Performance Enhancement of RMPA Using ESRR Metamaterial at THz

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Abstract— Left handed materials which have both negative permittivity and permeability, have been the area of potential research over a decade. This paper elucidates antenna parameter optimization using Double Negative Group (DNG) Electric SRR, having 19.13 THz as resonant frequency forming metamaterial array embedded in antenna substrate at high frequency (THz). Ansoft HFSS has been used to design and analyse the RMPA (Rectangular Microstrip Patch Antenna) with design frequency 22.5 THz and operating range of 20 THz to 25 THz having FR4 ($\varepsilon_r = 4.4$) as substrate material. Nicolson Ross Wier (NRW) method has been used to retrieve the material parameters from transmission and reflection coefficient. Upon incorporation, remarkable enhancement in parameters is observed whereby bandwidth increases by factor of 3.75, directivity increases by 5% and front to back lobe ratio improves by 31% with ESRR metamaterial.

1. INTRODUCTION

The past few years have been very eventful with respect to the evolution of the concept and implementation of 'left-handed materials (LHMs)'. 'Metamaterials' (MTMs) are engineered to modify the bulk permeability and/or permittivity of the medium [1]. It is realized by placing periodically, structures that alter the material parameters, with elements of size less than the wavelength of the incoming electromagnetic wave. It results in "meta" i.e., "altered" behaviour or behaviour unattainable by natural materials. Slight changes to a repeated unit cell can be used to tune the effective bulk material properties of a MTM, replacing the need to discover suitable materials for an application with the ability to design a structure for the desired effect. Examples of MTMs are single negative materials (SNG) like ε negative (ENG) which have effective negative permittivity and μ negative (MNG) which have effective negative permeability, and double negative materials (DNG).

It is worth recalling that negative values of permittivity are inherently bandlimited phenomena and such a condition can hold only at a certain frequency (accompanied with imaginary part of permittivity). Frequency for which real part of permittivity hits value ' -2' and infinity condition goes named as Frohlich frequency [2]. Particle shape has effect on the value of negative permittivity corresponding to Frohlich resonance. The geometry of negative permittivity particle has a strong effect on its surface plasmonic properties.

A fresh approach to microwave and optical devices presented itself with the interesting breakthrough in the area of MTMs at high frequencies. The need of hour is to optimize the antenna parameters (gain, bandwidth, directivity) without altering its dimensions, i.e., external control over antenna parameters using MTM. The software tool HFSS is used because it is a high performance full wave electromagnetic (EM) field simulator [3].

This paper abridges the design of RMPA with resonant frequency 22.5 THz and operating frequency range of 20 THz to 25 THz having FR4 ($\varepsilon_r = 4.4$) as substrate material in Section 2. Section 3 describes proposed DNG MTM Electric SRR having negative refraction in the designed RMPA range. Section 4 elucidates upon their application in antenna parameter optimization by embedding their array in the middle of the antenna substrate and just below the microstrip rectangular patch. Section 5 concludes the paper.

2. RMPA DEISGN

2.1. Design

RMPA, i.e., Rectangular Microstrip Patch Antenna, as the name implies consists of a rectangular patch over a microstrip substrate. Its major disadvantage is relatively low-impedance bandwidth which limits the field of application of these antennas. Bandwidth of RMPA can be improved by several methods available in literature, e.g., use of thick substrates, addition of parasitic patches.

The implication of such methods will not just increase the complexity of system, but will have adverse effect on gain of the antenna. Also, such methods involve changes in the parameters of the designed antenna. This calls for a novel technique to increase the bandwidth of antenna without altering its paramenters and without much effecting the antenna's radiation properties. Henceforth, metamaterial based antennas have been introduced [4].

Transmission Line model represents RMPA as two slots of width, w, and height, h, separated by transmission line of length, l. Thus, it is a non homogeneous structure made up pf two dielectrics, i.e., substrate and air. This shows that substrate and air will have different phase velocity and the dominant mode of propagation will be quasi-TEM. Therefore effective permittivity, ε_{eff}, comes into consideration. There is fringing effect at the edges of patch, due to which the patch appears to be longer. So, L_{eff}, i.e., effective length is defined which is obtained by adding $2\Delta l$ (additional length Δl due to fringing on each end) to the length obtained by using mathematical design equations [5]. Ground plane has length, l_g, and width, w_g. The tangential components of electric field are in phase. Therefore, maximum radiated field is normal to the surface of the structure. However, normal components of the electric field at the two edges along the width out of phase. Hence, no radiation in broadside direction.

