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Broadside Radiation Enhancement Using a Spiral Resonator MNZ Metamaterial Substrate

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Introduction

Artificial Magnetic Materials (AMMs or metamaterials) are artificial engineered materials composed of periodic metallo-dielectric inclusions which may offer unusual and interesting properties. In particular, the same structure can present different electromagnetic behaviors depending on the frequency range of operation due to its peculiar dispersion characteristics. One remarkable property is the creation of highly directive beams from simple sources, such as dipoles or slots, placed inside such metamaterial substrates.

For instance, a metal backed wire-medium slab excited by an electric dipole source has recently proposed as a leaky-wave antenna with enhanced broadside radiation [1]-[2]. This phenomenon was due to the Epsilon-Near-Zero (ENZ) property of the wire medium, which, in a suitable frequency range and for particular polarizations, can be characterized by an effective relative permittivity $0 < \mathrm{Re}[\varepsilon_r] << 1$.

Metamaterial slabs composed of magnetic resonators such as loops, spirals or split-ring resonators (SRRs) are often used for their pass-band/stop-band properties. In fact, in the presence of large values (or even negative values) of the effective magnetic permeability, a wave impinging on such structures experiences a strong reflection. However, AMMs can also offer a Mu-Near-Zero (MNZ, i.e., $0 < \mathrm{Re}[\mu_r] << 1$) band of operation, which can be of interest in broadside radiation enhancement [3]. Several design guidelines have been presented in [3], in order to obtain a grounded metamaterial slab for enhanced broadside radiation, by either using an ENZ or an MNZ substrate, that correspond to high and low impedance substrates, respectively.

We consider here an infinite grounded MNZ slab of thickness h and excited by a magnetic dipole placed on the ground plane (e.g., a thin slot cut in the ground). The power density radiated at broadside ($\theta = 0^\circ$) can be expressed as [3]:

$$P_M(0) = \frac{k_0^2}{8\pi^2\eta_0} \frac{1}{\left|\cos(k_1 h) + j\eta_r \sin(k_1 h)\right|^2} \tag{1}$$

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where $k_1 = k_0 n_r = k_0 \sqrt{\mu_r \varepsilon_r}$ and $\eta_r = \sqrt{\mu_r / \varepsilon_r}$. It is worth noting that, when the slab thickness is chosen as $h_{\mathrm{opt}} = \lambda_l/4$ (with $\lambda_l = \lambda_0/n_{\mathrm{r}}$), the broadside power density is maximum.

A power enhancement factor $E_{P,M}$ can be defined as the ratio between the broadside power density radiated in the presence of the grounded slab $P_M(0)$ and that radiated in free space $P_{M,0}(0)$. It can easily be shown that, under the optimum condition $h = h_{\mathrm{opt}}$, it results $E_{P,M} = 4/\eta_r^2$, which can thus be maximized with a low-impedance substrate (e.g., an MNZ substrate). For the suboptimal case ($h < h_{\mathrm{opt}}$), the enhancement factor can be expressed as:

$$E_{P,M} = \frac{P_M(0)}{P_{M,0}(0)} = \frac{\dfrac{k_0^2}{8\pi^2\eta_0} \dfrac{1}{\left|\cos(k_1 h) + j\eta_r \sin(k_1 h)\right|^2}}{\dfrac{k_0^2}{32\pi^2\eta_0}} = \frac{4}{\left|\cos(k_1 h) + j\eta_r \sin(k_1 h)\right|^2} \tag{2}$$

MNZ metamaterial substrate design

In order to obtain an MNZ substrate, a metamaterial slab composed of square spiral resonators printed on RO4003C strips is considered [4]-[5]. The *xyz* unit-cell dimensions are 4×6×6 mm^3, being 6 mm the thickness of the metamaterial slab and 5.6 mm the width of the spiral resonator. The gap between adjacent layers of spirals is 4 mm. In the simulations, the incident electric field is linearly polarized along +*y* axis, this is, parallel to the dielectric strips which contain the spiral resonators. When used as a reflector, the metamaterial slab is operating around 2.6 GHz (close to the resonance). This can clearly be seen by observing the effective parameters (extracted according to the Nicolson-Ross-Weir formulas [6]) in Figure 1. In particular, the effective permeability μ_{r} shows a resonance at 2.58 GHz (Figure 1*a*). It can be observed that the MNZ band starts at 3.74 GHz (where Re[μ_{r}]= 0) up to 6.65 GHz (where Re[μ_{r}] = 1).

It should be noted that for very low values of Re[μ_{r}], the optimum thickness of the slab can be very large. The metamaterial slab we can build is only 6 mm thick, so it is expected that the excited leaky waves be not dominant since the structure operates under suboptimal conditions. However, by plotting the power enhancement factor as a function of frequency using the extracted effective medium parameters, a peak occurs around 5.5 GHz for the 6 mm thick slab, as shown in Figure 2.

Fabrication and Measurements

In order to verify the previous results, a preliminary example of a magnetic dipole has been fabricated on a $2\lambda_0 \times 2\lambda_0$ metal ground plane. The dimensions of the slot are 29×2 mm^2, and it is tuned around 5 GHz. The performance of the antenna has been tested with and without the square spiral MNZ substrate. A photo of the slot on the ground plane and a detail of the MNZ metamaterial slab are reported in Figure 3.

