Design and Analysis of Wide-Band Planar Antenna Using Meta-material for S-Band Applications

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Abstract. A patch antenna is a low-profile antenna that may be mounted on a surface and comprise of a flat sheet metal or "patch" placed above a larger metal sheet known as a ground plane. The sheet might be rectangular, round, triangular, or any other geometric shape depending on the use. This work proposes and investigates a patch antenna with meta-surface influence for S-band applications. To reduce size and improve bandwidth performance, the recommended antenna features a single-fed architecture and is equipped with a slew of meta-surfaced unit cell. Examined and illustrated with simulated results are the precise antenna radiation characteristics. Using Ansoft HFSS software, antenna is constructed on FR4 substrate at 2.5 Ghz for S band Frequency with loss tangent of 0.02 and ε_r is 4.4. The obtained simulation results include 10.4% (2.34–2.62 GHz) for a return loss bandwidth of 10 db, which outperforms antenna without meta surface by 4%, 6.7 dBi for performance in gain and 29% decrease in the patch's size while making utilization of a meta-surface. Applications for S-band Radar using this antenna include wide range of radar systems such as weather, surface ship and space borne type radar.

Keywords: Patch · Ground plane · S-band · Meta-surface · Antenna · Dielectric · Bandwidth · Space borne radar(SAR)

1 Introduction

In 1898 J.C Bose proposed first metamaterial and it was utilized in transmitters and other microwave parts. In 2001, D.M. Smith and Pendry carried out a follow-up investigation and discovered meta-material as well as its drawbacks. The permittivity and permeability of a periodic substance known as a metamaterial are determined by its structure rather than by its component components. Today, research into microwave frequencies is expanding. Because these materials haven't been widely seen in nature, they are made artificially using their structures and electromagnetic characteristics [1].

Employed metamaterials include Swiss Roll type, SRR based wire and Chiral materials according to polarity. Metamaterial usage reduces antenna size while boosting resonance efficiency and bandwidth [2]. It also lessens mutual coupling between antenna

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arrays. A substrate, a ground plane, array feeded network, a cloaking device, a superstrate, struts in reflector antenna and a random construction are just a few of the several ways that Meta-Material may be utilized to make antennas. Metamaterials (MTM) can be synthesized artificially. In mid of 1960's, Mr Veselago studied and researched on the behavioral properties of materials known as double negative materials as they possessed both permittivity is negative as well as permeability is also negative. Due to the Split Ring Resonators which make up such structure, the refractive index of these substance is negative. Metamaterials are used in a broad variety of fields [3].

Patch antenna provide a lot of benefits including low profile, minimal weight, simplicity of transportation, and compact size. Along with disadvantages including a bandwidth which is highly narrow, low efficiency as well as low gain and poor directivity, it also offers advantages. A Metamaterial unit cell placed on substrate can create a metamaterial which can be of numerous shapes and it is feed to antenna through multiple mechanism of feeding such as slot coupling or Electromagnetic coupling [4, 5].

The constraints of typical microstrip antennas include single-frequency operation, a narrow bandwidth of impedance, polarization difficulties, limited gain and large size. Improving performance of typical microstrip antenna, a number of strategies have been published. These includes various feeding methods, stacking, FSS, EBG, PBG, and metamaterials (FSS-"Frequency Selective Method", EBG-"Electro Band gap", PBG-"Photonic bandgap "). In 5^{th}Generation sub-6 GigaHertz and mm-based wave systems, microstrip patch antennas are frequently employed [6].

For such interaction and controlling of electromagnetic waves, an artificial homogeneous electromagnetic structure, a metamaterial can be defined as having special qualities that are not frequently observed in nature [6, 7].

Metamaterials should have a structure that is no larger than a quarter wave-length. Based on their electromagnetic properties, metamaterials can be categorized as Negative refractive Index(NRI), Right Handed (RH), Left handed(LH), Double Negative(DNG), Artificial magnetic Couplers and magneto. In addition to being known as metamaterials EBG, PBG and Defective ground Structure (DGS) [8].

