Enhanced-Gain Microstrip Antenna Using Engineered Magnetic Superstrates

Hussein Attia, *Student Member, IEEE*, Leila Yousefi, Mohammed M. Bait-Suwailam, Muhammed S. Boybay, and Omar M. Ramahi

***Abstract*—This letter presents a novel engineered magnetic superstrate designed to enhance the gain and efficiency of a microstrip patch antenna without any substantial increase in the profile of the whole structure (the antenna with the superstrate). The modified split ring resonator (MSRR) inclusions are used in the design of the engineered magnetic superstrate. Numerical full-wave simulations as well as analytical models are used to analyze the entire radiating system. Considering as an example a microstrip antenna operating within the UMTS band, the broadside gain of the antenna was improved by 3.4 dB and the efficiency was improved by 17% when using the engineered superstrate. The total height of the proposed structure, antenna with superstrate, is $\lambda_0/7$, where λ_0 is the free-space wavelength at the resonance frequency of the antenna.**

***Index Terms*—Engineered magnetic materials, engineered superstrate, metamaterials, microstrip antenna, modified split ring resonator (MSRR).**

I. Introduction

RECENTLY, it was shown that using magneto-dielectric materials instead of dielectrics with high permittivity offers many advantages in an important class of electromagnetic applications [1], [2]. Magneto-dielectrics are materials that can be polarized both electrically and magnetically when exposed to an applied electromagnetic field, so they have both relative permeability and permittivity higher than 1.

When nonmagnetic superstrates are used for gain enhancement, the thickness of the superstrate should be about half of the wavelength in the media [3]. Using magneto-dielectric materials as the superstrate decreases the wavelength in the media, leading to a lower profile. However, in the microwave regime, natural magnetization cannot occur in materials due to the inertia of atomic system that is not able to track an electromagnetic field with high frequency. Therefore, artificial magnetic materials, which represent a branch of metamaterials, are designed to provide magnetic properties that do not exist in natural materials [4], [5].

Previous trends to enhance the gain of planar antennas include the use of nonmagnetic dielectric [3] or electromagnetic band-gap (EBG) structures [6], [7] as a superstrate. However, all these trends require fairly thick layers, leading to a significant increase of antenna profile. In [2], the potential application of magneto-dielectric materials as a superstrate to improve the gain of microstrip antennas was investigated without considering physical realization of the artificial superstrate. Latrach *et al.* [8] used a split ring resonator (SRR) inclusion to provide a negative effective permeability at the resonance frequency of the antenna without investigating the effect of the permittivity of the superstrate.

In this work, a novel engineered magnetic superstrate using modified split ring resonator (MSRR) inclusions is designed for gain enhancement of microstrip patch antennas. The MSRR unit cell is designed to have *positive* values for the effective permeability and permittivity at the resonance frequency of the antenna. The designed superstrate along with the patch antenna is numerically simulated, and the effect of superstrate on gain, bandwidth, and efficiency of the antenna is investigated.

II. Artificial Magnetic Superstrate With MSRR Inclusions

The MSRR unit cell acting as the building block of the artificial magnetic superstrate is shown in Fig. 1(a). The MSRR inclusion consists of two parallel broken square loops. The host dielectric is made of Rogers RO4350 with a thickness of 0.762 mm, relative permittivity of $\varepsilon_r = 3.48$, and loss tangent of $\tan\delta = 0.004$. A planar 10×10 array of MSRRs was printed on the host dielectric layer to provide the engineered magnetic material. The superstrate used here consists of three layers of printed magnetic inclusions. The layers are separated by 2 mm of air layers [see Fig. 1(c)].

