Artificial Magneto-superstrates for Gain and Efficiency Improvement of Microstrip Antenna Arrays

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Abstract—This paper presents an engineered magneto-dielectric superstrates designed to enhance the gain and efficiency of a microstrip antenna array without any substantial increase in the antenna profile. The broadside coupled split ring resonator (SRR) inclusions are used in the design of the superstrate. Numerical full-wave simulations of a $4 \times 1$ linear microstrip antenna array working at the resonance frequency of 2.18 GHz and covered by the superstrate show a gain enhancement of about 3.5 dB and an efficiency improvement of 10%. The total height of the proposed structure is $\lambda_0/7$ where $\lambda_0$ is the free-space operating wavelength.

1. INTRODUCTION

The magnetic metamaterials demonstrate larger than unity permeability ($\mu$) values due to the fact that they are magnetically polarized under the influence of electromagnetic (EM) field. However, such materials do not occur naturally in the microwave regime because the inertia of their atomic system is not able to track the high frequency EM field. Another related metamaterial is the magneto-dielectric which can be polarized both electrically and magnetically when exposed to an applied EM field, so that it has both relative permeability ($\mu$) and permittivity ($\varepsilon$) greater than one [1, 2]. There are many potential applications of magneto-dielectrics particularly where miniaturization of microwave components is desired. For example, magneto-dielectric materials have been utilized recently as substrates for miniaturization of microstrip antenna [3, 4], and as superstrates for gain enhancement of planar antenna [5]. In [6], High-permittivity materials have been used as superstrates for gain enhancements where a half wave-length thickness of the superstrates was required to achieve the gain-enhancement, resulting in high profile antenna systems. On the other hand, the antenna profile can be substantially reduced by using magneto-dielectric superstrates because of the simultaneously large permittivity and permeability.

In this work, a magneto-dielectric superstrate using modified split ring resonators (SRR) is designed for gain and efficiency enhancement of microstrip antenna arrays. The designed SRR-based material has effective positive values for the effective permeability and permittivity at the resonance frequency of the antenna array. The antenna system is simulated using Microwave CST Studio and the effect of superstrate on the far-field antenna parameters is investigated. In particular, a significant enhancement in gain and efficiency of the antenna is demonstrated. The proposed method is anticipated to combat some of the downsides of the microstrip array antennas such as feed network losses and gain reduction due to surface wave radiations. Other contemporary trends of gain enhancement include the use of non-magnetic dielectric [6] or electromagnetic bandgap structures (EBG) [7, 8] as superstrates. However, they all require fairly thick superstrates layers, leading to a significant increase of antenna profile. In [5], the use of magneto-dielectric materials as a gain enhancing superstrate is investigated without practical design considerations.

2. THE PROPOSED ARTIFICIAL MAGNETIC SUPERSTRATE

The SRR unit cell of the proposed artificial magneto-dielectric is shown in Fig. 1(a). The SRR inclusion consists of two parallel broken square loops printed on both sides of the host dielectric Rogers RO4350 substrate that has a thickness of 0.762 mm, a relative permittivity ($\varepsilon_r$) of 3.48, and a loss tangent (tan $\delta$) of 0.004.

The SRR unit cell is analytically modeled by obtaining its effective relative permeability as [1, 2]

$$
\mu_{r,\text{eff}} = 1 - \frac{j\omega L_{\text{eff}} S}{\Delta x \Delta z \left( R_{\text{eff}} - \frac{j}{2\omega \varepsilon_{\text{eff}}} + j \omega L_{\text{eff}} \right)}
$$

(1)

where $S$ is the surface area of the inclusion ($l_x \times l_y$) $\Delta x$ and $\Delta z$ are the unit cell sizes in $x$ and $z$ directions as shown in Fig. 1(a). The dimensions of the designed SRR unit cell are $\Delta x = \Delta y =$...
Figure 1: Geometry of a $4 \times 1$ microstrip antenna array covered by an engineered magnetic superstrate. (a) SRR unit cell. (b) Side view. (c) Top view. ($a = 0.762$ mm, $b = 2$ mm, $c = 210$ mm and $d = 12$ mm).

Figure 2: Analytically calculated relative permeability of the SRRs.

8.5 mm, $\Delta z = 2.762$ mm, $l_x = l_y = 6.5$ mm, $w = 0.3$ mm. The width of metallic strips ($s$) is equal to 0.3 mm, and the metallic strips are assumed to be made of copper. Formulas for $R_{\text{eff}}, C_{\text{eff}}$ and $L_{\text{eff}}$ can be found in [1]. The effective relative permeability calculated from (1) is depicted in Fig. 2.