Metamaterials are materials that have been developed to produce uncommon or difficult-to-obtain electromagnetic characteristics. Due to its potential to provide engineerable permeability, permittivity and index of refraction, metamaterials have attracted a lot of attention. This has made it is feasible for them to use in broad variety of electromagnetic applications, especially for radiated-wave devices, from the microwave to the optical regime.

Present report comprehensively analyses the most current research initiatives pertaining to those small antennas built with metamaterials. They are discussed and divided into a number of groups, including meta resonators, metamaterial loadings, and antennas based on dispersion engineering. A few real-world obstacles or restrictions to the creation of small antennas based on metamaterials are identified, and potential solutions are also shown. In order to aid general readers in comprehending, a wide range of antenna examples are included. [9, 10].

The use of metamaterials is covered in the second portion. A analysis of microstrip patch antennas employing MTM is addressed in the third section. The development of a the array of meta surface unit cells that is loaded underneath a patch antenna are covered in the fourth part. The simulation outcomes for an antenna containing and without a meta-surface are also covered in the fourth part.

2 Meta Material Applications

2.1 Antenna Miniaturisation

A keen interest is developing in ESAs have owing to their miniature size with a low profile making them feasible for application in mobile phones, airborne, IOT devices and wearables. When no ground is involved, antennas are considered tiny under condition $k\alpha < 1$ or $k\alpha < 0.5$ wave vector at the operating on corresponding frequency with radius minimal sphere around the antenna. ESAs suffices the need for compact transceivers, however their radiation efficiency and bandwidth undergoes a compromise. There is a major limitation in achieving excellent performance along with small size as a smaller antenna does not serve as an efficient radiator. The radiation properties undergo degradation by using traditional miniaturization techniques such as shortening pins, lumped elements and ceramic materials with high permittivity dielectrics. Therefore, development of tiny antennas made up of metamaterials can overcome these constrains and improve the quality of radiation.

Gain Enhancement

In a fixed point to point communication and radar systems, the critical feature of an antenna is gain. The transmission range for a given broadcast power can be extended by the use of high gain antennas which are additionally more resistant to interference. A popular method of generating higher gain is by making use of electrically massive antennas or arrays sets along with several radiating elements as directivity of the antennae is related to its aperture [6]. The use of small antennas in applications which require higher gain has become popular owing to the relationship between it's directivity and small size. Metamaterial randomness superstrates and lenses prove to be a practical, viable, low cost alternative in building otherwise complicated ultra compact and high gain antenna platforms. The use of these materials serve to increase the gain without reducing the volume of antennae considerably. The far field emission pattern is affected by the placement of these structures above the radiating elements as they interacts electromagnetic fields surrounding the radiator [9, 10].

There are two basic metamaterial-based approaches that can provide gain enhancement:

- Materials such as ZIM or NZRI are placed as superstrate.
- Materials with refractive index close to zero are known NZRI material the GRIN metamaterial lenses are placed in front of the antenna.

2.2 Isolation

For many applications, when the antenna elements are positioned closely together either by design (such as the common interelement spacing of by 2 in antenna array arrangements) or to reduce the bulk of the construction, isolation is crucial. Cross talks develop owing to interaction among antennas. Plantar antennas which are printed on the similar board,the surface waves which are considered as the primary source for development of cross talk [11, 12].

2.3 Reduction of Coupling Effects

Metasurfaces can be used in order to either mutual coupling among the antenna array elements or between the support structure and antenna. This may also boost directivity. For these goals, both grounded metasurface substrates and metasurface superstrates have been researched [12, 13].

2.4 Aperture Field Shaping– Directivity and Gain Enhancement

Metasurfaces act as lenses or transmit array for the distribution of desirable transmitted aperture field specially when high directivity is need. Metasurface which is partially reflecting can form a Fabry-Perot.In addition to this for a completely reflecting metasurface a front feeding like a reflecting array is essential. A single radiating unit or an antenna array situated behind the metasurface forms a radiator. This leads to an increase in gain as well as rise in directivity which is brought on the metasurface and is not offset by a corresponding ohmic loss [12].