The MSRR unit cell is analytically modeled by obtaining its effective relative permeability as [4], [5]

$$\mu_{r_{\rm eff}} = 1 - \frac{j\omega L_{\rm eff} S}{\Delta x \Delta z (R_{\rm eff} - \frac{1}{\omega C_{\rm eff}} + j\omega L_{\rm eff})} \qquad (1)$$

where S is the surface area of the inclusion ($l_x \times l_y$), Δx and Δz are the unit cell sizes in x- and z-direction as shown in Fig. 1(a). The dimensions of the designed MSRR unit cell are $\Delta x = \Delta y = 8.5$ mm, $\Delta z = 2.762$ mm, $lx = ly = 6.5$ 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 $R_{\rm eff}$, $C_{\rm eff}$, and $L_{\rm eff}$ can be found in [4].

Since the MSRRs are aligned in the xy-plane, the resultant effective enhanced permeability as given by (1) is provided only in the z-direction. Any incident magnetic field in the x- or y-direction will not couple to the MSRR inclusion, resulting in a permeability equal to that of free-space in those directions. Hence,

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The authors are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: h2attia@engmail.uwaterloo.ca; lyousefiz@gmail.com; mbaitsuw@uwaterloo.ca; msboybay@gmail.com; oramahi@ece.uwaterloo.ca).

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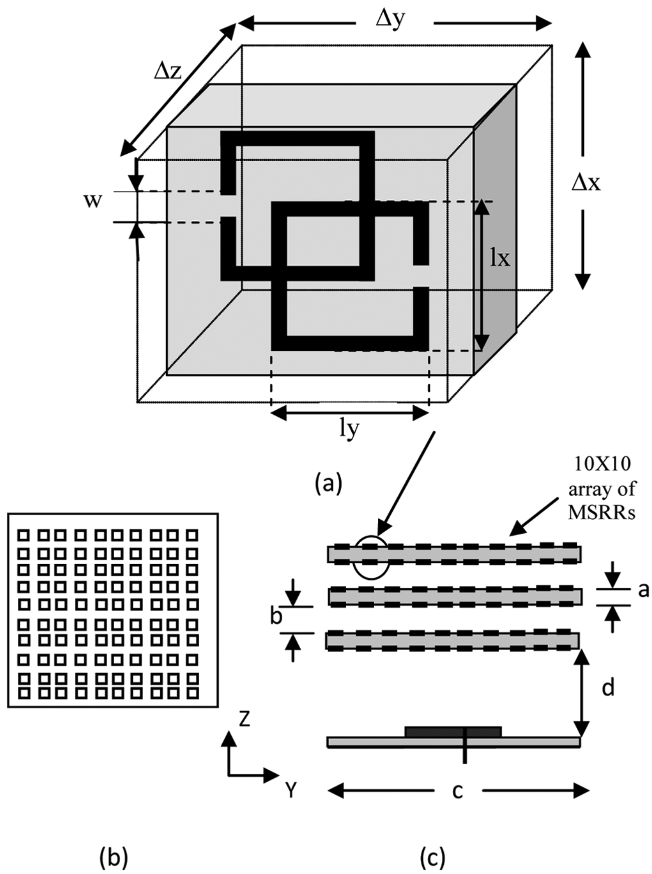

Fig. 1. Geometry of a patch antenna covered by an engineered magnetic superstrate. (a) MSRR unit cell. (b) Top view. (c) Side view ($\mathrm{a} = 0.762$ mm, $\mathrm{b} = 2$ mm, $\mathrm{c} = 85$ mm, and $\mathrm{d} = 12$ mm).

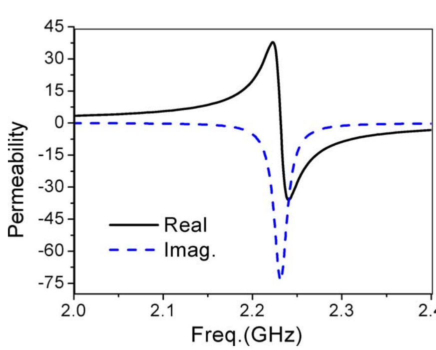

Fig. 2. Analytically calculated relative permeability of the MSRR inclusions.

the engineered material composed of the MSRR inclusions will experience the anisotropic permeability tensor of

$$\bar{\bar{\mu}} = \mu_o \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \mu_{r_{\rm eff}} \end{bmatrix}. \tag{2}$$

The analytically calculated effective relative permeability is shown in Fig. 2.

