



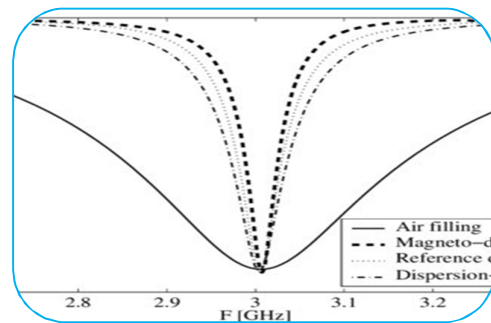
## STUDY OF ARTIFICIAL MAGNETO-DIELECTRIC LOADING FOR IMPROVED IMPEDANCE-BANDWIDTH OF MICROSTRIP ANTENNA DEVICES.

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### ABSTRACT

Micro strip antennas are widely used in modern wireless communication due to their low profile, ease of fabrication, conformability, and integration with planar circuits. However, a fundamental limitation is their relatively narrow impedance bandwidth, which constrains applications that require broadband performance, miniaturization, or multi-band operation. Researchers have investigated numerous techniques to overcome this limitation, and one promising solution is the use of artificial magneto-dielectric materials to load the antenna substrate. Artificial magneto-dielectric loading has emerged as a promising strategy to enhance the performance of microstrip antennas, particularly in terms of impedance bandwidth and miniaturization. Introducing engineered magneto-dielectric substrates—often constructed with metamaterial inclusions such as split-ring resonators or meta solenoids—modifies the effective permeability and permittivity of the substrate, enabling controlled inductive and capacitive loading of the radiating structure. In practical realizations, the frequency dispersion and loss associated with realistic magneto-dielectric media critically influence the achievable bandwidth improvements. Experimental studies validate that while MD loading facilitates size reduction and can improve bandwidth under certain conditions, optimized design of resonant inclusions and consideration of dispersion and loss are essential for practical wideband microstrip antenna implementations. This paper presents recent advancements in artificial magneto-dielectric loading, physical mechanisms, design methodologies, and measured performance improvements in microstrip antenna systems.



**KEYWORDS** - Microstrip antennas, magneto-dielectric materials, electromagnetic energy, optimized design.

### 1. INTRODUCTION:

Microstrip antennas, especially patch antennas, are omnipresent in modern wireless systems including mobile devices, satellite communication, IoT devices, and 5G networks due to their planar nature and ease of integration with printed circuits. Despite these advantages, a significant drawback is their inherent narrow impedance bandwidth. These limitations originate mainly from the resonant nature of the patch and the typical dielectric substrates used, which provide restricted electromagnetic performance when considering miniaturization and wideband operation simultaneously [1].

To overcome such constraints, researchers have explored multiple enhancement strategies including structural modifications, multilayer dielectric configurations, and the integration of novel

materials. One particularly compelling approach involves the use of magneto-dielectric and metamaterial-inspired substrates that introduce artificial magnetic properties into the antenna environment. These artificial magneto-dielectric materials engineered composites exhibiting both effective permittivity and permeability. It offers additional degrees of freedom in controlling electromagnetic fields. By tailoring these parameters, it is possible to simultaneously miniaturize the antenna and extend its impedance bandwidth beyond what conventional dielectric loading can achieve [2]. For applications requiring wide bandwidth, compact size, or multi-frequency operation, design improvements are necessary. Traditional methods for bandwidth enhancement include using thicker substrates. It is limited by surface wave excitation and fabrication. By using low dielectric constant materials, employing multi-resonant structures, and utilizing advanced feed techniques the band width can be enhanced. The concept of using materials with engineered permittivity and permeability is rooted in metamaterials and engineered composites, where the substrate is designed to exhibit tailored electromagnetic responses. By incorporating magnetic loading, we can influence both the electric and magnetic stored energy in the antenna cavity, thus affecting the quality factor and bandwidth [3]. Classical approaches to bandwidth enhancement typically rely on increasing the physical thickness of the substrate or using high-permittivity dielectrics; however, these often lead to increased surface-wave excitation and impedance matching challenges, which can degrade radiation performance. In contrast, magneto-dielectric loading introduces an artificial inductive response that can counterbalance the capacitive effects of high permittivity, leading to better impedance matching and broader bandwidth without excessively increasing antenna dimensions. The theoretical foundation for artificial magneto-dielectric loading was laid out in seminal works dating back to the early 2000s. These studies analytically and experimentally demonstrated that embedding resonant magnetic inclusions or metamaterial unit-cells within the substrate can significantly alter the antenna's electromagnetic quality factor and bandwidth properties. The impedance bandwidth, which is inversely related to the quality factor, can be enhanced when both effective permeability ( $\mu$ ) and permittivity ( $\epsilon$ ) are optimized [4].