Microstrip feed using quarter wave transformer has been used for feeding the antenna as calculated from Equation (7). The input impedance is taken at the base of microstrip feedline and is referred to $50\,\Omega$. i.e., Z_o.

$$Z_{qw} = \sqrt{Z_{rmpa} * Z_o} \tag{1}$$

where the W_{qw} and L_{qw} represent the width and length of the quarter wave transformer as calculated from Z_{qw}, i.e., impedance of quarter wave transformer using txline software by AWR. The operating frequency range of the RMPA, shown in Figure 1, designed for Electric SRR MTM is from 20 THz to 25 THz with centre frequency 22.5 THz with FR4 ($\varepsilon_r = 4.4$) as substrate. Constructional details are shown in Table 1.

Frequency range	20–25 THz
Center frequency	22.5 THz
ε_r	4.44
ε_{eff}	3.78
$\boldsymbol{h}$	0.5 µm
$\boldsymbol{w}$	4.06 µm
$\boldsymbol{L_{eff}}$	3.43 µm
$\boldsymbol{\Delta L}$	0.22 µm
$\boldsymbol{L}$	2.98 µm
$\boldsymbol{L_g}$	15 µm
$\boldsymbol{W_g}$	15 µm
$\boldsymbol{L_{qw}}$	1.88 µm
$\boldsymbol{W_{qw}}$	0.15 µm
$\boldsymbol{L_{zo}}$	1.76 µm
$\boldsymbol{W_{zo}}$	0.98 µm

Table 1: Design parameters of RMPA for ESRR MTM.

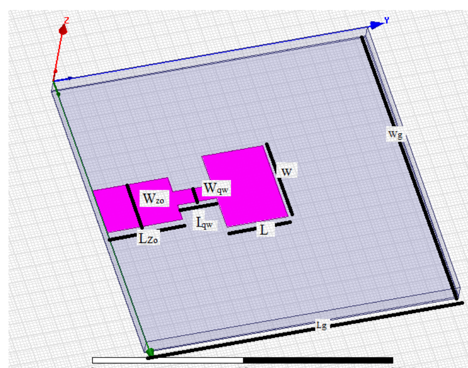


Figure 1: Rectangular microstrip patch antenna.

2.2. Simulation Results

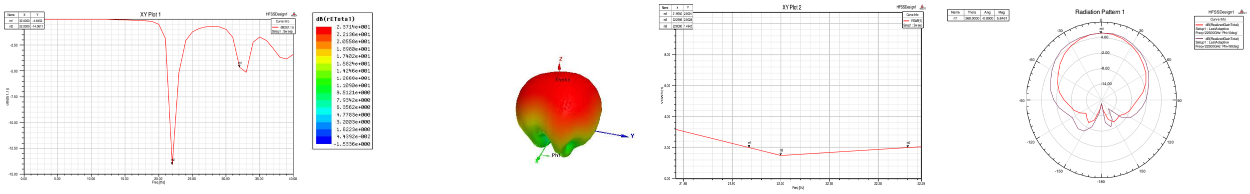
RMPA has been simulated in HFSS. Figure 2 shows the simulation results where S_{11} is return loss or reflection coefficient.

Simulation results have been shown in Table 2.

It can be seen that S_{11} is crossing 10 dB line and VSWR is less than 2. Bandwidth is 0.326 THz, which is range of frequencies with VSWR < 2.

3. PROPOSED MTM

In 1968, Russian scientist Veselago [6] postulated a negative material and theoretically proved the phenomenon that a uniform plane-wave followed the left hand rule in a medium with negative permittivity (ε) and negative permeability (μ). The first work in this direction was by Pendry. He created a medium consisting of thin wires arranged in a periodic array [7]. These wires acted as a plasma medium, whereby ε varies with frequency, Pendry next achieved a negative μ with a periodic array of metallic loops called Split Ring Resonators [8]. In a medium composed of these rings the permeability, μ, varied with frequency, and could become negative. In 1999, Smith



(a) (b) (c) (d)

