A Frequency-Selective Absorbing Ground and High-Impedance Surfaces (HIS), Metamaterial

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Abstract: ***Conductor-backed electromagnetic wave absorbers with periodically arranged pattern conductors on the surface layer (pattern absorbers) were designed. The pattern absorbers in this work were composed of a patterned layer acting as a frequency selective surface, such that the pattern served as a resonator together with a back reflector. Electromagnetic wave simulations predicted that the absorption characteristics of these devices could be tuned by varying the shape, alignment, and occupied area ratio of the pattern conductor so as to match the surface impedance to that of free space. Pattern absorbers with various pattern shapes were fabricated operating at 2.45 GHz and their absorption characteristics were evaluated. The experimental results were found to agree with the theoretical predictions and it was experimentally shown that a patterned electromagnetic wave absorber fabricated using a magnetic material exhibited wideband characteristics. A scaling law was also found to hold between the pattern size and absorption center frequency, which will allow the design of electromagnetic wave absorbers that can operate over a wide frequency range with excellent absorbing characteristics. frequency selective surface (FSS)-based electromagnetic absorbers with an insight into their operational principles. Various techniques commonly used to design and develop FSS-based absorbers for several vital metrics are discussed to assess their efficacies and highlight the benefits and limitations of each solution. The absorbers are discussed in light of their major attributes, starting from their evolution to the state-of-the-art. It includes the most popular configurations of FSS-based absorbers-single/multilayer, radar absorbing material, metamaterial, to more recently used active and conformal absorbers. These absorbers can provide absorption bandwidth in both narrowband and wideband frequencies, which find numerous applications throughout the frequency spectrum, ranging from the VHF range to visible light. Some important aspects of the absorber's performance have been highlighted. It includes minimum possible thickness for maximum achievable bandwidth, polarization stability, oblique angle insensitivity, and mitigation of cross-polarized reflection required to design an efficient absorber. Moreover, some of the most popular manufacturing and measurement techniques of FSS-based absorbers are discussed before concluding with some future aspects. In the conclusion, the need for economical electromagnetic absorbers to achieve good absorption performances over a wide range of frequencies is justified. The approaches presented in this article offer a broader view of capabilities and forthcoming developments in this crucial area.***

Keywords: Artificial Magnetic Conductor (AMC), Artificial Impedance Surface (AIS), Electromagnetic Absorbers, Frequency Selective Surface (FSS), High Impedance Surfaces (HIS), Metamaterial

1. Introduction

Recent developments in the synthesis of metamaterials have generated a great interest on thin electromagnetic absorbing structures due to the high number of practical applications spanning from microwaves to optical frequencies. At microwave frequencies thin absorbing structures are beneficial to reduce the radar signature of targets [1]–[5], to improve the electromagnetic compatibility of devices [6], to avoid multiple reflections in complex indoor environments, to minimize mutual coupling between antennas or to synthesize power imaging devices [7].

A wide operating bandwidth is one of the main requirements across the microwave range while frequency selective ultra-narrowband absorbing structures are more desirable in THz range to design novel devices such as photodetectors, microbolometers [8], [9] or phase modulators [10]. Promising applications of metamaterial absorbers at optical frequencies regard the use of such structures as frequency selective emitters to improve the efficiency of conventional and thermophotovoltaic solar cells [1], [12]. The possibility of employing frequency selective surfaces for reducing the thickness of the classical absorbing structures (Salisbury, Jaumann and Dallenbach screens [13]) has been intensively investigated, particularly in the last decade, even if there exist older publications on periodic surfaces employed in absorbers design [4]–[16].

FSS-based absorbers can be partitioned into two main categories: those employing lossy FSSs and those employing metalized FSSs. The former class employs lossy FSS in order to minimize scattered energy through ohmic and dielectric dissipation in a reduced thickness. Lossy FSSs usually replace uniform lossy layers, such as in Salisbury or Jaumann absorbers, in order to introduce a reactive part into surface impedance together with a resistive component.

Lossy surfaces can be synthesized either by employing a resistor in each unit cell of the periodic surface on a metallic surface [7]–[19] or by printing periodic shapes using resistive inks [2]. On the other hand, metallic FSSs can be employed in conjunctions with uniform lossy sheets in order to provide larger or multi-band operating bands [1]–[3]. More recently fully metallic FSS-based absorbers were proposed to achieve perfect absorption (single frequency, absorption at all incident angles) through the maximizations of the dielectric dissipation [4], [5]. A simple layout allowing the synthesis of both ultranarrow bands, narrowband, wideband and ultra-wideband electrically-thin absorbers is the High-Impedance Surface (HIS) formed by a thin substrate, a frequency selective surface with a suitable shaped element and a ground plane.