Complete radiation patterns have been measured in the anechoic chamber. The measured E- and H-plane patterns of the slot with and without the MNZ metamaterial substrate are shown in Figure 4. It can be observed that an enhancement of broadside radiation is achieved at 5.7 GHz. In particular, the directivity in the E plane has significantly increased, whereas the H-plane pattern is weakly affected by the MNZ slab. The slot itself has a directivity of 8.57 dB, whereas the directivity of the slot in presence of the MNZ substrate is 9.73 dB.

Conclusions

The broadside power radiation enhancement has been tested for the case of a magnetic dipole in presence of an MNZ metamaterial substrate. In order to assess the theoretical estimations, a slot antenna on a ground plane has been fabricated and an AMC composed of 1 layer square spiral resonators has been used as an MNZ metamaterial slab. The radiation patterns have been measured in the anechoic chamber, achieving a gain in directivity of more than 1 dB. However, it should be taken into account that the thickness of the fabricated metamaterial slab (6 mm) is much smaller than the theoretical optimum thickness (hundreds of mm). The directivity of the antenna might be improved when increasing the number of layers of the metamaterial slab; in fact, in such a case, the leaky waves responsible of directive radiation are expected to be more significantly excited giving rise to the sought broadside power enhancement.

Acknowledgements

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Figures

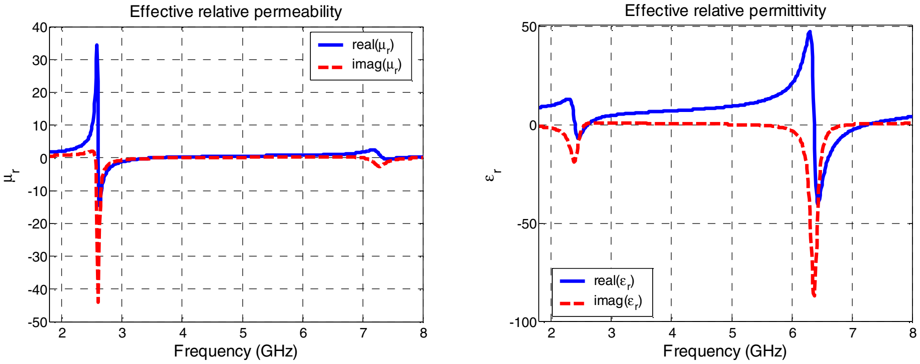

Figure 1: Extracted effective relative permeability (left) and permittivity (right).

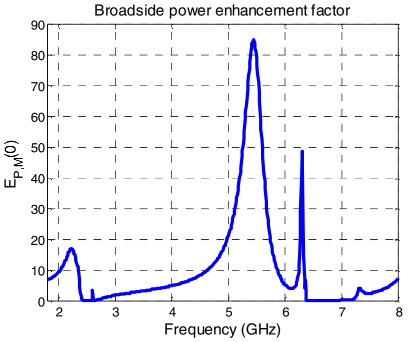

Figure 2: Broadside power enhancement factor computed using (2).

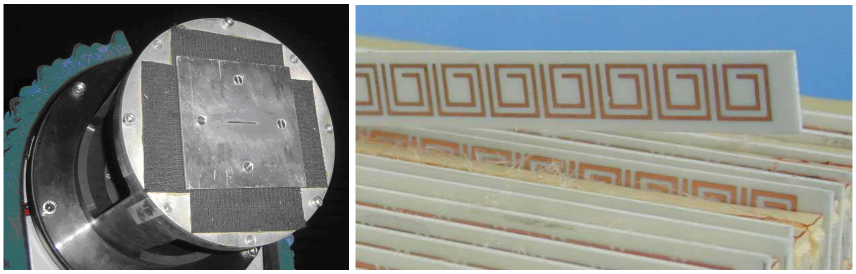

Figure 3: Slot on the ground plane (left) and a detail of the square spiral MNZ metamaterial slab (right).

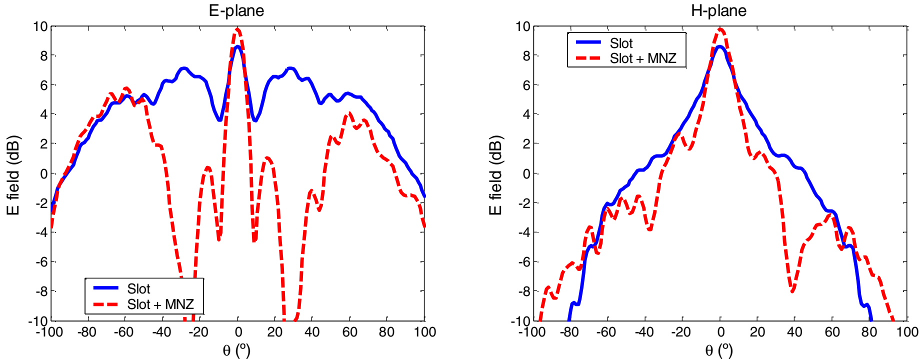

Figure 4: E- and H-plane electric-field patterns radiated by the slot with and without the MNZ metamaterial substrate.