Wideband metamaterial absorbing antenna ground planes for 21cm radio cosmology applications

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***Abstract*—This paper presents the design of an absorbing ground plane as a solution for ground reflections in 21cm radio cosmology applications. The proposed ground plane is formed by a metamaterial, specially designed to achieve high absorption at a large frequency band. The metamaterial consists of a periodic array of hybrid unit cells, that are based on split ring resonators. The frequency band under investigation is 50 MHz to 200 MHz. The proposed absorber covers 77% of the band, achieving more than 95% of absorption.**

***Index Terms*—metamaterials, ultra-wideband absorbers, radioastronomy**

I. Introduction

Modern radio cosmology experiments aim at detecting and studying extremely faint radio signals (tens of mK in amplitude) that originated during the early epochs of our Universe and are buried under noise signals up to millions of times brighter [1]. An example of this type of experiments is the Global 21-cm experiments, dedicated to the study of the Cosmic Dawn and the Epoch of Re-ionization by means of observing the radio emission from primordial Hydrogen redshifted from 21 cm to wavelengths between 1.5 m and 6 m by the time the waves reach the Earth. Global experiments differ from interferometric experiments in that they try to observe the monopole (sky-averaged) radio emission from Hydrogen using very carefully calibrated single antenna radiometers [2]. At these frequencies (50 - 200 MHz) the radio antennas used in these experiments, exhibiting very large beam widths, are also very sensitive to soil conditions (eg. changing humidity conditions over the few weeks required to obtain sufficiently good data). For this reason, electrical ground planes have been typically used (see Fig. 1) in order to isolate the antenna from the changing soil conditions. However, the finite size and fabrication tolerances of such ground planes produce reflections introducing undesired chromatic effects in the antenna response complicating its calibration [3]. The authors propose in this paper an alternative novel approach in which a metamaterial absorbing ground plane is used to minimize the effect of these reflections while isolating the antenna from the soil behind the ground plane. This is an initial design based on an infinite ground plane that will be further optimized on a finite structure.

Metamaterials are artificial structures that exhibit unusual features in sub-wavelength scale, that cannot be found in natural materials, such as negative effective permittivity ϵ_{eff} and permeability μ_{eff} [4]. Due to their ability for tailored electric and magnetic response, they have gained popularity and many designs can be found in literature for applications such as antennas[5], RCS reduction [6], lenses [7], and filters [8].

Fig. 1. Photograph of an early version of the EDGES antenna [1] on a finite metallic ground plane, partially solid, and partially built with wire mesh, over the soil at the Murchison Radio Observatory in Western Australia. Picture from Wikipedia

Another application of metamaterials, is the design of absorbers. A metamaterial absorber is usually composed of two metallic layers, separated by a dielectric material[9]. The top metallic layer is a periodic pattern, and the bottom layer acts as ground plane, usually made of a continuous metallic film. When an incident EM wave interacts with the metamaterial absorber, an electric resonance is created by the top metallic periodic pattern. Furthermore, the coupling between the top and bottom metallic layers leads to magnetic resonance. In order to achieve near to unity absorption, the metamaterial should be impedance matched to free space[10]. This is possible by properly adjusting the parameters that define the electric resonator of the top layer, the bottom layer, and the dielectric substrate. Reflection and transmission are simultaneously minimized, and thus all the incident energy is absorbed by the metamaterial.

The design of a metamaterial absorber is based on the occurring resonances. Therefore an important disadvantage of these structures is their narrow-band performance [11], [12], [13], [14], [15] which reduces the applications where the absorbers can be used. Nevertheless, many examples of designs that enhance the bandwidth of an absorber can be found in literature. A common solution for broad-band performance, is the design of hybrid unit cells, either by combining different patterns in one super-unit cell [16], or by stacking unit cells one on top of the other[17], [18]. Other solutions introduce lumped elements in the design[19], or even active ones [20] and achieve ultra-wideband absorption. However, when adding lumped or active elements in the design process, although the bandwidth is significantly enhanced, the fabrication is more complex and the cost is increased.

In this paper, we propose an ultra-wideband metamaterial absorber, that is designed to cover the bandwidth of the radioastronomy experiment *REACH* [2], from 50 MHz to 200 MHz. The aim of this design is to minimize the reflections from the natural ground beneath the receiving antennas. Therefore, high absorption is required, possibly reaching 100%. In this paper we show that with the proposed absorber, more than 95% absorption is obtained, from 85 MHz to 200 MHz, 77% of the band. The proposed absorber consists of two stacked split ring resonators that form a hybrid unit cell, placed periodically.