As shown in Fig. 1(c), one layer of the superstrate is constructed by arranging an $44 \times 24$ array of SRRs. The superstrates consists of three layers of the SRR arrays, aligned in the $XY$ plane and separated from each other by 2 mm air layers, as depicted in Fig. 1(b). It may be noted that only $z$-directed magnetic fields are coupled to the superstrates layers. Any incident magnetic field in the $x$ or $y$ direction will not couple to the SRR inclusion resulting in a permeability equal to that of free-space in those directions. Hence, the anisotropic permeability tensor is given by

$$\vec{\mu} = \mu_0 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \mu_{r,\text{eff}} \end{bmatrix}$$

(2)

The effective permittivity of the artificial materials arises from the capacitive gap regions of width ‘$w$’ between the SRR inclusions and also from the gap regions between the vertically stacked metallic inclusions (unit cells). The unit cell thus reacts to the incident $x$-and $y$-directed electric field to produce the capacitive effect.

The resulting $x$- and $y$-directed effective permittivity is given by [3]

$$\varepsilon_{r,\text{eff}} = \varepsilon_{r,\text{rel}} \left[ 1 + \frac{\Delta z l_x}{\Delta x \Delta y} \frac{K(\sqrt{1 - g^2})}{K(g)} \right], \quad g = \frac{\frac{g}{2} + w}{\frac{g}{2}}, \quad K(g) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - g^2 \sin^2 \theta}}$$

(3)

However, in case of $z$-directed electric field, the metamaterials superstrate will experience an effective permittivity equal to that of its host dielectric as the electric field would be perpendicular to
the plane of the unit cell. Thus, the permittivity matrix of the magneto-dielectric is given by

$$\bar{\varepsilon} = \varepsilon_o \begin{bmatrix} \varepsilon_{r_{\text{eff}}} & 0 & 0 \\ 0 & \varepsilon_{r_{\text{eff}}} & 0 \\ 0 & 0 & \varepsilon_{r_{\text{die}}} \end{bmatrix}$$  

(4)

3. THE ANTENNA SYSTEM SIMULATIONS

The $4 \times 1$ antenna array used to demonstrate the gain and efficiency enhancement is shown in Fig. 3(a). The antenna elements are printed on the substrate that is identical to the one mentioned in the previous section. The separation between adjacent antenna elements is optimized for obtaining the highest gain. Each antenna is designed to operate at a center frequency of 2.18 GHz which lies in the UMTS band. The feeding network provides a zero progressive phase to the antenna elements to obtain broadside radiation. At the operating frequency, the $\varepsilon_{r_{\text{eff}}}$ and $\mu_{r_{\text{eff}}}$ are given respectively by 5.62 and 15. All simulations are performed using the full-wave electromagnetic simulation tool CST taking into account the actual structure of the SRR based superstrate.

First, in order to show the coupling between the magnetic field and the SRR unit cell, the distribution of the magnetic field due to the antenna array system when the superstrate is removed is plotted in Fig. 3(b). As shown in the figure, the dominant component of the magnetic field vector lies in the $z$ direction. This confirms that the superstrate with permeability tensor given in (2) is indeed suitable for the microwave antenna array considered in this example.

Using the CST simulation package, the optimized distance between the patch antenna and superstrate is determined by parametric analysis to be 12 mm. When the gain is optimized, the resulting overall antenna profile is only $\lambda_o/7$ (where $\lambda_o$ is the free-space wavelength at the resonance frequency). As shown in the gain plot given in Fig. 3(c), the gain in the broadside direction is improved by about 3.5 dB at the antenna resonance. The return loss plot, also depicted in Fig. 3(c), shows that the antenna array is matched, before and after the application of the superstrates.

A slight change in the resonant frequency and the antenna bandwidth is observed because of the change in the near field properties of the antenna when the superstrates is added. To further illustrate the effect of superstrate on the antenna gain, a comparison of the far-field radiation patterns is provided in Fig. 4(a). The overall pattern shape before and after the addition of superstrates are identical showing that the principle $E$-plane of the antenna array is not disturbed. Finally, Fig. 4(b) provides the efficiency of the antenna before and after the addition of the superstrates.

![Figure 3](image_url)

Figure 3: (a) Top view of a conventional $4 \times 1$ microstrip antenna array with $L = 36$ mm, and $X_1 = 24.5$ mm. (b) A snapshot of the magnetic field vectors plotted on a surface at the superstrate location when the superstrate is removed. (c) The return loss and gain of the microstrip antenna array before and after using the artificial magnetic superstrate.
A 10% increase in efficiency shows that the losses due to surface waves are somehow reduced. This can be understood by considering the inherent anisotropy of the band gap structure.

4. CONCLUSION
A magneto-dielectric superstrate constructed by split-ring-resonators is used with a $4 \times 1$ linear microstrip array to enhance its far-field properties. The distance between the patches and the superstrates is optimized to achieve a gain enhancement of about 3.5 dB. The antenna properties such as radiation patterns and the return loss characteristics are not significantly affected by the superstrates. However, there is an improvement in efficiency of about 10%. An overall profile of $\lambda_o/7$ resulted when the superstrates is added, which is appreciably better than the other techniques of gain enhancements such as EBG based superstrates.

REFERENCES