Intercell capacitors are formed in the gap regions between the metallic inclusions (unit cells) due to the incident x-directed electric field. Therefore, an effective x-directed permittivity is provided by the stored electrical energy in those intercell capacitors given by [1]

$$\varepsilon_{r_{\rm eff}} = \varepsilon_{r_{\rm diel}} \left[1 + \frac{\Delta z l_x}{\Delta x \Delta y} \frac{K(\sqrt{1-g^2})}{K(g)} \right] \tag{3}$$

$$g = \frac{\frac{s}{r}}{\frac{s}{2}+w}, \; K(g) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1-g^2 \sin^2\theta}}. \tag{4}$$

The same phenomenon is observed for a y-directed incident electric field. However, in case of a 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. Therefore, the artificial magnetic material composed of the MSRRs inclusions will experience anisotropic electric permittivity of

$$\bar{\bar{\varepsilon}} = \varepsilon_o \begin{bmatrix} \varepsilon_{r_{\rm eff}} & 0 & 0 \\ 0 & \varepsilon_{r_{\rm eff}} & 0 \\ 0 & 0 & \varepsilon_{r_{\rm diel}} \end{bmatrix}. \tag{5}$$

According to the above formulas, the effective relative permittivity of the designed structure in the x- and y-direction would be equal to 5.62.

III. Artificial Magnetic Structure as a Superstrate for Planar Antennas

The MSRR unit cell characterized in the previous section acts as a building block for an artificial magnetic superstrate as shown in Fig. 1(c) to improve the gain of a microstrip antenna. The patch antenna used here has dimensions of 36 mm × 36 mm and is printed on a substrate of Rogers RO4350 having a relative permittivity of 3.48, loss tangent of 0.004, and a thickness of 0.762 mm. This antenna is designed to operate at the frequency band of 2190–2210 MHz (which is very close the downlink band of UMTS) at which the magnetic superstrate has an effective permeability of about 15 (real part) and a magnetic loss tangent of 0.11 (see Fig. 2). Note that with a slight change in the patch size, the resonance frequency can be shifted for specific design requirements.

The full-wave electromagnetic simulation tool CST was used to simulate the proposed antenna shown in Fig. 1(c). Fig. 3 shows the magnetic field vector generated by the antenna and plotted on a surface at the superstrate location when the superstrate is removed. As shown in this figure, the dominant component of the magnetic field vector lies in the z-direction. Therefore, the superstrate with permeability tensor shown in (2) is suitable for gain enhancement of this antenna.

The distance between the patch antenna and superstrate was optimized numerically using CST to achieve the highest possible gain. Fig. 4 shows the return loss of the microstrip antenna before and after using the artificial magnetic superstrate at the optimized distance of 12 mm from the substrate. The overall profile of the structure is only $\lambda_o/7$, where λ_o is the free-space wavelength at the resonance frequency. As shown in Fig. 4, the antenna impedance bandwidth ($S_{11} < -10$ dB) and the resonance frequency of 2.2 GHz are practically unchanged when using the metamaterial superstrate in comparison to the case without superstrate. (The bandwidth of the proposed antenna