II. Absorption mechanism in metamaterials

Metamaterial absorbers typically consist of a metallic printed pattern, which is separated from a continuous conducting plane by a layer of a dielectric material. For the absorption mechanism, two resonances must take place when an incident EM wave interacts with the metamaterial. On one hand the top metallic layer is responsible of an electric resonance, and on the other hand, the coupling between the top and bottom metallic layers, leads to a magnetic resonance.

As we will show later on this paper, the performance of the absorber can be controlled by the geometry of the top metallic pattern, the effective material properties, and also the thickness of the dielectric.

The absorption of a metamaterial structure can be calculated by the following expression [21]:

$$A(\omega) = 1 - |R(\omega)|^2 - |T(\omega)|^2 \tag{1}$$

where $R(\omega)$ is the reflection, and $T(\omega)$ is the transmission, as a function of the frequency. By this expression it is clear that to maximize the performance of an absorber, the $R(\omega)$ and $T(\omega)$ terms, should be minimized simultaneously. In addition, in a typical metamaterial absorber, the bottom layer is a conducting plane. Therefore in Eq.1 the term $T(\omega)$ is equal to zero, leading to the reduction of the expression to $A(\omega) = 1 - |R(\omega)|^2$. Consequently, the performance of the absorber depends on the reflectivity of the metamaterial, and will be maximum when $R(\omega)$ is minimized. Now let us consider the metamaterial as an infinite array of periodic unit cells. The unit cell is considered an homogeneous medium [22], with complex permittivity $\widetilde{\epsilon}$ and permeability $\widetilde{\mu}$. Furthermore, we consider an EM wave with normal incidence upon the unit cell. The absorption of the unit cell, will be : $A = 1 - |S_{11}|^2$. The reflection coefficient S_{11} depends on the input impedance Z_{in} of the unit cell, as follows:

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{2}$$

where Z_0 is the free space impedance, and the input impedance of the medium is $Z_{in} = \sqrt{\frac{\widetilde{\mu}}{\widetilde{\epsilon}}}$. Therefore, by properly tuning the permittivity $\widetilde{\epsilon}$ and permeability $\widetilde{\mu}$ of the metamaterial, impedance matching can be achieved with the free space ($Z_{in} = Z_0$), which in an ideal case scenario, would result to $S_{11} = 0$, hence the absorption would reach its maximum value, and all the incident EM power would be consumed inside the unit cell.

III. Proposed design and simulation results

As previously mentioned, the aim of this design is to achieve near to unity absorption for the frequency range going from 50 MHz to 200 MHz, to meet with the requirements for low noise in the receiver antennas, minimizing the reflection from the soil.

To design the proposed hybrid unit cell, first we studied the single layer split ring resonator [23]. It consists of two interleaved circular rings, each one having two slots that are oriented parallel to the diagonal direction of the unit cell. The split ring unit cell, was simulated as an infinite array, in CST Microwave Studio. After parametric studies of the dimensions of the unit cell that are shown in Fig.2, and for a grounded dielectric substrate with $\epsilon_r = 4.2$ and $tan\delta = 0.02$, we have obtained the dimensions presented in Table I. The simulations showed an absorption of more than 90% from 128 MHz to 172 MHz, which is 30% of our frequency range of insterest as seen in Fig.3. As expected, the absorption reaches its maximum values when the reflectivity is minimized. Let us note here, that for applications without strict requirements for absorption (e.g. absorption>80%), the metamaterial absorber consisting of this unit cell would meet the requirements for 55% of the band.

Apart from the geometry of the metallic pattern of the unit cell that affects its response, another important parameter to be taken under consideration is the thickness of the dielectric substrate. There is a direct connection relating the absorption achieved, not only with the loss factor of the dielectric, but also its thickness. To achieve the result of Fig.3, a thickness of $0.33\lambda_0$ was chosen, with λ_0 being the wavelength at the highest frequency of the band, 200 MHz. In Fig.4, the absorption of the unit cell for three values of thickness, is presented. As the thickness increases, there is a shift towards lower frequencies in the response of the unit cell, meaning that its parameters need to be re-adjusted for optimal performance. For a decreased thickness, dual-band absorption is obtained.

The surface currents distributions of the top and bottom layers are presented in Fig.5, for two cases: at 165 MHz where the absorber is at resonance, and at 60 MHz where there is

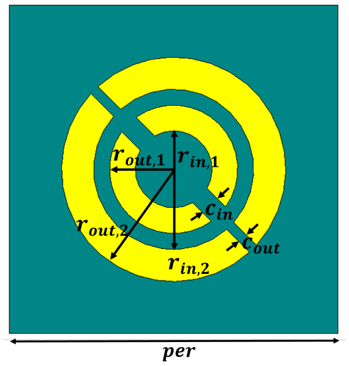

Fig. 2. Unit cell of the proposed ultra wide-band metamaterial absorber. In the case of the hybrid unit cell, both layers consist of split ring resonators, each one on a dielectric substrate, with different dimensions.