However, practical realizations of artificial magneto-dielectric media often exhibit frequency dispersion and material losses, which limit the ideal performance predicted by simple non-dispersive models. Realistic artificial magnetic substrates tend to show dispersive magnetic permeability, which affects the bandwidth improvement and miniaturization trade-offs. For example, experimentally verifiable results have indicated that while non-dispersive high  $\mu$  can theoretically reduce antenna size and increase bandwidth, frequency-dependent magnetic response must be carefully considered in actual designs. In recent years, advancements in metamaterial engineering and composite fabrication techniques such as polymer-matrix magneto-dielectric composites and nanostructured fillers have enabled more practical implementations of magneto-dielectric loading. These materials can be tailored to exhibit desired electromagnetic responses at targeted microwave frequencies, facilitating enhanced impedance bandwidth and radiation performance for microstrip antennas devices. Given this backdrop, the present work investigates how artificial magneto-dielectric loading can be strategically applied to microstrip antennas to achieve significant improvements in impedance bandwidth while maintaining compact form factor and acceptable radiation efficiency. This research contributes to the ongoing effort to design wideband, high-performance antennas for next-generation wireless communication systems.

**2.1 Microstrip Antenna Fundamentals:** A microstrip antenna is a low-profile, planar radiating structure widely used in modern wireless communication systems due to its compact size, light weight, and ease of integration with microwave circuits. It typically consists of a conducting patch printed on one side of a dielectric substrate, with a ground plane on the opposite side. The patch can take various shapes such as rectangular, circular, triangular, or more complex geometries, depending on the required operating frequency and radiation characteristics. The radiation mechanism of a microstrip antenna arises mainly from fringing fields at the edges of the patch, which occur due to the discontinuity between the patch and the surrounding air. These fringing fields make the antenna behave as a resonant cavity, where the resonant frequency is primarily determined by the patch dimensions, substrate permittivity, and substrate thickness. The resonant frequency  $f_r$  is approximately

$$f_r \approx \frac{c}{2L\sqrt{\epsilon_r}} \text{-----}[1]$$

Where  $c$  is the speed of light,  $L$  is the patch length, and  $\epsilon_r$  is the effective permittivity of the substrate. The impedance bandwidth depends on the ratio of stored reactive energy to radiated energy. Higher substrate permittivity increases confinement but also increases the quality factor ( $Q$ ), narrowing the bandwidth. Microstrip antennas are commonly excited using feeding techniques such as microstrip line feed, coaxial probe feed, aperture coupling, or proximity coupling, each offering different impedance matching and bandwidth characteristics [4]. Despite their advantages, microstrip antennas inherently suffer from narrow impedance bandwidth and relatively low gain, especially when fabricated on thin, high-permittivity substrates. Consequently, recent research focuses on bandwidth enhancement, size reduction, and performance improvement using techniques such as multilayer substrates, slots, parasitic elements, and advanced materials including metamaterials and magneto-dielectric loading.

**2.2. Magneto-Dielectric Materials:** Magneto-dielectric materials are engineered or composite materials that simultaneously exhibit electric (permittivity,  $\epsilon$ ) and magnetic (permeability,  $\mu$ ) responses when subjected to electromagnetic fields. Unlike conventional dielectric substrates, which primarily influence the electric field, magneto-dielectric materials provide additional control over the magnetic field component, enabling enhanced electromagnetic performance in microwave and antenna applications. These materials are often realized using artificial structures or composites, such as ferrite-based inclusions, magnetic nanoparticles embedded in polymer matrices, or metamaterial unit cells designed to produce an effective magnetic response at microwave frequencies. In antenna engineering, magneto-dielectric materials are particularly attractive for miniaturization and bandwidth enhancement. By increasing both  $\epsilon$  and  $\mu$ , the guided wavelength can be reduced without excessively increasing the quality factor, leading to improved impedance bandwidth compared to purely dielectric loading. However, practical magneto-dielectric materials often exhibit frequency dispersion and material losses, which must be carefully optimized to achieve efficient radiation. Recent advances in metamaterial fabrication and composite synthesis have improved the feasibility of low-loss magneto-dielectric substrates for compact, wideband antenna designs.