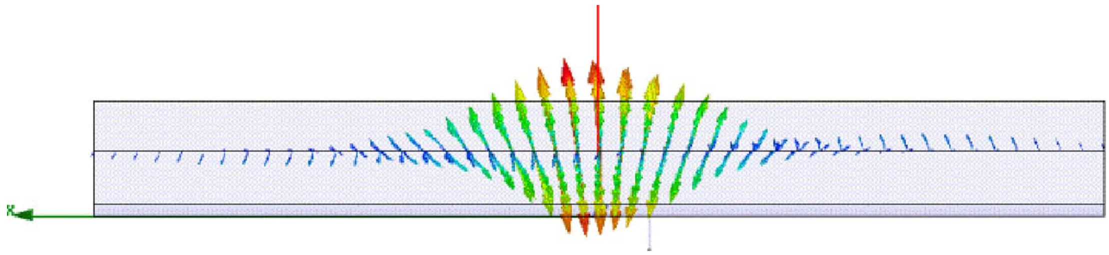

Fig. 3. A snapshot of the magnetic field vectors plotted on a surface at the superstrate location when the superstrate is removed.

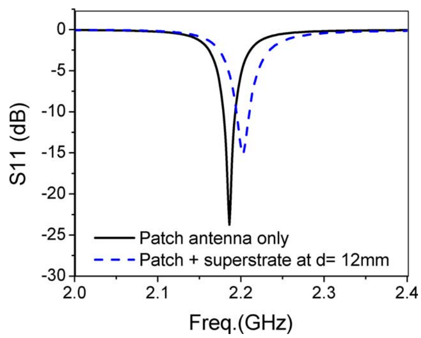

Fig. 4. The return loss of the microstrip antenna before and after using the artificial magnetic superstrate.

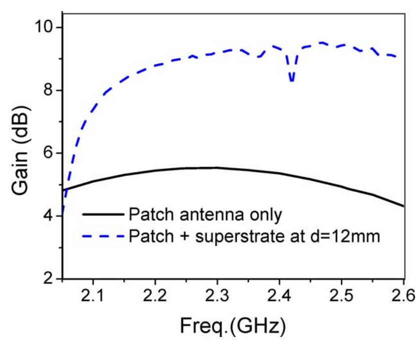

Fig. 5. The gain of the microstrip antenna before and after using the artificial magnetic superstrate for different distances between the antenna and superstrate.

is less than 1% and therefore smaller than that required for the mentioned downlink UMTS application. Note that the substrate considered here was chosen to be that of a commercially available board. In fact, a slight increase of the substrate thickness can easily broaden the bandwidth.) We note that the feed location had to be changed after using the superstrate due to the loading effect of the superstrate.

Fig. 5 shows the gain of the microstrip antenna before and after using the artificial magnetic superstrate. The gain is improved by 3.4 dB at the resonance frequency after using the engineered superstrate.

Figs. 6 and 7 show the radiation patterns (E-plane and H-plane) at the resonance frequency (2.2 GHz) of the patch antenna before and after using the engineered magnetic superstrate; the gain of the antenna in the broadside direction is enhanced by 3.4 dB. In the E-plane pattern shown in Fig. 6, the 3-dB beamwidth for the patch antenna only is 80°, compared to 57° for the patch antenna covered with the superstrate. The reduction in the 3-dB beamwidth is an indication of the improved

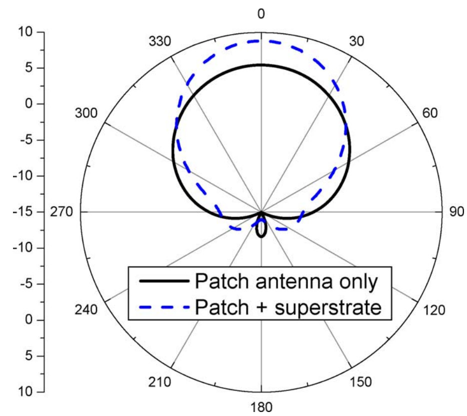

Fig. 6. The radiation pattern (E-plane, $\varnothing = 0$) at 2.2 GHz of the patch antenna before and after using the engineered magnetic superstrate at $d = 12$ mm.

