Progress In Electromagnetics Research, PIER 64, 43–51, 2006

A NOVEL AMC WITH LITTLE SENSITIVITY TO THE ANGLE OF INCIDENCE USING 2-LAYER JERUSALEM CROSS FSS

M. Hosseini, A. Pirhadi †, and M. Hakkak†

Iran Telecommunication Research Center (ITRC)
P.O. Box 14155-3961, Tehran 14399, Iran

Abstract—A novel artificial magnetic conductor (AMC), i.e., high-impedance surface (HIS), is proposed. The structure, which utilizes the well know Jerusalem Cross Frequency Selective Surface (JC-FSS), is a novel 3D AMC. It offers stable resonance frequency with respect to the incidence angle of both TE and TM-polarized plane waves, very compact size and acceptable bandwidth.

1. INTRODUCTION

AMCs, behaving as perfect magnetic walls at resonance [1], are widely studied as prospective antenna substrates [2]. Recently, electromagnetic bandgap (EBG) structures have been widely studied for their behavior as AMC. Principally, they show stop band frequencies in which the tangential magnetic fields are considerably reduced. AMC is a special member of HIS family, which is designed to imitate the behavior of a Perfect Magnetic Conductor (PMC). In fact, the AMC condition is characterized by the frequencies where the magnitude/phase of the reflection coefficient ($|\Gamma|/\angle\Gamma$) is $1/0°$ [5]. In contrast, a HIS may deviate a little from this condition, sometimes yielding more flexibility in antenna design. For example, in [3], the mushroom-like EBG structure plays the role of a ground plane for a dipole antenna a little lower than its resonance or AMC condition. Besides, in [12] the behavior of the same structure as a reactive impedance surface (RIS) is introduced, and the idea is applied to patch and dipole antennas. Although it has been shown that AMCs improve antenna performance and reduce the effects of surface waves [3], there

† Also with Electrical Engineering Department, Tarbiat Modares University, Tehran, Iran

is however a problem with most of proposed AMCs. The shift of the resonance frequency versus the incidence angle affects the performance of most well known AMCs [4]. If the frequency bandwidth of low-profile antennas, placed near a particular AMC, is within the resonance band of AMC, a significant improvement in radiation efficiency is expected. However, the improvement is not always as much as desired. An explanation for this behavior is that the AMC does not exhibit uniform surface impedance with respect to the large angular spectrum of TE and TM-polarized plane waves radiated by an antenna [2, 4]. Therefore, it is expected that an AMC with high degree of stability against incidence angle be able to improve the antenna performance more than a usual AMC. [8] explicitly satisfies this expectation by analyzing a dipole antenna near an angularly stable AMC and showing a considerable improvement in the antenna performance. Considering the statements above, this letter tries to attack the problem of angular sensitivity in AMCs and like [2, 4–10] presents a design for angularly stable AMCs. It must be noted that the applications of a full-angle HIS/AMC are not limited to just antenna design. For example, in [13] (also pointed out in [4]), the application of such an AMC, in designing co-planar isolators, is investigated. In order to analyze the scattering properties of the structures Ansoft's Designer software, which is an electromagnetic solver based on the Method of Moments (MoM) is used. It incorporates the Floquet's theory into MoM (PMM [5]) for analyzing planar periodic structures. Besides, it has the ability to evaluate periodic structures in all directions of plane-wave incidence, as required in this research.

2. THE MAIN IDEA

In [4], it is analytically demonstrated that the resonance frequency (f_r) of a planar AMC made of a FSS placed on a PEC backed dielectric slab is independent of incidence angle, subject to the following conditions:

I. the FSS is a closely coupled (period$\ll \lambda$) self-resonant grid (SRG), like JC-FSS, with the circuit model of Fig. 1(d).

II. the dielectric slab does not contain vias.

III. the dielectric slab is thin, i.e., $k_d h \ll 1$, where $k_d = \omega\sqrt{\mu_0\varepsilon_0}\sqrt{\varepsilon_r}$, h is the thickness and ε_r is the permittivity factor.

IV. the period is comparable to h, i.e., it is not very larger than h. The condition guarantees the credibility of the circuit model, thus can be regarded as a supplement for the condition (I).