TABLE I
DIMENSIONS IN MM

$r_{in,1}$	$r_{out,1}$	c_{in}	$r_{in,2}$	$r_{out,2}$	c_{out}	per
108	180	15	225	315	315	900

Dimensions of the split ring resonator unit cell.

no absorption. It can be seen, that the surface currents are mainly distributed between the two rings, in the case where high absorption is achieved.

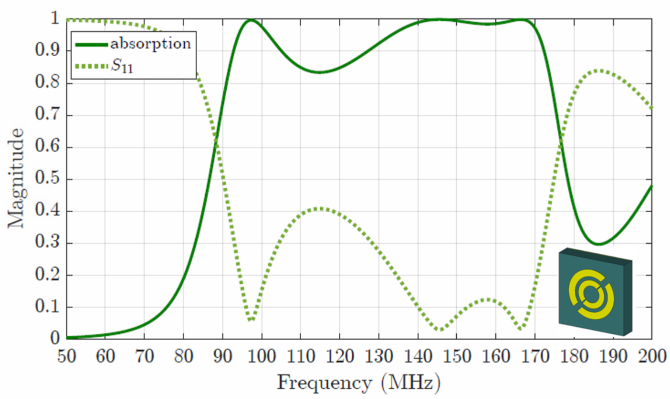

Fig. 3. Absorption and reflectivity for normal incidence, of the single layer split ring resonator.

In order to achieve enhanced performance of the split ring resonator, we decided to design a hybrid unit cell, by stacking two split rings, each one on top of a dielectric material (as seen in Fig.6). For the bottom layer, we chose a dielectric with $\epsilon_r = 4.3$ and $tan\delta = 0.025$, resembling the characteristics of FR-4. For the top layer, a foam-like material was chosen, with $\epsilon_r = 1.5$ and without dielectric losses.

The simulations of the hybrid unit cell, showed that it meets with the requirement for very high absorption (more than 95%) for 77% of the frequency range of interest, as seen in Fig.7, and for the values presented in Table II. In this case the thickness is $0.17\lambda_0$ and $0.3\lambda_0$ for the top and bottom layer

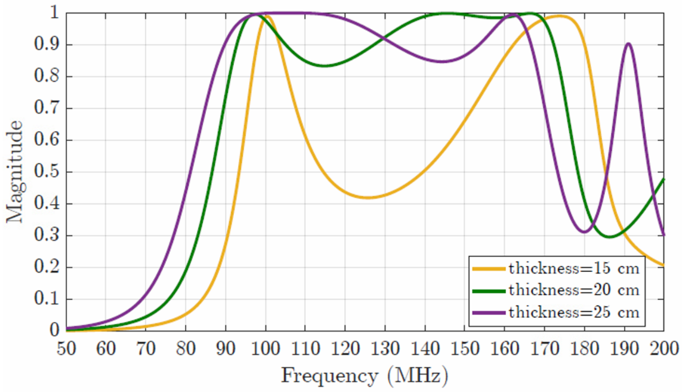

Fig. 4. Absorption of the split ring unit cell, for three values of the dielectric thickness.

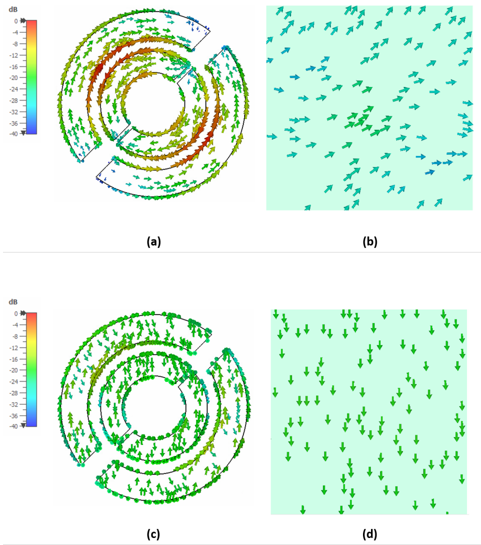

Fig. 5. Surface current distributions for the simple split ring resonator unit cell. In (a) and (b) the top and bottom metallic layers can be seen, at 165 MHz where the absorption reaches 100%. In (c) and (d) the top and bottom layers are shown, when minimum absorption occurs, at 60 MHz.

respectively.

The performance of the proposed hybrid unit cell, has been examined for a range of angles of incidence of the incoming EM radiation. In an ideal case scenario, the designed absorber would be angle insensitive, to ensure good levels of absorption for the same frequency range, at all incident angles. For the proposed hybrid unit cell, as shown in Fig.8, the optimal performance is obtained for normal incidence θ_0. Moreover, it can be seen, that for angles up to 50 degrees, good absorption levels are maintained, reaching 90%. Nevertheless, the performance of the unit cell, changes from wideband to dual band with increasing oblique incident angles.