2.5 Scanning of Main Beam Direction

Varactor diodes having voltage based controlled type capacitance have been used in metamaterial to Fabry-Perot cavity antennas surface that partly reflects, composite right-left leaky wave antennas, and high-impedance reflectors in an effort to change reflection/transmission phase or propagation constant and subsequently the radiation direction [12].

3 Survey of Various Microstrip Antennae Using MTM

This section provides a variety of MTM structural variations using patch antennas to enhance the functionality of a standard patch antenna. Later, a comparison is conducted between patch antennas with and without metamaterial in terms of metrics like gain and bandwidth.

RIS acting as a metamaterial on a substrate is been used. In his paper, patch antenna with low profile circularly polarized radiation that was inspired by Metamaterials. The antenna is loaded for downsize with a composite CRLH mushroom-like framework and RIS layout structure. It features a single feed arrangement. Unit cell based on RIS being positioned at a height of 2.6 mm on the substrate based on “Megtron 6”. We thoroughly study the radiation properties of a single feed patch antenna equipped with RIS & CRLH resonators. The frequency at which the suggested antenna works is 2.58 GHz [13, 14].

The tested antenna has a return loss of 10 dB as well as 3 dB axial bandwidth were determined to be 4.62% and 1.46%, respectively. The gain received is 2.98dB. The recommended antenna can be used with wire-less networks like WLAN [14, 15].

The construction of the proposed CP antenna is identical to that of in, except instead of the CRLH constructed as mushroom based structure, a pair of CSRR complementary type split ring based resonators are utilized. The CSRR functioned as a parallel LC based resonator and enabling the antenna area to be reduced. An antenna's observed 10-dB return loss that is 4.9% and 3-dB axial ratio bandwidths which corresponds 1.68%, respectively, and its gain is 3.7 dB. A frequency corresponding to 2.8 GHz is used by the proposed antenna [14, 15].

An antenna is made up of a slot-loaded with square based patch that is printed on a carefully thought-out reactive impedance's surface. The antenna, which operates at a frequency of 3 GHz, has a high gain of more than 4.15 dBi and a corresponding impedance of over 1.05%. The suggested antenna can be used with handheld and mobile communication equipment [16, 17].

In K. Agarwal study's on a small non - symmetric based slotted or slit designed microstrip based patched antenna upon RIS was shown and tested for CP radiation. Antenna has a total volume of 0.292λ0 by 0.292λ0 by 0.0308λ0 and operates at a frequency of 2.5 GHz. Compact asymmetrical crossed slot square patch antenna measurements show gain across 3-dB axial ratio bandwidth of 3.41 dBic, 5.2% for 10-decibel return loss bandwidth, and 1.6% for 3-decibels bandwidth [17].

L. Bernard et al. demonstrated a wideband antenna developed on RIS and exhibiting CP radiation. Telemetry-based applications in the region around 2300 MHz can be used to develop a wide band single-feed circular polarized patch antenna with a reduced dimension. A slot–loaded patch antenna (RIS) is used to produce and optimize the reactive impedance for the proposed structure. The fundamental role of each antenna component shown one by one comparison of statistical and experimental performance of numerous antenna designs over just one substrate as well as double layer substrate , slot loaded patch antenna , regular patch with or without RIS. The construction which has been substantially optimized has a wider bandwidth than a typically printed antenna, even though it is made up of same materials given axial-ratio of bandwidth roughly around 15% with an impedance bandwidth of 11% [18] (Table 1).

