Novel hybrid metamaterial to improve the performance of a beamforming antenna

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Abstract. This paper investigates the design and implementation of a novel hybrid metamaterial unit cell to improve a beamforming Wi-Fi antenna's performance. The proposed metamaterial unit cell is created on an FR-4 substrate ($\varepsilon_r = 4.4$) and a thickness of 1.6 mm. The metallization height of the unit cell is maintained at 0.035 mm. The designed metamaterial unit cell is simulated using HFSS Ver. 18.2 to verify the double negative behaviour. The unit cell consists of five Split Ring Resonators (SRR's) at the bottom and a hexagonal ring of six triangles. Initially, a conventional inset fed microstrip patch antenna is designed then an array of the proposed unit cell is created and used as a superstrate to study the performance. A Three Element Antenna Array (TEAA) is designed to operate at 2.4 GHz Wi-Fi band, and the superstrate created out of the proposed unit cell is used to study its effect. Metamaterial superstrate improved the conventional Single Element Antenna (SEA) gain by approximately 2 dB. Superstrate with TEAA exhibited an improved gain of 1 dB over TEAA.

1. Introduction
Today's wireless communication advancements enhance user's lifestyle with Wi-Fi enabled devices such as Personal Digital Assistant (PDA) and smartphones. The modern wireless communication technologies often promise advanced techniques for improving Wi-Fi reception and reducing interferences. One such promising technology emerged in recent years to enhance the experience of Wi-Fi users is beamforming. Before developing the 802.11n standard, almost all the commercially available access points (AP) used antennas with static radiation patterns. Antennas used with traditional AP deployment were almost omnidirectional for both AP and the mobile client [1]. The possible challenges with standard AP deployment are, the requirement of more AP's due to small cell coverage, interference between adjacent cells, increased deployment and maintenance cost due to more equipment. Since the omnidirectional antenna sends energy in all directions, the radio channel is busy and results in more power consumption. The development of the 802.11n standard enabled the best use of available transmitter power to reach the client device effectively. With 802.11n standard, one can focus on energy transmission toward a receiver by adopting beamforming. The significant advantage of beamforming has improved the Signal to Noise ratio (SNR), leading to support the maximum data rates. Beamforming promises a faster, stronger signal with longer ranges.

In literature, many researchers reported the benefit of Metamaterials (MTM's) in improving radiating elements' performance. Metamaterials are artificially engineered periodic structures, exhibit negative permittivity, negative permeability and negative refractive index [1-3]. Suganthi et al. used metamaterial array in the ground plane of a fractal antenna to enhance the resonance characteristics [4]. In [5], Arora et al. presented an MTM superstrate loaded 1x2 corporate fed antenna array. They showed enhancement in the gain of the conventional antenna array with the use of MTM superstrate.
Gao et al. reported a dual-layer single ring resonator pair MTM array to improve the Wi-Fi antenna's gain (5.2 GHz), they also achieved reduced half-power beamwidth due to the use of MTM [6]. In [7], Devapriya et al. used circular SRR MTM surface to improve the gain and reduce the antenna size. In [8], Ali et al. presented a multiband antenna using rectangular Complementary Split Ring Resonators (CSRR's). The CSRR has reduced the overall size of the antenna by 46% and increased bandwidth. Islam et al. proposed a circular SRR with a closed inner ring to improve the gain and bandwidth of the UWB antenna [9].

In this paper, the authors presented a novel hybrid metamaterial unit cell to increase the beamforming array antenna's gain. The developed unit cell is used as an element to create a superstrate. This superstrate is used to enhance the gain to improve the range of antenna array further.

### 2. Metamaterial Unit Cell Design and Parameter Extraction

A hybrid metamaterial unit cell is designed and simulated in HFSS Ver. 18.2. A hexagonal ring made of six triangles on the top and an SRR with five concentric circles on the other bottom plane of the FR4 substrate is simulated to verify the double negative behaviour. The metamaterial unit cell's physical dimensions are as follows: \( G = 0.5 \text{ mm} \), \( S_r = 0.5 \text{ mm} \), \( W = 0.5 \text{ mm} \), \( a = 9.18 \text{ mm} \), \( b = 20 \text{ mm} \), \( c = 0.9 \text{ mm} \) and \( R_{out} = 7 \text{ mm} \).

![Proposed metamaterial unit cell simulation setup](image1)

Figure 1. Proposed metamaterial unit cell simulation setup

![Geometry of MTM unit cell](image2)

Figure 2. Geometry of MTM unit cell (a) Bottom view (b) Top view

Proper boundary conditions and excitations are assigned to simulation set up of the unit cell. Figure 1 presents the simulated metamaterial unit cell used to extract DNG property. The top and bottom layers of the unit cell are shown in Figure 2. While simulating the unit cell, a normally incident plane wave on the metamaterial surface is considered. The permittivity, permeability and the
conductivity define the characteristics of electric material. By extracting these values for different frequencies, one can quickly determine the material's propagation profile at a given frequency [10]. In this paper, the authors used refractive index and impedance to extract the permeability and permittivity. One can write the S parameters obtained from this system as [11].

\[ S_{11} = \frac{R_{01}(1 - e^{i2nk_0d})}{1 - R_{01}e^{i2nk_0d}} \]  

(1)

\[ S_{21} = \frac{(1 - R_{01}^2)e^{i2nk_0d}}{1 - R_{01}^2} \]  

(2)

where \( e^{i2nk_0d} = \frac{S_{21}}{1 - S_{11}\frac{z-1}{z+1}} \) and \( n = \frac{1}{k_0d} \left[\left\{[\ln(e^{i2nk_0d})]'' + 2mn\right\} - i[\ln(e^{i2nk_0d})]'\right] \)

The impedance of the unit cell can be obtained using equation (3)

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

(3)

The following expressions will relate the permittivity and the permeability to refractive index and impedance as written in equation (4) and (5) respectively.

\[ \varepsilon = \frac{n}{z} \]  

(4)

\[ \mu = nz \]  

(5)

The S parameters obtained from Ansys HFSS simulator is used to extract the impedance z, the refractive index n, the effective permittivity \( \varepsilon_{eff} \) and the effective permeability \( \mu_{eff} \).