**2.3 Quality Factor and Bandwidth Relation:** The antenna quality factor  $Q$  relates inversely to bandwidth for a given VSWR or reflection coefficient threshold. A classical formulation for the fractional bandwidth BW approximates is given as:

$$BW=1/Q \text{-----} [2]$$

Where  $q$  is the quality factor. Thus, by lowering the quality factor through engineered reactive loading (magnetic or magneto-dielectric) can broaden the impedance bandwidth. The quality factor ( $Q$ ) of an antenna is a measure of how efficiently it stores energy relative to the energy it radiates or dissipates. It is defined as the ratio of the stored energy to the energy lost per cycle. In resonant antennas such as microstrip antennas, the impedance bandwidth is inversely proportional to the quality factor. A high  $Q$  indicates strong energy storage and low radiation loss, resulting in a narrow bandwidth, whereas a low  $Q$  corresponds to higher radiation and loss, leading to a wider bandwidth. Therefore, bandwidth enhancement techniques primarily aim to reduce the antenna’s quality factor.

**3.1 Effect on Impedance and Bandwidth:** Impedance and bandwidth are critical performance parameters that determine the operational efficiency of an antenna. Input impedance represents how effectively power is transferred from the feed line to the antenna, and proper impedance matching is essential to minimize reflections and maximize radiation. In microstrip antennas, impedance is mainly influenced by the patch dimensions, feeding technique, substrate properties, and surrounding electromagnetic environment. Any mismatch between the antenna impedance and the characteristic

impedance of the feed line results in increased return loss and reduced operational bandwidth. The impedance bandwidth of an antenna is defined as the frequency range over which the antenna maintains acceptable impedance matching, typically for a return loss below -10 dB. Factors such as thin substrates, high dielectric constant materials, and strong energy confinement tend to increase Q, thereby reducing bandwidth. Various techniques are employed to improve impedance matching and bandwidth, including the use of slots, parasitic elements, multilayer substrates, and advanced materials such as magneto-dielectric or metamaterial loading. These methods modify the stored electric and magnetic energies, leading to improved impedance characteristics and enhanced bandwidth without significantly increasing antenna size.

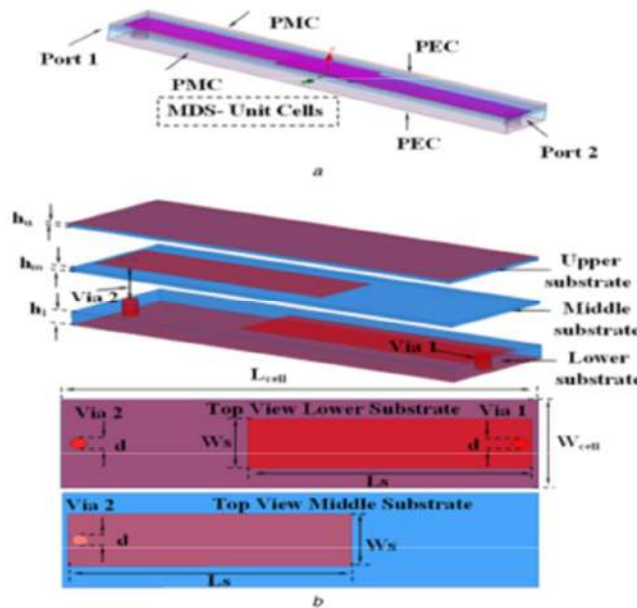
**3.2 Cavity and Transmission Line Models with Magnetic Loading:** In cavity models, the patch antenna can be considered a resonant cavity with electric and magnetic fields. The substrate’s inductive and capacitive contributions determine stored energy. Electric field storage is governed by permittivity  $\epsilon_r$  and Magnetic field storage is influenced by the effective permeability  $\mu_r$ . By increasing effective  $\mu_r$  while controlling  $\epsilon_r$ , one can reduce the net stored energy ratio without severely altering resonance, which leads to enhanced bandwidth and possibly miniaturization.

**3.3 Proposed Magneto Dielectric Substrate:** Microstrip patch antennas are popular and their use has become ubiquitous in wireless communication systems. However, microstrip patch antennas are narrowband due to the resonance nature of the antenna [5]. The dominant resonance frequency of a microstrip patch antenna can be calculated as:

$$f = \frac{c}{2(l+h)\sqrt{\mu_e \epsilon_e}} \text{-----[3]}$$

$$\epsilon_e = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} \left(1 + \frac{12h}{w}\right)^{-0.5} \text{-----[4]}$$