Table 1. Comparison of antenna using MTM

Antenna Configuration	Centre Frequency	10-dB Return Loss BW(%)	Gain (dBi)
Antenna structured along with CRLH mushroom and RIS	2.58 GHz	4.60	2.98
complementing split-ring resonators and RIS in an antenna	2.8 GHz	4.90	3.7
Antenna with a metasurface	3.0 GHz	2.33	5.1
Square patch with truncated corners over RIS	2.7 GHz	2.55	5.54
Square patch with ring slot on a metasurface	4.0 GHz	36.0	7.0–7.5
Metasurfaced square patch	2.3 GHz	24.0	2.5–5.7
Proposed Antenna	2.5 GHz	$\geq$ 7.0	$\geq$ 5.0

4 Design of Meta surface Antena

4.1 Design of Meta-Surface Cell Units

A meta surface cell unit having a dielectric constant value 4.4, 0.02 of a loss tangent, and 4.8 mm of thickness placed on FR4 substrate. The Meta- surface is 3,2 mm above the surface of the earth.

The figure below demonstrates the Meta-Surface unit cell design.

The cell unit dimensions are:

- The structure length of rectangular ring is 8.96 mm and the width of 5.6 mm
- the slot length of the rectangular ring is 7.46 mm with a slot width of 0.85 mm.

In the design and modelling of the meta- surface unit cell, master slave boundaries and unit cell's Floquet mode of excitation is utilized,mode of excitation was applied for analysis of utilizing an infinite structure. Figure 1 shows this sporadically.

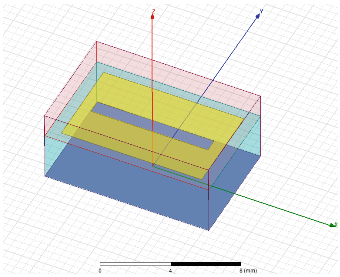

Fig. 1. Constructional Diagram of Meta-surface based Unit Cell

It's noted across a large frequency range, the unit cell's reflection phase oscillates between ±90 From 2.47 to 5.5 GHz, the range of frequency of the meta-surface unit cell is within a +90 degrees and –90 reflection phase variation. In Fig. 2, which is been displayed.

4.2 Design of Antenna in Presence and Absence of Meta-Surface

A rectangular shaped patch antenna is created at a frequency of 2.5 GHz upon a FR4 substrate with a dielectric constant of 4.4, a loss tangent of 0.02, and a thickness of 4.8 mm. The Patch Antenna has the following measurements:

- The ground plane's length and breadth are 90 mm and 180 mm, respectively.
- The patch's size is: $0.207\lambda_0$ * $0.483\lambda_0$, where λ_0 is forms a free space wavelength at 2.5 GHz.

The overall size of the antenna is 90 mm by 180 mm by 4.8 mm along with Coax-feed location: xp = –11 mm; yp = –15 mm.

Coaxial feeding is used to feed the specified antenna, and HFSS is used to mimic it.Below, in Fig. 3, is the simulation result for this antenna arrangement.