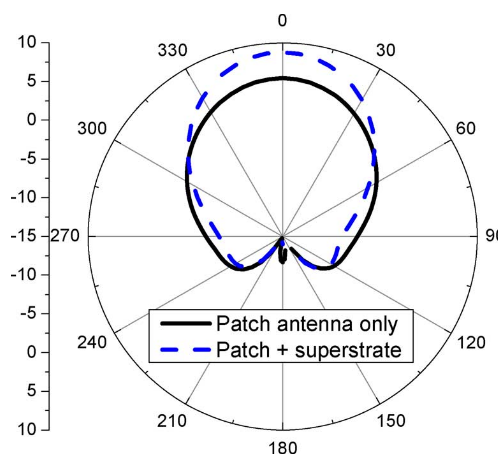

Fig. 7. The radiation pattern (H-plane, $\varnothing = 90$) at 2.2 GHz before and after using the engineered magnetic superstrate at $d = 12$ mm.

directivity in the broadside direction and the sharpening of the radiation pattern's main lobe.

Fig. 8 shows the radiation efficiency of the microstrip antenna before and after using the artificial magnetic superstrate; it is clear that the radiation efficiency of the antenna has been improved over the relevant range of frequencies. Notice that the radiation efficiency is increased by 17% at the resonant frequency once the superstrate is used.

The artificial magnetic material structure results in an enhancement of both permittivity and permeability. To investigate the impact of the permeability on the gain enhancement, a comparison is made with a structure having the same stack up and

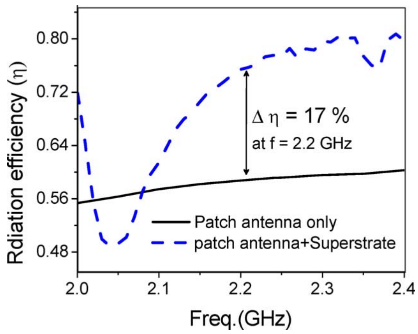

Fig. 8. The radiation efficiency of the microstrip antenna before and after using the artificial magnetic superstrate.

TABLE I
PERFORMANCE OF THE ANTENNA WITH THE MAGNETIC SUPERSTRATE AT THE RESONANCE FREQUENCY OF 2.2 GHz FOR DIFFERENT PANEL SIZES (L IS THE PATCH ANTENNA SIZE)

Panel size	Gain (dB)	Efficiency (%)
4X4 array (0.9 *L*)	6.3	65
6X6 array (1.4 *L*)	7.2	69
8X8 array (1.9 *L*)	8.15	74
10X10 array (2.3 *L*)	8.8	76
12X12 array (2.8 *L*)	9.14	73

dimensions of Fig. 1(c) using a dielectric substrates with permittivity of 5.62 and permeability of 1. Our numerical study shows that the resultant gain for this structure is 6.36 dB at the resonance frequency of 2.2 GHz, compared to 8.8 dB in the case when using the engineered superstrate. Therefore, the effect of permeability on gain enhancement is an increase of 2.44 dB.

The effect of the superstrate's panel size on the antenna performance is presented in Table I. As the panel size increases, the gain increases (notice that as the panel size increases, the effective aperture of the antenna increases, hence the increase in the gain and efficiency). To avoid enlarging the antenna size, we have chosen a panel size of 10×10 array to consider here as it is approximately 2.3 times the patch size.

IV. CONCLUSION

An engineered superstrate was introduced for gain and efficiency enhancement of low-profile antenna. The engineered superstrate based on the MSRR was analytically designed and characterized. The patch antenna covered with the engineered superstrate was numerically investigated and compared to the case of patch without superstrate. It was shown that for a patch antenna resonating at 2.2 GHz, using the engineered magnetic superstrate results in a 3.4-dB enhancement in gain and 17% enhancement in efficiency while maintaining an antenna profile of $\lambda_o/7$, where λ_o is the free-space wavelength at the resonance frequency. These improvements were achieved while having an insignificant effect on the impedance bandwidth of the antenna.

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