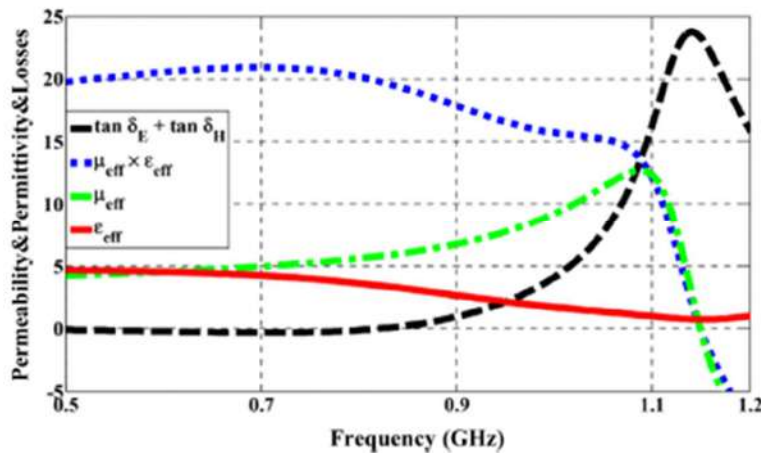
Where  $\epsilon_e$  and  $\mu_e$  are the effective electric permittivity and effective magnetic permeability of the host substrate, respectively.  $\epsilon_r$  is the relative electric permittivity, h is the thickness of the host substrate,



**Fig. (1) Proposed magneto-dielectric unit cell.**

The unit cell physical dimensions are  $W_{cell} = 2.75\text{mm}$ ,  $L_{cell} = 20\text{mm}$ ,  $W_s = 1.6\text{mm}$ ,  $L_s = 11.9\text{mm}$ ,  $d = 0.7\text{mm}$ ,  $h_l = 0.813\text{mm}$ ,  $h_m = 0.203\text{mm}$ ,  $h_u = 0.203\text{mm}$ . (a) Unit cell under specified boundary condition, (b) Top and side views of the proposed unit cell and  $w$  and  $l$  are the width and length of the rectangular patch antenna [6]. According to (1) and (2), the resonance frequency is inversely proportional to the product of the effective permeability and the permittivity. Consequently, the resonance frequency can be shifted downwards by increasing the product of the permeability and permittivity. In metamaterial structures, such as the split ring resonators (SRRs) proposed in, the perpendicular magnetic field vectors induce current in the ring [7]. The induced current creates magneto-dipoles, which persist against the primary magnetic field, augmenting the magnetic permeability of the substrate.

The proposed unit cell, shown in Fig. 1, lower, middle and top three substrates are composed. The lower substrates consist of two vias, a ground layer and a metallic strip. The middle substrates consist of one via and one metallic strip. The top substrates consist of a perfect electric conductor (PEC) layer on the top, which represents the patch. The two vias, with ground and two strips form an SRR-like structure. The proposed MDS is placed under near the patch antenna, which is printed on the top substrate [8]. The MDS is composed of 40 unit cells, arranged in two rows ( $2 \times 20$ ) embedded in the lower and middle substrates. The host dielectric substrate is RO4003, with  $\epsilon_r = 3.55$ , and  $\tan \delta = 0.0027$ . The thicknesses of the lower substrate ( $h_l$ ), middle substrate ( $h_m$ ) and upper substrate ( $h_u$ ) are  $0.813\text{mm}$ ,  $0.203\text{mm}$  and  $0.203\text{mm}$ , respectively. Each unit cell has two vias with lengths of  $0.813\text{mm}$  and  $1.016\text{mm}$ . The effective constitutive parameters of the proposed metamaterial design structure (MDS) were retrieved from the simulated frequency response of the unit cell by employing the parameter extraction technique developed by Smith et al. [9], under appropriate electromagnetic boundary conditions (Fig. 1a). In this configuration, the top and bottom surfaces of the unit cell were assigned perfect electric conductor (PEC) boundary conditions, whereas the lateral boundaries along the  $yz$ -plane were modeled as perfect magnetic conductors (PMCs), as illustrated in Fig. 1a. The resonant characteristics of the structure can be systematically tuned by varying the geometrical dimensions of the unit cell, thereby enabling control over its electromagnetic response. The length of the unit cell ( $L_{cell}$ ) is the most important parameter, as it affects the unit cell resonance frequency. Increasing the length of the unit cell ( $L_{cell}$ ) decreases the resonance frequency [10]. The constitutive parameters of the proposed MDS are depicted in Fig. 2.