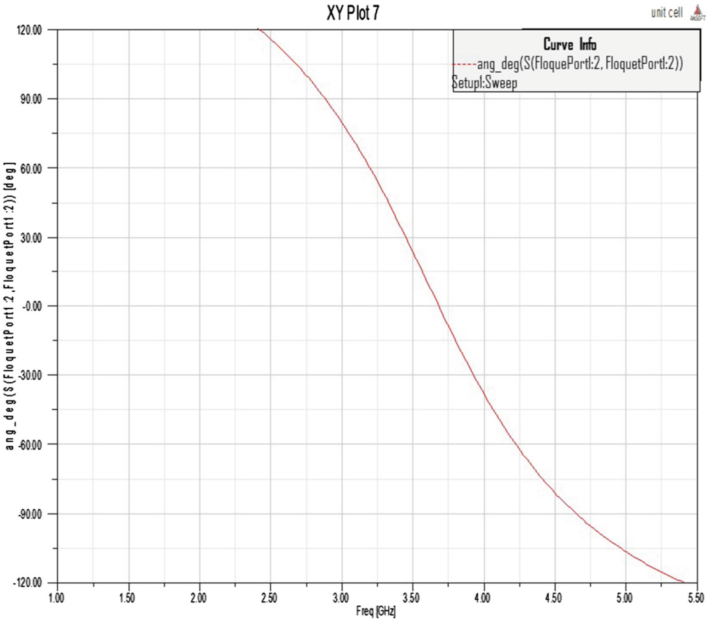

Fig. 2. Diagram illustrating the meta-surface unit cell's reflection phase

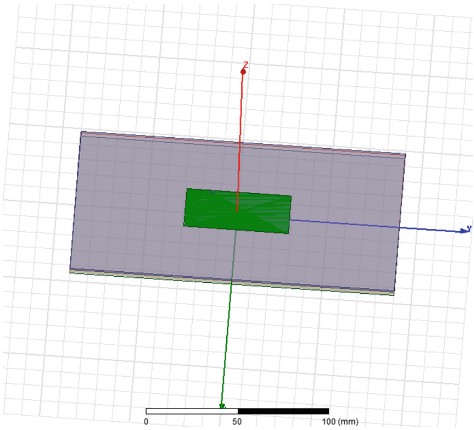

Fig. 3. Design without a meta-surface, a rectangular patch antenna

4.3 Antenna Fabricated with Meta-Surface

Following the built-up and simulation of the unit cell, the conventional antenna is designed with a 7*7 collection of meta-surface cell unit at given height of 3.2 mm, and it is positioned at 1.6 mm over the meta-surface.

The following are the overall measurements:

Ground plane dimensions are 90 mm by 180 mm.

Patch size is 0.155 λ0 *0.454 λ0 where λ0 represents the open space using a 2.5 GHz wavelength.

Location of the coax feed given as xp = –8 mm along with yp = –8 mm.

Antenna dimensions in total are 90 mm × 180 mm × 4.8 mm (Fig. 4).

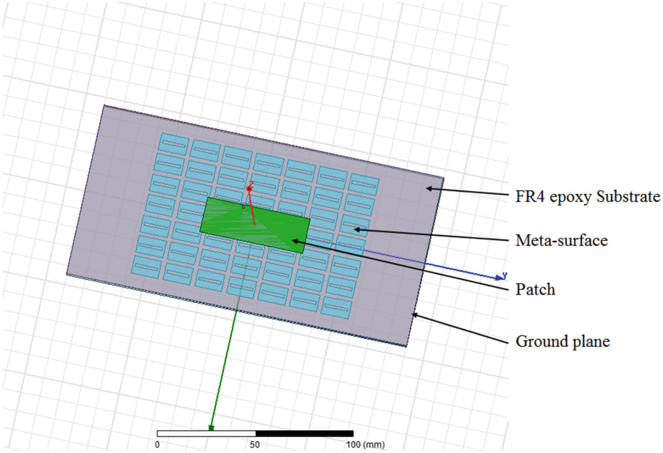

Fig. 4. Rectangular patch antenna with meta-surface

5 Results of Antenna Simulation Including and Excluding Metasurface

Ansoft HFSS is used to design the antenna and simulated outcomes are illustrated in the figure below.

Figure below shows the antenna's actual return loss, at the resonance frequency which is around –14 dB. Return loss of 10 dB has a bandwidth of around 150 MHz that is 6% (Fig. 5).

Gain (dBi), that's around 7 dBi at zero degrees, is a characteristic of far field radiation seen in Fig. 6.

Figure 7 demonstrates the approximately –13 dBi cross-pol discrimination.

5.1 Results of Meta-surface-Loaded Antenna's Simulation

Radiation pattern, gain (dBi), Figs. 8 and 9 display a meta-surface antenna's 10 dB return loss. At the resonant frequency at 2.5 GHz, return loss as much as –26 dB is seen in Fig. 9. The meta-surface antenna's 10 dB return loss having 10.4% bandwidth (2.34 GHz–2.62 GHz). Conventional antenna's return loss and a meta-surface based antenna are both contrasted in this graph.

