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Enhancing the angular stability of artificial magnetic conductors through lumped inductors

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ABSTRACT

A novel method to efficiently improve the angular stability of AMCs is introduced. Aiming to obtain an AMC with fixed design specifications (resonance frequency, proper bandwidth, size limitations and specific dielectric), the method relies on increasing the grid inductance through the introduction of lumped inductors. To date, lumped capacitors and/or inductors have been used to decrease the unit-cell dimensions especially for applications below 1 GHz. However, to the author's knowledge their potential applications on angular stability enhancement have not been explored yet. The proposed method is applied to non-angularly stable AMC comprising square loop-based unit-cells on a RO4003C dielectric. The validity of the method is demonstrated not only through electromagnetic simulations but also using an equivalent circuit model which clearly explains the behavior of the AMC. Moreover, guidelines to choose a proper lumped inductance are given. At the end, a comparison with previous literature contributions shows the great potential of this method.

1. Introduction

Artificial magnetic conductors (AMCs) have been widely studied over the last years, mostly due to their applications on antennas: improving their radiation properties (efficiency and gain) and even their bandwidth [1–5] when arrange as antenna's ground plane. Moreover, miniaturizing the antenna profile can also be possible [6]. The radar cross section (RCS) reduction [7] is another potential application in fields like surveillance and sensing of people and/or objects. The decreasing of the specific absorption rate (SAR) for "weareable" devices [5,8] has a great impact in medical applications among others.

AMCs are two dimensional metamaterials (metasurfaces), commonly designed using a grounded metallo-dielectric frequency selective surface (FSS) [9,10]. An AMC exhibits in phase reflection for plane waves at its resonance frequency [11]. This phenomenon can be explained using the transmission line (TL) theory to model the structure. Doing so, the reflection coefficient of the AMC illuminated by a normally incident plane wave can be represented as [12]:

$$\Gamma(w, \theta, \phi) = \frac{Z_s(w, \theta, \phi) - \eta_0}{Z_s(w, \theta, \phi) + \eta_0} \quad (1)$$

where η_0 is the free space impedance and $Z_s(w, \theta, \phi)$ is the effective impedance of the structure, which varies with the frequency (w), polarization (ϕ) and incidence angle (θ) of the incident wave. Providing the periodicity of the structure is much smaller than the operational wavelength, this impedance can be represented as a parallel connection between the grid impedance and the metal-backed dielectric impedance (also known as grounded dielectric impedance) [13]. This reflection coefficient varies with frequency between $\pm180^\circ$ and crosses 0° at the resonance frequency. However, around this frequency the wave is reflected more in phase than out of phase. Thus, the AMC behavior is mostly considered to be within $\pm90^\circ$ in the reflection coefficient phase [5,11,13–15]. Although this is the bandwidth used in most of literature contributions, some applications require more restricted considerations [16,17].

A designer usually looks for a wide AMC's operation bandwidth over a large variety of polarizations and angles of incidence. Therefore, observing the expression (1) and taking into consideration the previous remarks, it is obvious that the main AMC's limitations are two: bandwidth and angular stability. Bandwidth constrains

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have been widely tackled in many articles using multiresonance structures [7,8,18,19]. Some solutions are to stack several layers [18] or using unit-cells with close resonances [7]. However, not so many contributions deal with the angular stability of AMCs [1]-[4,13,20–22], which will be the aim of this paper.

Using a non-angularly stable AMC as an antenna reflector can reduce the improvements on its performance, since different harmonics excited by the antenna impinge on the AMC at different angles. Thus, they are reflected with different phase values and hence, the contributions will not always be added constructively (in phase) [1–4]. Therefore, the improvement in the radiation efficiency is marginal, being mainly due to the suppression of surface waves rather than to the constructive interference contributions between the antenna and the AMC.

Theoretical basis for a uniaxial material which exhibits angular independence high impedance behavior over a wide range of frequencies are presented in [20]. However, it is not easily realizable for whatever polarization of the incident wave.

One of the first contributions on improving the angular stability of AMCs was carried out on [21]. It is known that vias only improve AMC's angular stability for TM polarization. Therefore, in [21] the duality principle is used introducing spiral elements which excite vertical magnetic current and produce the same effect for transverse electric (TE) polarization. In [4], several grids along with grounded dielectric slabs, with and without vias, are analyzed with the aim of finding the best combination that avoids angular dependence. As a conclusion, a series-resonant grid (SRG) (modeled as a series connection of an inductance (L_g) and a capacitance (C_g)) above a grounded dielectric slab without vias will be the best combination. Although analytically it seems to be no angular dependence, electromagnetic simulations differ mainly due to the approximations used to obtain the analytical models. In [1] authors gather the work done in [4] and summarize the requirements for an angularly independent AMC:

- The grid should be closely coupled (period $\ll\lambda$) and consist of a SRG.
- The dielectric slab have not to contain vias and must be thin ($k_d h \ll 1$), where $k_d = w\sqrt{\varepsilon_0 \varepsilon_r \mu_0}$ and h is the dielectric thickness.
- The period should be comparable with h. This is essential to model the structure using the expressions given in [4].