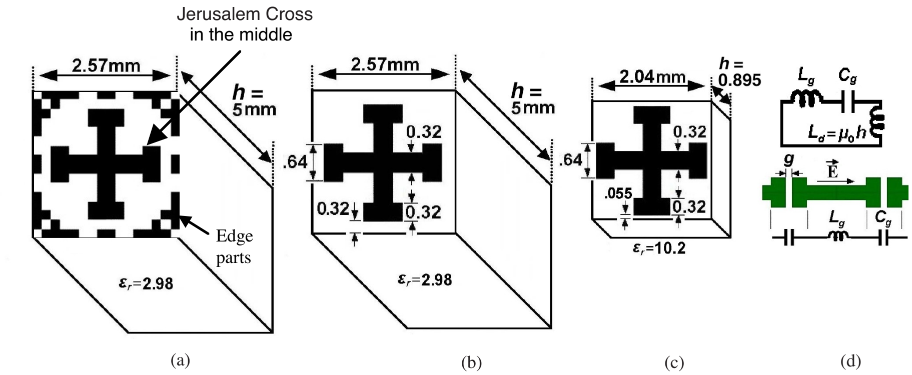

Figure 1. The unit cell, (a) GA-designed broadband AMC [5], (b) the initial broadband JC-based AMC extracted from Fig. 1(a), (c) the initial AMC after optimization for angular stability, (d) the equivalent circuit model (all dimensions are in millimeters).

For such a structure, f_r can be written as [4, 7]:

$$f_r^{TM} = f_r^{TE} = 1/2\pi\sqrt{C_g(\mu_0 h + L_g)} \tag{1}$$

Where $\mu_0 h$ is the inductance of the PEC-backed dielectric slab. Also, the bandwidth can be written as [7]:

$$BW \propto \sqrt{(\mu_0 h + L_g)/C_g} \tag{2}$$

Therefore, by providing the conditions (I–IV), the improvement in angular stability can be expected. It is noted that fortunately, achieving compact size is a by-product of angular stability because the condition (I) spontaneously causes some cell reduction.

We begin with the AMC structure in Fig. 1(a), which has been optimized by Genetic Algorithm (GA) to have very broadband characteristic [5], which its properties are listed in Table 1 as Result 1. At the first glance, a JC-FSS is recognized in the middle of the cell. Keeping just the JC-FSS and removing the perimeter parts highlighted in Fig. 1(a), while all other parameters are kept fixed, a new cell, shown in Fig. 1(b), is obtained. The resonance frequency of this AMC is the same as that of Fig. 1(a), 8 GHz. Note that in [5], the usable bandwidth is taken to be where, in normal incidence condition, for the phase of the reflection coefficient we have $|\angle\Gamma_{\mathrm{TE,TM}}| < 90°$. Accordingly, the percent bandwidth for Fig. 1(a) is reported as 67.2% at 8 GHz. However, if we use $|\angle\Gamma_{\mathrm{TE,TM}}| < 45°$ criterion for bandwidth, as in

[6], the bandwidth of Fig. 1(a) at 8 GHz is about 32%. Based on the same criterion, the bandwidth for Fig. 1(b) is about 27%. As seen, the decrease in bandwidth is little, and so a broadband AMC composed of JC-FSS placed on a dielectric slab backed by a PEC is available. Hereafter, this AMC is referred to as JC-based AMC. Result 2 in Table 1 gives the relevant properties. It worths noting that due to being broadband, this initial AMC design lets us much tolerate the deterioration of BW when h is reduced during the optimization. In the following, we try to provide the rendered stability conditions for this AMC in order to improve its angular stability.

3. IMPROVING ANGULARLY STABILITY FOR JC-BASED AMC

In an attempt to satisfy the stated stability conditions for the AMC in Fig. 1(b), this AMC is optimized under the following circumstances:

- Optimization objectives: period $< \lambda/10$, $k_d h \ll 1$, period $< 0.3h$, bandwidth $(BW) > 7\%$, and angular stability up to incidence angle of 75°
- Optimization variables: h
- Optimization constants: dimensions of JC-FSS (see Fig. 1(b)), ε_r(=10.2), and the gap size ($g = 0.11$ mm, see Fig. 1(c) and (d)). It is noted that for JC-FSS, the less the gap size is, the more C_g [4]. Based on the Equation (1), the more C_g is, the less f_r and the period. Therefore, the stability conditions, (I) and (III) are better satisfied. Accordingly, g is chosen to be the smallest size that can easily be constructed in practice, 0.11 mm.

