Perfect Metamaterial Absorbers in the Ultra-High Frequency Range

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Abstract— Metamaterial absorbers synthesized by extremely-thin High-Impedance Surfaces (HIS) are analyzed by resorting to a simple transmission line model. The equivalent circuit representation, which takes into account also the high-order Floquet modes effects, allows to interpret the absorption properties of the analyzed structure and to derive closed form relations containing all the degree of freedom involved in the design. By exploiting the guidelines achieved from the circuitual analysis, a $h_0/108$ thick absorber operating within the UHF RFID frequency band has been designed and tested.

I. INTRODUCTION

An ultra-low profile electromagnetic absorber can be synthesized by printing a periodic frequency selective surface on top a thin grounded dielectric slab. The structure has a subwavelength profile and its resonance frequency is dictated by capacitive loading of the periodic surface. Such periodic structure is usually referred to as High-Impedance Surface (HIS) in microwave range [1], [2]. The resonant structure is able to perform perfect absorption at a single frequency or in a wide band. In order to perform the desired absorption the input impedance of the structure must be matched with the free space impedance [3]. To achieve this, a ohmic or dielectric loss component must be introduced in the subwavelength device. Losses in metamaterial has always been one the main limitation. In metamaterial absorbers losses are instead exploited (if you cannot get rid of it, try to exploit it). The suitable amount of losses depends on the thickness of the substrate and on the shape of the unit cell of the periodic pattern. Losses can be introduced in different ways: lumped resistors or resistive inks can be used to introduce ohmic losses in the periodic pattern. This configuration allows to design narrowband and wideband absorbers [4]-[8]. Alternatively, if the dielectric slab is ultra-thin a perfect absorption can be achieved within a narrow frequency band by simply exploiting the intrinsic loss factor of commercial substrates. While the former structure has been extensively studied and employed in microwave, the latter configuration is instead more frequently studied within THz gap and optical range by physicist and it is called Perfect Metamaterial Absorber [9]. The word ‘perfect’ is used since the structure is able to absorb incoming signals not only at normal incidence but also at very off-normal angles. The working principle of this structure is usually explained by recurring to complex effective medium parameters $\varepsilon$ and $\mu$ but an engineering approach based on a circuit model allows to interpret the absorber in a more classical and intuitive way [3]. The interest on so-called metamaterial absorbers has grown up in the last years since their properties have been discovered useful for several applications in very different scenarios and frequency range. Moreover these absorbers are low-cost and simple to manufacture. At microwaves for example they could be employed for improving the readability within RFID portals [10], for power imaging purposes [11], to improve the electromagnetic compatibility of electronic devices [12] or as Chipless Radio Frequency Identification tags [13]. In the THz range they are used in photodetectors or microbolometers [14], [15] and phase modulators [16]. In optical regime they could be potentially employed as thermal emitters matched with the bandgap of solar cells to improve the efficiency of thermophotovoltaic systems [17].

II. DETAILED CIRCUIT MODEL OF THE METAMATERIAL ABSORBER

A sketch of the investigated structure and its equivalent circuit is reported in Fig. 1. From an equivalent network perspective, the thin grounded dielectric slab is represented with a short-circuited transmission line. Since the thickness is very small compared to the operating wavelength, the short circuited transmission line could be also represented by a lumped inductor. Since the dielectric substrate is lossy, the input impedance of the grounded dielectric slab has also a real part. In order to understand the physical mechanisms which determine the matching of the structure with the free space impedance, it is essential to model accurately the effect of the periodic metallic surface and its interaction with the ground plane. As well known, a single resonant FSS element is modeled with LC series circuit. As the surface is printed on top a dielectric substrate, the capacitance needs to be multiplied for the effective dielectric permittivity of the host medium. Since the host medium is lossy, a resistor which takes in to account the dielectric losses should be put in parallel with the lumped capacitance. In order to get some insight on the working principle of the resonator, it is useful to derive a simple analytical relation the real part of the input
impedance of the resonant structure $Z_{IN}$ by using the equivalent circuit approach. Indeed $Z_{IN}$ is directly related with the reflection coefficient magnitude. The input impedance of the structure is the parallel connection of the ground substrate impedance and the FSS impedance. After some approximations [18], the real part of the input impedance, at the resonance frequency $\omega = \omega_0$ can be derived as follows [3], [18]:

$$\text{Re}\{Z_{IN}^{\text{real}}\} = \frac{\frac{\pi^2}{2} \varepsilon' r}{D^2} \left[ \frac{1}{\varepsilon'} + \frac{2\varepsilon_r' - 1}{\varepsilon_r + 1} \right] \left[ \kappa_0 d \sqrt{\varepsilon_r'} \right]$$

(1)

where $\omega_0$ is the first resonance frequency, $\varepsilon'_r$ is the characteristic impedance of free space; $\kappa_0$ is the free space propagation constant, $D$ is the thickness of the dielectric substrate; $d$ is the unit cell periodicity, $M_r$ is the metalized surface within the unit cell, and $\sigma$ are the skin depth and the conductivity of the metallic surface, $\varepsilon'_r$ and $\varepsilon''_r$ are the real and imaginary part of the dielectric permittivity of the substrate. $C_r$ represents the FSS capacitance and it can be computed by using analytical formulas in the case of simple FSS elements or by matching the full-wave response of the FSS at normal incidence [19]. As the substrate thickness is reduced below the limit $0.3D$ (which is the case of thin metamaterial absorbers) the influence of higher-order Floquet modes reflected by the ground plane must be taken into account by adequately. This can be done by complicating the circuit model with several terms or more simply by correcting the capacitance value. In particular, the value of the capacitor increases exponentially according to the following relation [20]:

$$C_0^{\text{ohm}} = C_0 - \frac{2D\varepsilon'_0}{\pi} \log \left( 1 - e^{-\frac{4\pi d}{D}} \right)$$

(2)

where $d$ represents the thickness of the dielectric substrate. The expression of the real part of $Z'_n$ in (1) contains all the degrees of freedom of the metamaterial absorber: it is a function of the FSS capacitance, of the electrical substrate thickness and of the real and imaginary part of the dielectric permittivity. The simplified expression in (1) is directly proportional to the imaginary part of the substrate input impedance and it is inversely proportional to the FSS resistor $R = R_0 + R_s$. The dielectric losses are much higher than ohmic losses in the sub GHz frequency range. The increase of dielectric losses, $\varepsilon''$, leads to a reduction of the real part of the input impedance towards the free space impedance with a consequent reflection increase. However, if the losses are too high a mismatch with a free space is obtained leading to a poor absorption. The geometrical and the electrical parameters contained in (1) must be tuned in order to achieve a good matching with the free space impedance.

III. A PRACTICAL DESIGN WITHIN UHF-RFID BAND

Even if metamaterial absorbers are usually investigated within THz gap, their properties can be efficiently employed in microwave region for applications where narrow frequency bands are used, e.g. UHF-RFID systems (865 MHz – 868 MHz). Incorrect reading or tags identified multiple times can be reduced by avoiding multi-path propagation through electromagnetic absorbers [10].

![Fig. 1](image-url)
The possibility of analyzing the absorption properties of metamaterial absorbers by resorting to a simple equivalent transmission line circuit has been discussed. A practical design and a prototype of an absorber operating within the UHF RFID frequency band has been designed manufactured and tested.

REFERENCES