Gain is shown against angle in degrees in Fig. 9. About 6.74 dBi of gain is attained using a meta-surface antenna. This is seen in the diagram.

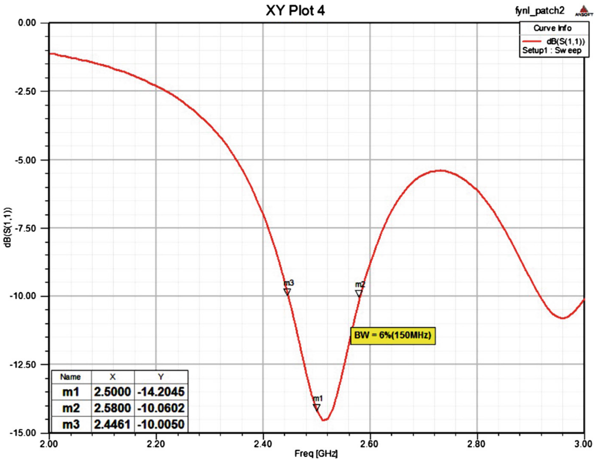

Fig. 5. A non-metasurface antenna's return loss (dB)

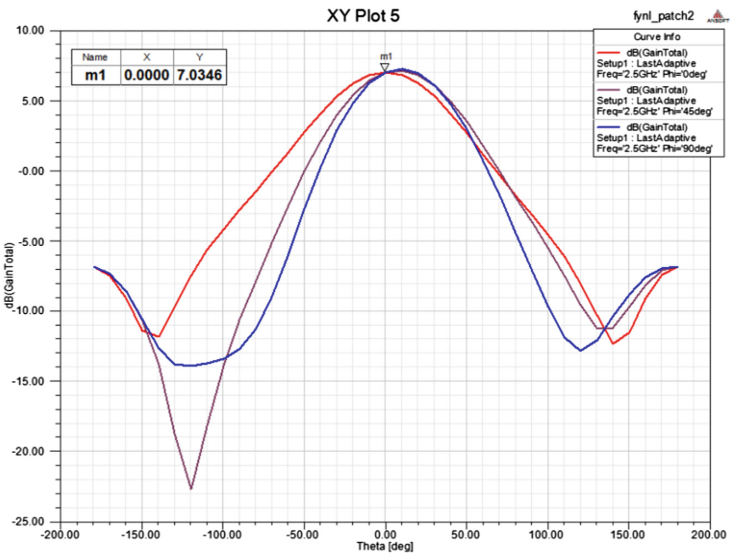

Fig. 6. Gain in dBi vs theta in deg

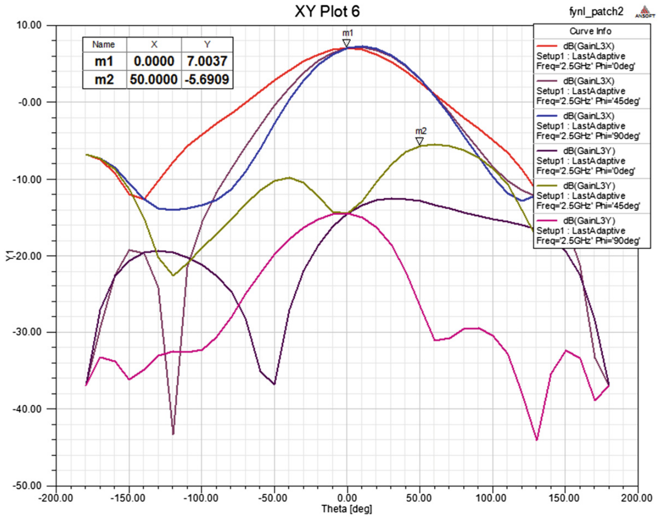

Fig. 7. Cross-pol discrimination

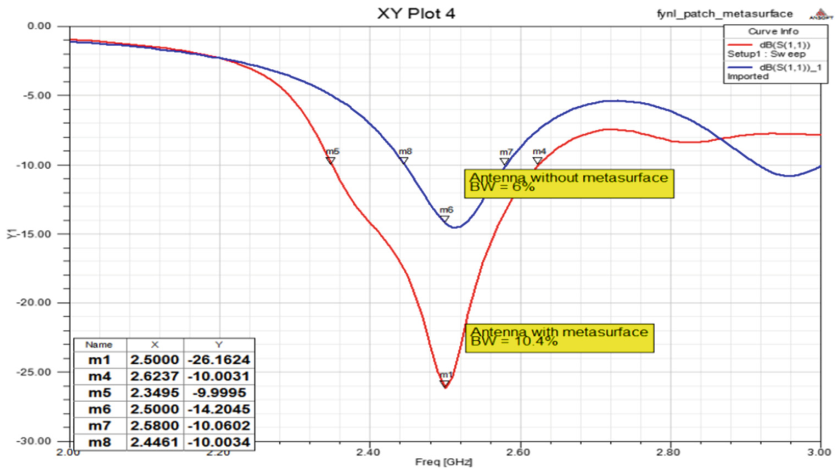

Fig. 8. A meta-surface antenna having return loss in dB

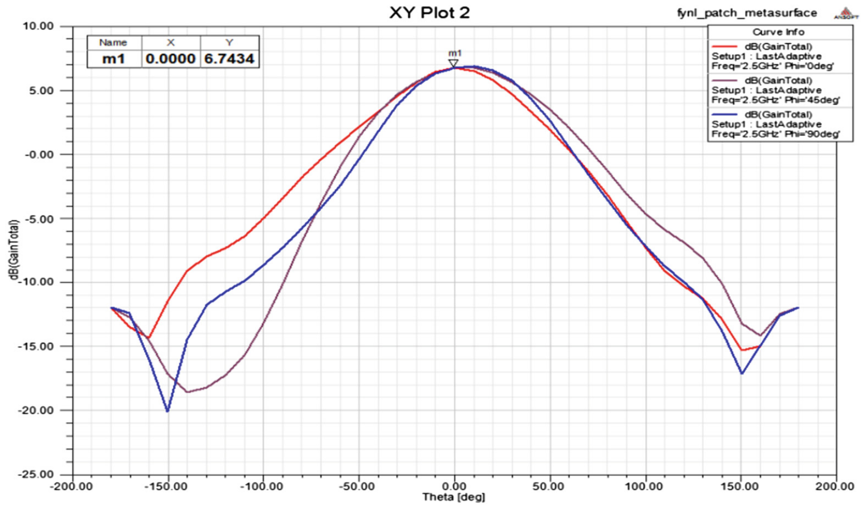

Fig. 9. Gain(dBi) versus theta(deg)

6 Conclusion

To do this, a thorough and methodical analysis of metamaterials and their properties was conducted. Through a review of the literature, Meta-materials come in a variety of shapes, including RIS,RIS,SRR etc. were examined and researched. This sort of analysis has also been used to study microstrip antennas and their feeding systems.On a FR4 epoxy substrate, a patch antenna has also been constructed and put to the test. Its performance has been assessed both with and without a meta-surface.The gain in dBi for a 10 dB return loss bandwidth is about 7.2 dBi without a meta-surface and 6.7 dBi with a meta-surface. Additionally, it has been discovered that the employment of meta-surfaces causes rise in bandwidth as the strength of the link seen between patch and indeed the meta-surface increases. Comparing the patch antenna to an antenna without such a meta-surface can result in a size reduction of up to 29% (Table 2).