Table 1. Scattering and physical properties of the AMCs under study.

	Result 1 [5]	Result 2	Result 3	Result 4	Result 5
Resonance frequency, GHz	8	8	14.0	9.73	6.28
Cell size, mm	2.57(λ/14.6)	2.57 (λ/14.6)	2.04 (λ /10.5)	2.04 (λ/15.1)	2.04 (λ /23.5)
Dielectric permittivity constant	2.98	2.98	10.2	10.2	25
Substrate thickness, mm	5 (λ/7.5)	5 (λ/7.5)	0.895 (λ/24)	.995 (λ /31)	.995 (λ/48)
Bandwidth, % ($\lvert\angle\Gamma\rvert < 45^{\circ}$)	32	27	7.8	6.8	4.3
Angular stability, deg	---	---	74	79	77

The properties of the optimized AMC are shown in Table 1 as Result 3. For more details on the optimization and design procedure, the reader is referred to [7]. It is highlighted that here, two conditions are considered as the angular stability criteria; First, $|\angle\Gamma_{\mathrm{TE,TM}}| < 45°$ [5, 6], and second, $|\Gamma_{\mathrm{TE,TM}}| < 0.8$ [10], which is a supplementary condition to avoid much decrease in $|\Gamma|$ occurring at large incidence angles, especially for TE modes (e.g., see Fig. 5). Both conditions must be satisfied at f_r. It must be noted that when a plane wave (P_{inc}) impinges an AMC cell, no power can infiltrate the AMC backside because the infinite PEC under the dielectric blocks the energy. This is the condition happens when the cell is modeled by Ansoft's Designer or other softwares using Floquet's theory. Under this condition, having $|\Gamma| < 1$ means that some of the power $((1-|\Gamma|^2) \times P_{inc})$ is not reflected by the AMC structure and flows as surface wave sidewards. In antenna applications, for example, where a limited number of these AMC cells (normally, $N = 8 - 10$, e.g., see [1,3]) are used as the antenna ground plane, the surface wave radiates at sides of the ground plane and illuminates the antenna backside; Hence, the antenna gain and F/B ratio are degraded [1]. For this reason, in this work, not only $\angle\Gamma$ but also $|\Gamma|$ is watched during the design procedure.

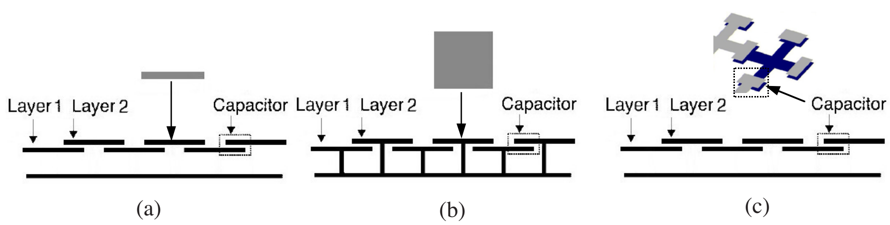

Figure 2. Improving the capacitive coupling for, (a) CCMEBG structure [11], (b) mushroom like EBG structure [1], (c) 2-layer JC-based AMC structure presented in this paper.

In the next step, to improve the capacitive coupling ($C_g\uparrow$) of the optimized JC-based AMC again, a scheme like what used for the Closely Coupled Metallo-dielectric Electromagnetic Band-Gap (CCMEBG) structure [11] is applied as depicted in Fig. 2(a). Also, as in Fig. 2(b), a similar idea is used for the 2-layer mushroom like EBG structure presented in [1]. As shown in Fig. 2(c) and Fig. 3, an extra thin dielectric layer is put over the preceding AMC while the dimensions of JC-FSS are kept fixed. Besides, the capacitive edges of two adjacent JC-FSS overlap. In fact, this scheme changes the coplanar capacitor of the usual JC-FSS to a parallel plate capacitor, and therefore, improves the capacitive area while needing less space, as

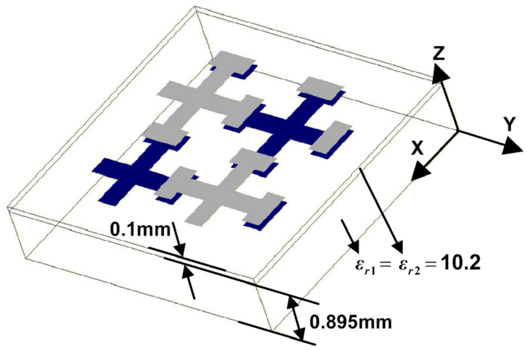

Figure 3. The unit cell geometry for the novel 2-layer JC-based AMC.