In [1], authors use a double layer Jerusalem cross, which increases the capacitive coupling between neighbor unit-cells. Therefore, the condition of closely coupled grid (first condition) is better fulfilled, improving the AMC's angular stability. In [2], a similar procedure is employed: the capacitance is increased due to both the shape of the unit-cell and the introduction of a double layer structure. However, in both articles double layer structures are used so that the thickness and the fabrication complexity are increased. Moreover, the study of the angular stability is performed at only one frequency. An array of one dimensional periodic wires distributed in a non-uniform way is used in [3] as a dipole antenna reflector, concluding that this non-uniform distribution improves the angular stability of the array and hence the performance of the antenna. Another study on the angular dependence of a perturbed array of dipoles is carried out in [23]. However, this structure only improves its performance for TE polarized incident waves. A more detailed angular stability analysis was carried out in [24] for AMCs based on an array of hexagonal as well as square dipoles.

On the other hand, the introduction of lumped components has been studied with the aim of miniaturizing AMCs [25], but no angular stability analysis has been tackled yet.

Although some breakthroughs have been introduced in the realm of AMCs' angular stability, there is still much work to do on this topic. Thus, the aim of this paper is to introduce a new idea for improving the AMCs' angular stability. As it was mentioned some papers tend to increase the coupling between neighbor unit-cells (increase the grid capacitance). However, to the authors' best knowledge there is no previous work analyzing the effect of altering the grid inductance. So this will be the focus of this contribution. Moreover, the advantages of tailoring the grid inductance are highlighted and compared with other contributions in which the angular stability is pursued.

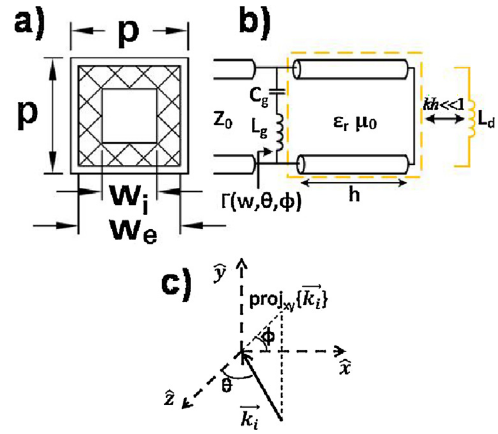

Fig. 1. (a) Geometry of LUC (*top view*). (b) Equivalent circuit model of LUC based AMC. (c) Coordinate system for angular stability analysis.

2. Description of the problem, designs and methodology

As it was pointed out in the introduction, this work aims to improve the angular stability of AMCs giving some guidelines to achieve it. The angular stability depends on both the dielectric (thickness and permittivity) and the grid characteristics (unit-cell's metallization geometry and size (periodicity) as compared to the dielectric thickness) of the AMC. Once the dielectric substrate and the unit-cell periodicity are fixed, both the angular stability and the AMC bandwidth only depend on the unit-cell's metallization geometry. It is well known that by increasing the substrate relative dielectric permittivity and/or reducing its thickness the angular stability is improved. However, whichever of these methods gives rise to a shift in the resonance frequency and a narrowing in the AMC bandwidth. Therefore, a trade-off solution concerning these two parameters must be adopted [13].

In this work both the dielectric substrate and the AMC unit-cell periodicity will be fixed and hence, conclusions regarding the unit-cell's metallization geometry influence on the angular stability will be obtained.

From previous works, it has been concluded that loop-based unit-cells are more angularly stable than patch-based ones [13]. In addition, the hexagonal-shaped unit-cells outperform the square-shaped ones as regards angular stability provided a proper gap distance between neighbor unit-cells is considered. Since the aim of this work is to obtain an effective method for improving the AMCs' angular stability, a unit-cell's metallization geometry from a non-angularly stable AMC is chosen. Therefore, the square loop-based unit-cell (LUC) of Fig. 1(a) is considered as a starting point. The geometry parameters of the LUC are as follows: $p = 7.3$ mm, $w_e = 6.3$ mm, and $w_i = 3.4$ mm. The dielectric substrate is a RO4003C ($\varepsilon_r = 3.38$ and loss tangent 0.0027) with a dielectric thickness of 1.524 mm.

The behavior of the LUC based AMC can be modeled by the equivalent circuit of Fig. 1(b). The grid impedance in this case is a series connection of a grid inductance (L_g) and a grid capacitance (C_g) as it has been explained in [26]. The grounded dielectric slab can be