Figure 3. Extracted permittivity of proposed MTM unit cell
Figure 3 shows the permittivity plot extracted from S parameters of the simulated unit cell. From the graph, one can infer that the unit cell exhibits negative permittivity up to 4.5 GHz. Similarly, the permeability of the unit cell is plotted in Figure 4. From the traces, it is observed that the unit cell shows negative permeability up to 6 GHz. With these observations, one can conclude that the simulated metamaterial unit cell exhibits DNG property at the desired 2.4 GHz frequency. Hence the proposed metamaterial unit cell can be used as an element for the superstrate to improve the performance of the antenna for 2.4 GHz Wi-Fi applications.

Figure 4. Extracted permeability of proposed MTM unit cell

3. Design of TEAA and Meta material Superstrate

Initially, Authors designed an inset fed microstrip patch antenna to resonate at 2.4 GHz and a superstrate consisting of an array of 42 MTM unit cells. Later, four scenarios are considered for the simulation: SEA, TEAA, Single element Antenna with Superstrate (SEAS) and Three Element Antenna Array with Superstrate (TEAAS). The results obtained in the simulation are analyzed to study the effect of proposed MTM unit cell.

Figure 5 shows the geometry and physical dimensions of the inset fed single element antenna. Figure 6 presents the array of 42 unit cells arranged in a plane to form a superstrate. Figure 7 shows the simulation set up of all four scenarios. The physical dimensions of the inset fed antenna element are: Wg=42 mm, Lg=43.05 mm, Wp=32.4 mm, Lp=28.734 mm, Gap=1.0167 mm, Lins=10 mm, Wf=3.0612 mm, Lf=14.7212 mm.

Figure 5. Geometry of inset fed antenna element
Figure 6. Array of MTM unit cell (a) Top view (b) Bottom view

Figure 7. Simulated scenarios (a) Single element without superstrate (b) Three elements without superstrate (c) Single element with superstrate (d) Three elements with superstrate

4. Results and discussion
The designed antennas are simulated using HFSS ver.18.2. The simulated radiation patterns and reflection coefficient are analyzed to understand the influence of MTM.
The three-dimensional radiation patterns of SEA, TEAA, SEAS and TEAAS are presented in Figure 8. From the plots, it is observed that there is approximately 2 dB gain improvement with the use of MTM superstrate along with the single element antenna.

Similarly, when MTM superstrate is used with TEAA, the gain is improved by close to 1 dB. This increased gain will help in improving the range of communication in Wi-Fi applications.

The three-dimensional radiation patterns of beamforming TEAAS for progressive phase shift are shown in Figure 9. When the progressive phase angle $\delta t$ is $0^\circ$, the main lobe is oriented normal to the plane containing the array elements. The main lobe is shifted towards the positive $XY$ plane when $\delta t = 90^\circ$. At $\delta t = 180^\circ$, one can observe that the main lobe power splits in to positive and negative X-axis. At $\delta t = 270^\circ$, the main lobe shifts to negative $XY$ plane and finally at $\delta t = 360^\circ$ the main lobe gets back to the initial position. The transmit beamforming mechanism will help focus on the desired location and avoid losing energy in unwanted directions.
Figure 9. Simulated 3D gain of Beamforming antenna array with progressive phase angle (a) at 0° (b) at 90° (c) 180° (d) 270°

Figure 10 shows the comparison of reflection coefficients obtained from simulations. From the plot, one can observe that the SEA and the SEAS are resonating at the desired 2.4 GHz frequency band. The -10 dB bandwidth observed in either case is 500 MHz within the 2.4 GHz Wi-Fi band.

Figure 10. Comparison of simulated reflection coefficients of single element antenna with and without superstrate

The comparison of reflection coefficients of TEAA and the TEAAS are plotted in Figure 11. From the plot traces, one can observe that the $S_{11}$, $S_{22}$ and $S_{33}$ of TEAA are slightly shifted to the left of 2.4 GHz. With MTM superstrate, the resonance is moved close to the desired 2.4 GHz resonant frequency.
Figure 11. Comparison of simulated reflection coefficients of three element antenna with and without superstrate

5. Conclusion

A novel hybrid MTM unit cell is designed and extracted its parameters to verify the DNG behaviour at 2.4 GHz Wi-Fi frequency band. The proposed MTM unit cell's effect is studied by creating a superstrate and integrating it with the SEA and TEAAS. From the simulation results obtained, it is observed that there is a substantial amount of gain increment when an MTM superstrate is integrated with the conventional antenna and antenna arrays. Since this metamaterial unit cell is used to enhance the antenna array's performance, the beamforming Wi-Fi antenna's throughput and communication range gets improved. As an extension to this work, authors will fabricate and measure the presented antennas' performance and the superstrate to verify the simulation results and feasibility of fitting into the application.

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