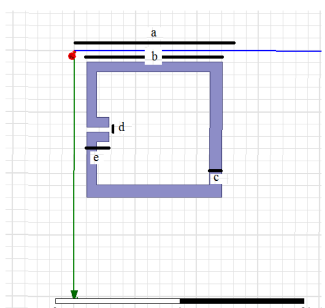
Figure 2: (a) Return loss, (b) 3D polar plot, (c) VSWR, (d) radiation pattern in E and H plane of RMPA.

combined the rod and ring materials to finally produce a material with simultaneously negative ε and μ, a left-handed material [9]. The wire strips affect the ε and the split-ring resonators (SRRs) alter the μ of the medium thus giving a frequency dependent negative material with both the parameters negative. The wire medium and the SRRs have certain frequency dependence. The rod gives negative permittivity, ε, and ring material creates a negative permeability, μ, this combined rod and ring material gives negative index of refraction.

Electric SRR metamaterial has been proposed behaving as DNG, i.e., Double Negative Group. Such materials have negative permittivity and negative permeability in the same frequency region. Thus having negative refraction in the same [10, 11] region. The parameter retrieval, i.e., parameter extraction using S parameters [12] has been followed using NRW approach to observe the negative refraction region of MTM. The constructional details along with the curve showing negative refraction are as under.

3.1. Constructional Details

It is constructionally very simple, and has been designed as per Figure 3(a) with design parameters specified in Figure 3(b). It forms the LC resonant structure by having capacitance due to the dielectric gaps and inductance due to the conducting loops [13]. Each unit cell is designed on a 0.5 µm thick FR4 substrate with length $a = 1.3$ µm. The thickness of the metal strip is 0.035 µm and is made up of gold.



Parameter	Value (in µm)
a	1.3
b	1.1
c	0.08
d	0.04
e	0.18

(a) (b)

Figure 3: Electric SRR shaped MTM, (a) unit cell designed in HFSS, (b) constructional details.

3.2. Simulation Results

Ansoft HFSS has been used to simulate the unit cell designed in Figure 3(a) by assigning the boundaries (E field and H field) and lumped ports (1 and 2). Nicolson Ross Wier method has been used to calculate the material properties from transmission and reflection coefficients. It can be observed as in Figure 4(a) that region of negative refraction extends from 19.12 THz.

4. MATHEMATICAL PROOF

Proposed MTM has magnetic properties because of internal inductances and capacitances. It can be simplified in terms of combinations of C and L. Using transmission line theory (quasi-static regime), we can draw its equivalent circuit as in Figures 5(a), (b).

The L is the inductance per unit length of the loop and C_1 and C_2 are the capacitances of the gap.

The expressions for L and C are given by Equations (2) and (3) as below [11]:

$$Ls = \frac{2\mu_o b}{\pi}\left[\sinh^{-1}\left(\frac{b}{c/2}\right) - 1\right] \tag{2}$$

where $\mu = \mu_o$ is the vacuum permeability and parameter values can be referred to Figure 4(b).

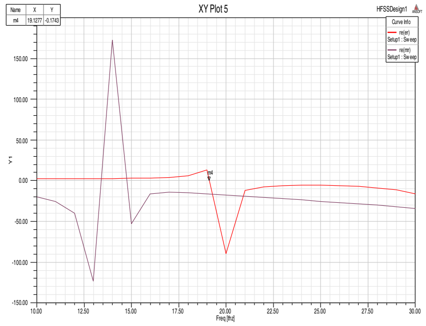
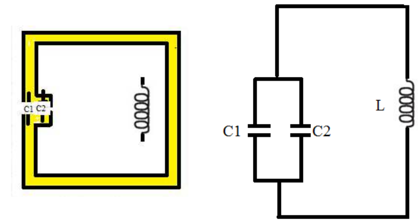
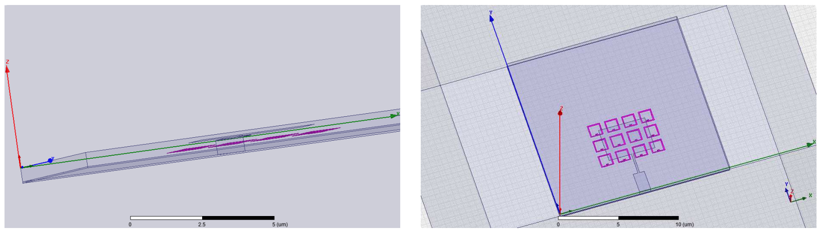


Figure 4: Resonance at 19.12 THz.