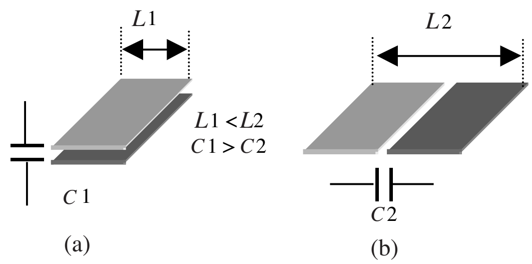

Figure 4. Comparison between the capacitance and the required space for (a) parallel plate capacitor, (b) coplanar capacitor.

depicted in Fig. 4. The thinner the thickness of the upper layer is the larger C_g. Considering practical constraints, this thickness is chosen to be 0.1 mm. Also, ε_r is chosen to be the same as that of the lower layer, 10.2. Note that on the one hand (1) implies that the more C_g, the less f_r. On the other hand, as deduced from the stability conditions, the less f_r, the better the conditions are satisfied. Therefore, we can expect that as a result of increasing C_g, the structure becomes more compact and more angularly stable. The values of $\angle\Gamma$ and $|\Gamma|$ for the resultant AMC versus incidence angle are shown in Fig. 5. Also, Table 1 lists the other corresponding properties as Result 4. As seen, compared to Result 3, we notice slightly improved angular stability, cell size reduction by 50% and thickness decrease by 30% ($\approx$300% decrease in the cell volume).

To verify the credibility of the circuit model in Fig. 1(d) and the related formulas, (1) and (2), for this new AMC, ε_r is increased from 10.2 to 25. The resultant properties listed as Result 5 in Table 1

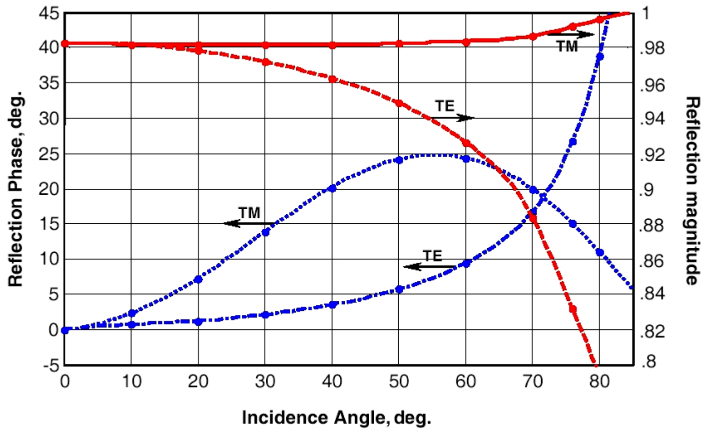

Figure 5. Reflection phase versus incidence angle for the AMC in Fig. 3.

are compared with Result 4 (for $\varepsilon_r = 10.2$). We observe that, with nearly the same angular stability, the f_r, cell size, thickness and BW are multiplied by $\sqrt{\varepsilon_{r1}/\varepsilon_{r2}} = 0.64$, i.e., we have $\approx 380\%$ decrease in the cell volume at the expense of $\approx 50\%$ decrease in BW. Note that because for the parallel plate capacitor we have $C_g \propto \varepsilon_r$, just the same behavior is predicted from the circuit model described by (1) and (2), i.e., f_r and BW are proportional to $1/\sqrt{\varepsilon_r}$. This exactly predictable behavior enables the designer to exchange BW for the cell size, and vice versa, depending on the application requirements.

4. CONCLUSION

The paper begins with extracting a broadband planar AMC made of JC-FSS from a GA-designed AMC. Afterwards, this AMC is optimized to improve angular stability making use of the relevant theoretical conditions presented in the literature. Finally, by skillfully adding an extra layer, a novel 3D AMC utilizing a 2-layer JC-FSS is obtained that yields smaller cell size and thickness with better angular stability.

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