for the for TM_{31} mode. Inner and outer radii of ring are calculated as 7.52 mm. [10] and 11.28 mm. respectively, so that ARSMA resonates at 10.5 GHz.

The feed point on the ring is optimised to obtain best matching at the desired frequency, as shown in Fig. 4.
IV. DESIGN OF ANNULAR RING ANTENNA WITH DOUBLE S STRUCTURE AS METAMATERIAL

Double S structure designed on two opposite faces of upper dielectric layer, results in the substrate behaving as a metamaterial. The ARSMA is designed on this metamaterial substrate as shown in Fig. 5 with inner radius of 2.65 mm and outer radius of 3.975 mm. Patch dimensions are reduced drastically, such that the antenna resonates at the operating frequency of reference patch antenna (ARSMA). Using metamaterial as antenna substrate size of the antenna is reduced. Size of the ARSMA with double S as metamaterial is reduced by 87.58% and a compact antenna is obtained.

V. DESIGN OF ANNULAR RING ANTENNA WITH ARRAYS OF 8 S STRUCTURES AS METAMATERIAL

Figure 6 shows array of eight S structures forming four 8’s on two opposite faces of upper dielectric layer, of dielectric material RT Duroid 5870. Fig.7 gives the comparative graph of refractive index, permittivity and permeability verses frequency. This graph indicates that the permittivity, permeability and refractive index are negative within a frequency range from 8.2 GHz to 10.9 GHz. It proves that the above medium is a metamaterial for the specific frequency range. The ARMSA is then designed on the metamaterial structure to resonate at 10.5 GHz as shown in Fig. 8. The inner diameter of the ring is 2.65mm and the outer diameter is 3.975mm. The feed position is optimized for best matching at this frequency.
VI. FABRICATED ANTENNAS

The metamaterial substrates were developed by etching the S structures on RT Duroid. The antennas were fabricated on these substrates using chemical photolithography. Fig. 9 shows the fabricated reference antenna and the antenna on metamaterial substrate. As it is clearly visible, the size reduction is enormous. Fig. 10 shows the two rings on different metamaterials.

Fig.9. Reference antenna and ARSMA with arrays of S.

Fig.10. ARSMA with arrays of S and ARSMA double S.

VII. EXPERIMENTAL RESULTS AND DISCUSSIONS

For experimental studies the reference antenna is fabricated along with annular ring antenna with double S structure and annular ring antenna with arrays of 8 S structures. S\textsubscript{11} of fabricated antennas are measured with the help of the Vector Network Analyzer (N5230A, 10 MHz – 20 GHz). The radiation pattern was measured and plotted using the Signal generator (SMR20, 1 GHz – 20 GHz) for generating the required signal and spectrum analyzer (FSP, 9 KHz – 30 GHz) for getting the values of received power. Fig.11 shows comparative experimental and simulated reflection loss of reference antenna. Fig.12 and Fig.13 shows comparative experimental and simulated reflection loss of reference antenna and annular ring antenna with double S structure and reference antenna and annular ring antenna with arrays of 8 S structures. Comparative simulated reflection loss annular ring antenna with double S structure and annular ring antenna with arrays of 8 S structures are also given in Fig 14. Radiation characteristics were also studied. Fig. 15, Fig.16 and Fig.17 presents the experimental and simulated E plane pattern at resonance for the reference antenna, annular ring antenna with double S structure and annular ring antenna with arrays of S structures.

Fig.11. Simulated and experimental reflection loss of reference antenna
Fig. 12. Simulated and experimental reflection loss of reference antenna and ARSMA with double S structure.

Fig. 13. Simulated and experimental reflection loss of reference antenna and ARSMA with arrays of S structure.

Fig. 14. Simulated and experimental reflection loss of ARSMA with double S structure and ARSMA with arrays of S structure.

Fig. 15. Simulated and experimental radiation pattern of the reference antenna.
Table I: Comparative table of three antennas

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>$S_{11}$</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
<td>Experimental</td>
</tr>
<tr>
<td>Reference Antenna</td>
<td>-27.9 dB</td>
<td>-14.4 dB 10.5 GHz</td>
</tr>
<tr>
<td>ARSMA with double S structure</td>
<td>-21.0 dB</td>
<td>-16 dB 10.5 GHz</td>
</tr>
<tr>
<td>ARSMA with arrays of S structure</td>
<td>-19 dB 10.5 GHz</td>
<td>-34.75 dB 10.9 GHz</td>
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</tbody>
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Fig.11 shows comparative experimental and simulated reflection loss of reference antenna. Reflection loss is used to describe the matching. In this present work reflection loss of all antennas are below -10 dB, means matching is obtained. Reference antenna experimentally resonates at 10.7 GHz with reflection loss of -17.38 dB and simulated value is 10.5 GHz with -16.2 dB respectively. Comparative experimental and simulated reflection loss of reference antenna and ARSMA with double S structure observed in Fig.12, which resonates at 10.5 GHz with simulated reflection loss of -13.38 dB and experimentally resonates at 10.6 GHz with reflection loss of -14.5 dB. Matching improves with metamaterial but there is a slight shift in experimental resonant frequency. Fig.13 highlights comparative experimental and simulated reflection loss for reference antenna and ARSMA with arrays of S structure, which resonates at 10.5 GHz with simulated reflection loss of -12.48 dB and experimentally resonates at 10.6 GHz with reflection loss of -12.45 dB. The slight shift in the resonance frequency of experimental results of both the antennas can be attributed to little bit of fabrication inaccuracy.
The shift of 0.2GHz and 0.1 GHz in frequency corresponds to a change of 0.125 mm and 0.085 mm in dimensions. This inaccuracy occurred due to the difference in resolution of masking used in chemical photolithography. Fig. 14 highlights comparative experimental and simulated reflection loss for annular ring antenna with double of S structure and ARMSA with arrays of S structure, which resonates at 10.5 GHz with simulated reflection loss of $-17.5$ dB. Bandwidth of antenna using metamaterial as substrate has increased by two and one and half times of the reference antenna. Bandwidth of reference antenna is 1.86%, bandwidth of antenna with double S is 2.83% and bandwidth of antenna with arrays of 8 S as metamaterial is 3.77%. The reference annular ring antenna has experimental and simulated maximum gain of 1dB and 1.5 dB as shown in Fig. 15 at an angle of 58° and 56° respectively. This can be attributed to higher mode excitation of annular ring antenna for impedance matching. At higher order modes maximum gain is obtained at oblique angles. ARMSA with double S structure has experimental and simulated maximum gain 7.23 dB and 6.11 dB at 0° respectively as shown in Table I. ARMSA with arrays of eight S structures has experimental and simulated gain 7.42 dB and 6.22 dB at 0°. Fabricated antenna gains are reduced slightly due to some losses occurring in fabrication and testing process. Fig. 16 and Fig 17 indicates the radiation pattern of ARMSA with metamaterials, both of the patterns exhibit a maxima at 0° showing a significant improvement from a distorted higher mode pattern to a good broadside pattern. Introduction of metamaterial as antenna substrate changes the effective dielectric constant of the medium, this variation of dielectric constant changes the mode of operation and improves the pattern.

VIII. CONCLUSION

From the detailed analysis carried out in the present research it can be concluded that use of metamaterial as antenna substrate enhanced the performance of such annular ring antenna, which has low gain due to the excitation of TM_{31} mode. ARMSA with double S structure as metamaterial enhanced the gain of antenna by 5.11dB. ARSMA with arrays of S structure enhanced the gain by 5.22dB and also improved its radiation pattern. The antenna size has reduced enormously to 1/8th of the reference antenna size.

REFERENCES