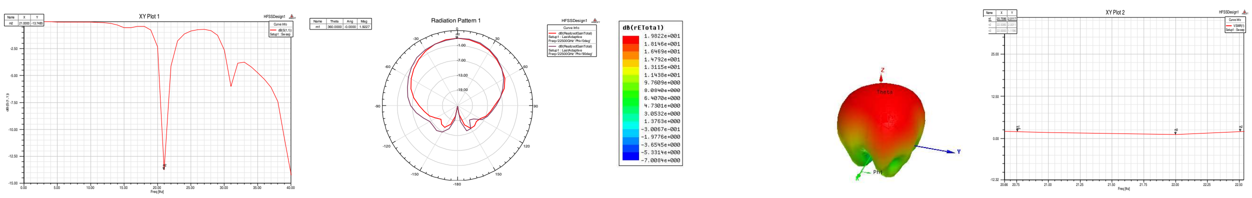
(a) (b)

Figure 5: (a), (b) Equivalent LC circuit of ESRR.



(a) (b)

Figure 6: Embedding ESRR MTM array inside RMPA substrate, (a) side view, (b) top view.



(a) (b) (c) (d)

Figure 7: (a) Return loss, (b) E and H radiation pattern, (c) 3D polar plot, (d) VSWR.

Therefore, L_m is 2.037×10^{-12} H.

$$C = \frac{\varepsilon A}{d} \tag{3}$$

where C is the expression for calculating parallel plate capacitance with C_1 as capacitance between the ring and C_2 as capacitance in the electric gap of the ring.

Therefore, C_1 is 0.0062×10^{-15} F and C_2 is 0.014×10^{-15} F.

Neglecting high frequency losses, magnetic resonance frequency is given by Equation (4)

$$\omega_m = \sqrt{\frac{1}{L \cdot (C_1 + C_2)}} \tag{4}$$

Thus, magnetic resonance frequency is found out to be 24.8 THz. However, using simulational study of MTM in Ansoft HFSS, magnetic resonance frequency has been found out to be 19.12 THz. Thus, net error between simulational and analytical study of Electric SRR is around 23%.

5. ANTENNA PARAMTER OPTIMIZATION

5.1. Design

Antenna is characterized by different parameters, e.g., gain, bandwidth, VSWR, 3 dB beamwidth in E, H plane, return loss. These parameters have been obtained for RMPA as in Table 2 using HFSS. Parameter optimization is done by embedding the proposed Electric SRR metamaterial in middle of substrate in array of 3×4 elements spaced at 0.4 µm from each other and center of the array coincides with the center of the antenna substrate just below the patch as shown in Figure 6.

5.2. Simulation

Simulation results for MTM array inside RMPA substrate are shown in Figure 7.

Table 3 gives the obtained simulated values of parameters and comparison of ESRR MTM array RMPA with RMPA without MTM.

Table 2: Simulation results of RMPA at 22.5 THz.

Parameters	**RMPA**
S_{11} (dB)	−14.06
VSWR	1.49
Bandwidth (THz)	0.326
***H* plane gain in dB**	5.86
***E* plane gain in dB**	5.86
Peak directivity (dB)	4
Front to back lobe ratio	121

Table 3: Simulation and comparison results of ESRR MTM array embedded in RMPA substrate.

Antenna/ Parameters	**RMPA**	**RMPA with MTM**	**Improvement (approx)**
S_{11} (dB)	−14.06	−13.75	−2%
VSWR	1.49	1.2	24%
Bandwidth (THz)	0.33	1.24	3.75 times increase
***H* plane gain in dB**	5.86	1.92	1/3rd
***E* plane gain in dB**	5.86	1.92	1/3rd
Peak directivity (dB)	4	4.21	5%
Front to back lobe ratio	121	158.95	31%

6. CONCLUSION

Upon designing and analysing proposed MTM inside RMPA substrate we obtain results as in Table 3. It can be seen that bandwidth is almost three times with proposed Electric SRR MTM, directivity has been enhanced by 5%. Thereby,improving Front to back lobe ratio by 31%. However, gain (S_{21}) is reduced by 33%. Trade off lies in improvement of above antenna parameters over gain and return loss.

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