IV. CONCLUSIONS

The design of an ultra-wideband metamaterial absorber has been presented in this paper. The absorber is formed by an

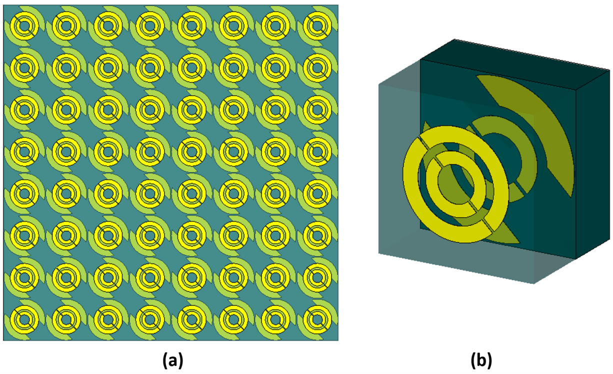

Fig. 6. (a) Schematic of the proposed absorbing ground plane in the simulation environment , (b) the proposed hybrid unit cell.

TABLE II
DIMENSIONS IN MM

Layer	$r_{in,1}$	$r_{out,1}$	c_{in}	$r_{in,2}$	$r_{out,2}$	c_{out}	per
Top	62.3	103.9	8.7	130	182	8.24	532.5
Bottom	81	135	11.3	168.8	261.3	245.6	532.5

Dimensions of the top and bottom layers of the hybrid unit cell.

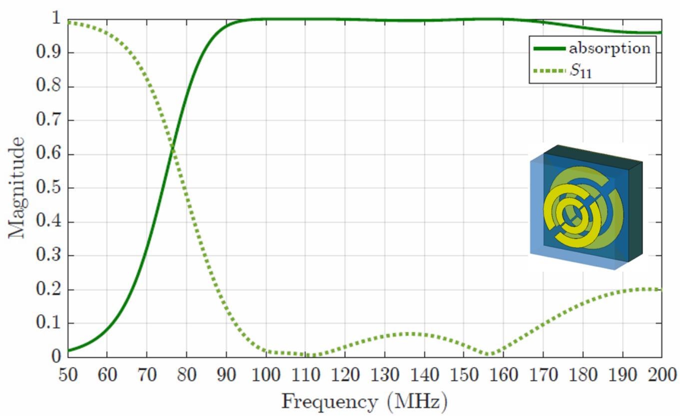

Fig. 7. Absorption and reflectivity for normal incidence, of the proposed hybrid unit cell that is shown in the inset.

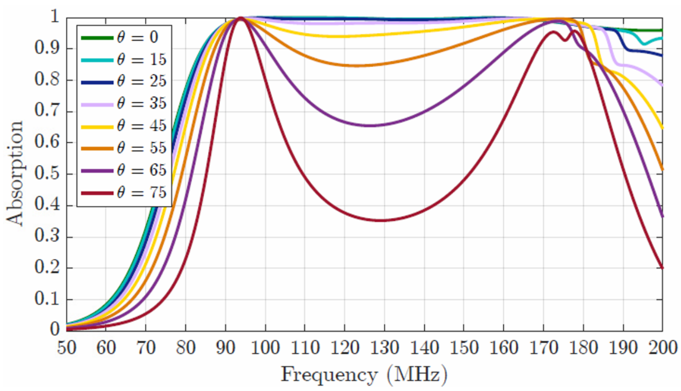

Fig. 8. Absorption for normal incidence $\theta = 0$, compared to different angles of incidence.

array of hybrid unit cells. Each hybrid unit cell consists of two stacked split ring resonators, lying on top of two separate dielectric substrates.

In 21cm Global radio cosmology experiments a big issue is the chromatic noise that is added to the received signal by reflections and direct emission from the natural ground beneath the antennas. The cosmic signal that is received by the antennas is very weak, which intensifies the need for the elimination of ground reflections from the surrounding environment.

The aim of this design is to achieve near to unity absorption, for the frequency range that goes from 50 MHz to 200 MHz, according to the requirements of the radioastronomy experiment *REACH*. The proposed metamaterial absorber, achieved wideband response. We obtained absorption of more than 95% from 85 MHz to 200 MHz which is 77% of the band. Compared to previously proposed split ring absorbers [23], the bandwidth of the proposed absorber has been increased by 33%.

The advantages of the proposed design, are its scalability, and the high levels of absorption in a wideband frequency range, without introducing lumped or active elements, keeping the design and fabrication simple.

Next steps on this work include the refinement of the design of a finite ground plane, the fabrication of a prototype and the quantification of improvement on the radio cosmology application using a simulated data observation pipeline.

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