Table 2. Comparison between Conventional Antenna and Metamaterial Antenna At 2.5 GHz frequency

No.	Parameters	Conventional Antenna	Meta-Material Antenna
1	Bandwidth	6%	10.4%
2	Gain	7.03 dBi	6.73 dBi
3	Size Reduction	(24.8*58) sq.mm	(18.6*54.5)sq.mm (29%)
4	Cross-pole Discrimination	–21 dBi	–16 dBi

References

1. Thomas, A.S., Prakash, A.K.: A survey on microstrip patch antenna using metamaterial. Int. J. Adv. Res. Electr. Electron. Instrum. Eng. **2**, 6289–6294 (2013)
2. Kumar, A., Kumar, N., Gupta, D.S.: Review on microstrip patch antennas using metamaterials. Int. J. Eng. Res. Gen. Sci. **2**(4), 678–682 (2014)
3. Kushwaha, R.S., Srivastava, D.K., Saini, J.P. Dhupkariya, S.: Bandwidth enhancement for microstrip patch antenna with microstrip line feed. In: 2012 Third International Conference on Computer and Communication Technology, pp. 183–185. IEEE 2012
4. Kaur, R., Singh, S., Kumar, N.: A review of various fractal geometries for wireless applications. Int. J. Electr. Electron. Eng. **2**(1), 34–36 (2015)
5. Pandey, G.K., Singh, H.S., Bharti, P.K., Meshram, M.K.: Metamaterial-based UWB antenna. Electron. Lett. **50**(18), 1266–1268 (2014)
6. Pendry, J.B., Holden, A.J., Robbins, D.J., Stewart, W.J.: Magnetism from conductors and enhanced nonlinear phenomena. IEEE Trans. Microw. Theory Tech. **47**(11), 2075–2084 (1999)
7. Viktor, G.V.: The electrodynamics of substances with simultaneously negative values of $\epsilon $ and M. Soviet Physics Uspekhi **10**(4), 509–514 (1968)
8. Martin, F., Sorolla, M., Marques, R.: Metamaterials with Negative Parameters: Theory, Design, and Microwave Applications (2008)
9. Lin, I.H., Caloz, C., Itoh, T.: Transmission line approach of left-handed (LH) non-uniform transmission lines (NTL). In: IEEE Asia Pacific Microw. Conference (APMC), pp. 1501–1504. IEEE (2002)
10. Belov, P.A., et al.: Strong spatial dispersion in wire media in the very large wavelength limit. Phys. Rev. B **67**(11), 113103 (2003)
11. Landau, L.D., Bell, J.S., Kearsley, M.J., Pitaevskii, L.P., Lifshitz, E.M., Sykes, J.B.: Electrodynamics of Continuous Media, vol. 8. Elsevier, Amsterdam (2013)
12. Milias, C., et al.: Metamaterial-inspired antennas: a review of the state of the art and future design challenges. IEEE Access, **9**, 89846–89865 (2021)
13. Rani, R., Kaur, P., Verma, N.: Metamaterials and their applications in patch antenna: a. Int. J. Hybrid Inf. Technol. **8**(11), 199–212 (2015)
14. Dong, Y., Toyao, H., Itoh, T.: Compact circularly-polarized patch antenna loaded with metamaterial structures. IEEE Trans. Antennas Propag. **59**(11), 4329–4333 (2011)
15. Dong, Y., Toyao, H., Itoh, T.: Design and characterization of miniaturized patch antennas loaded with complementary split-ring resonators. IEEE Trans. Antennas Propag. **60**(2), 772–785 (2011)
16. Xu, H.X., Wang, G.M., Liang, J.G., Qi, M.Q., Gao, X.: Compact circularly polarized antennas combining meta-surfaces and strong space-filling meta-resonators. IEEE Trans. Antennas Propag. **61**(7), 3442–3450 (2013)
17. Agarwal, K., Alphones, A.: RIS-based compact circularly polarized microstrip antennas. IEEE Trans. Antennas Propag. **61**(2), 547–554 (2012)
18. Bian, L., Guo, Y.X., Ong, L.C., Shi, X.Q.: Wideband circularly-polarized patch antenna. IEEE Trans. Antennas Propag. **54**(9), 2682–2686 (2006)