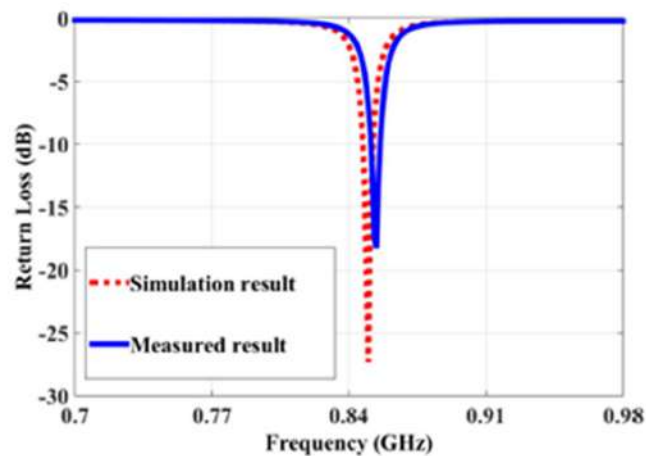


**Fig. (2) Effective constitutive parameters of the proposed MDS. The dashed curve represents the combined magnetic and electric losses, while the dotted curve illustrates the product of dielectric permittivity and magnetic permeability. The solid line corresponds to the electric permittivity, and the dash-dot line indicates the magnetic permeability.**

Fig. 2 clearly shows that the electric permittivity gradually decreases as the frequency increases, whereas the magnetic permeability shows an upward trend at higher frequency ranges. The

product of dielectric permittivity and magnetic permeability is around 20 in terms of bandwidth (500–900 MHz), it then goes down when the frequency is higher than 900 MHz. The summation of the magnetic and electric losses is roughly equal to zero in bandwidth (500–900 MHz) and then the losses increase when the frequency goes over 900 MHz. The optimum value at 850 MHz represents a trade-off between the product of dielectric permittivity and magnetic permeability and total losses, achieving the highest efficiency with the smallest possible size [11].

Fig. (3) depicts the measured and simulated input return loss of the proposed magneto-dielectric patch antenna. As can be observed in Fig. 3, the measured input return loss is shifted upwards a little bit. The corresponding frequency is responded of the simulated and measured results are only 7 MHz apart from each other (a 0.8% frequency shift). This frequency shift between simulated and measured results comes from the adhesive layer (Electrically Insulating Die Attach Adhesive – EPO-TEK TJ1104-LH) which attaches the three substrates onto each other. The experimental findings closely match the simulated results, demonstrating strong agreement between the two. The size of the proposed magneto-dielectric antenna is reduced by about 80% compared with the conventional microstrip patch antenna, and with almost the same frequency bandwidth [12].



**Fig. (3) Simulated (dashed line) and measured (solid line) return loss of the proposed magneto-dielectric patch antenna**

When compared with previously reported antennas, the proposed design demonstrates superior overall performance, offering higher radiation gain, improved radiation efficiency, and a greater miniaturization ratio relative to the referenced antennas. Table 2 also shows that the radiation efficiency, gain and bandwidth are the best for the antennas in among the other presented works. Nevertheless, the proposed antenna has a more compact size compared to the antennas reported in [13].

#### 4. CONCLUSION:

A miniaturised microstrip patch antenna using a new MDS has been proposed, designed, fabricated and tested. This micro strip patch antenna is placed on the host MDS, which consists of 40 unit cells arranged in two rows. The constitutive parameters' effects of the proposed MDS have been studied. This miniaturised microstrip allowed the antenna size to be reduced by 80% compared with a conventional patch antenna, with an impedance bandwidth that is almost the same as that of the conventional patch antenna and with acceptable gain and radiation efficiency. The proposed antenna has been compared with several others from selected papers, and its performance is deemed comparable. The simulated and measured results have shown a good agreement. The proposed magneto-dielectric antenna can be easily incorporated into planar circuit designs, highlighting its potential applicability in RFID systems. Artificial magneto-dielectric loading presents an effective strategy for overcoming the traditional bandwidth limitations of microstrip patch antennas. By

incorporating engineered magnetic response along with dielectric properties, one can reduce antenna quality factor, improve impedance bandwidth, and enable size miniaturization without major performance sacrifice. Recent advances such as 3D-printed magneto-dielectric substrates and functionally graded composites demonstrate practical implementations with significant performance enhancements. Moreover, theoretical analyses provide clear insight into how tailored electromagnetic properties influence field distributions and radiative mechanisms. While challenges remain in material losses, frequency dispersion, and fabrication consistency, magneto-dielectric loading remains a compelling area for advancing next-generation broadband antenna systems. In conclusion, artificial magneto-dielectric loading represents a powerful tool for next-generation microstrip antennas, enabling compact, wideband, and efficient designs. With continued research in materials, fabrication, and design methodologies, these antennas hold significant promise for high-performance wireless communication systems, bridging the gap between miniaturization and broadband operation.

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