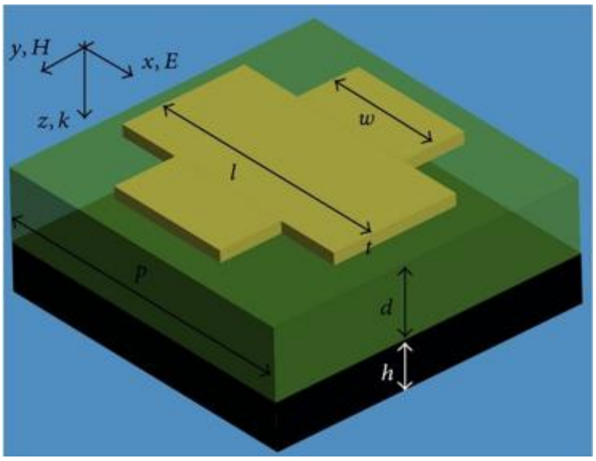

Figure 1: Side view of an Artificial Impedance Surface (AIS) absorber

This configuration is also known as Artificial Impedance Surface (AIS) because of its ability to act as an impedance boundary condition. Generally, the electric and geometric characteristics of the dielectric substrate are imposed as initial design parameters or can be chosen among an available set of materials. For this reason, a correct choice of the frequency selective surface elements is of vital importance for designing the absorber with the desired characteristics. The suitable amount of loss can be introduced in the resonant FSS structure (or near to it) or in the dielectric substrate or in both of them.

The absorbing structure can be optimized through a genetic algorithm [6], [17] or by using a simple equivalent circuit model. The latter approach is preferred in this article since it allows to get physical insight into absorbing mechanisms. Ultra-narrowband absorption is obtained by exploiting dielectric losses of the commercial substrates only. This kind of structures are frequently referred to as Perfect Metamaterial Absorbers [24] and are mostly investigated by physicists across THz gap and within the visible part of the electromagnetic spectrum even if they were also proposed for Sub-GHz communication applications with very low-cost manufacturing process [25].

As the ohmic losses are introduced close to the periodic pattern by use of resistive sheets [28] or directly in the periodic pattern through lumped resistors [17], [29] or resistive inks [20], the absorption bandwidth can be greatly enlarged. The bandwidth can be either narrow or wide depending on the number of parallel resonances (inductive-capacitive impedances connected in parallel) involved in the design.

Two resonances can be introduced both by designing a single resonant [10] or Mult resonant FSS elements [1] and by stacking more FSS layers [32]–[34]. The absorber can be efficiently analyzed by an equivalent transmission-line (TL) model [35].

2. Classification of Absorbing Structures

The artificial impedance surface displayed in Fig. 1 acts as a resonant cavity. The amount of power absorbed by the resonant cavity at the resonance is determined by the value of the real part of the input impedance since the imaginary part of the input impedance of a lossy structure is close to zero at the resonance. The magnitude of the reflection coefficient at the resonance of the cavity approximately reads [6]:

(1)

where ZHIS represents the input impedance of the absorbing HIS structure and ζ0 is the characteristic impedance of free space at normal incidence.

The input impedance of the HIS structure is equal to the parallel connection between the two complex impedances ZFSS and Zd which represent the FSS impedance and grounded substrate impedance, respectively. The impedances of the grounded substrate and the frequency selective surface in presence of a lossless or even lossy dielectric can be computed analytically on the basis of some well justified approximations. By deriving an explicit expression of the real part of the input impedance of the impedance surface, which is directly related to the amount of loss at the resonance, several properties of the AIS absorber having immediate practical implications can be easily extracted. A series LC circuit can model the impedance of a frequency selective surface and a couple of resistors can take into account both dielectric and ohmic losses:

(2)

where C and L represent the capacitance and the inductance of the FSS. The spacing between the edges of the elements controls the capacitance, and the magnetic flux created between the patches and the ground plane defines the inductance.

The capacitance of an FSS printed on a dielectric substrate is computed by multiplying the unloaded capacitor by the real part of the effective dielectric permittivity due the surrounding dielectrics. The capacitor formed between the adjacent elements has a loss component since the electric field lines are concentrated in a lossy medium. Such loss component is readily represented by the following series resistor [16]:

(3)

The FSS series resistor RD is inversely proportional to the FSS capacitance. The ohmic resistor connected in series with the aforementioned dielectric resistor can be evaluated by weighting the classical expression of the surface resistance valid for metals or resistive inks with the ratio between metalized area and periodicity of the unit cell:

(4)

where t, δ and σ represent the thickness, the skin-depth and the electrical conductivity of the metallic/resistive pattern, respectively. S is equal to D2, D is the cell periodicity and A is the surface area of the lossy element within a single unit cell. The relation (4) implies that an element with small scattering area (e.g. cross), require a higher surface resistance than an element with a large scattering area (e.g patch) [19].

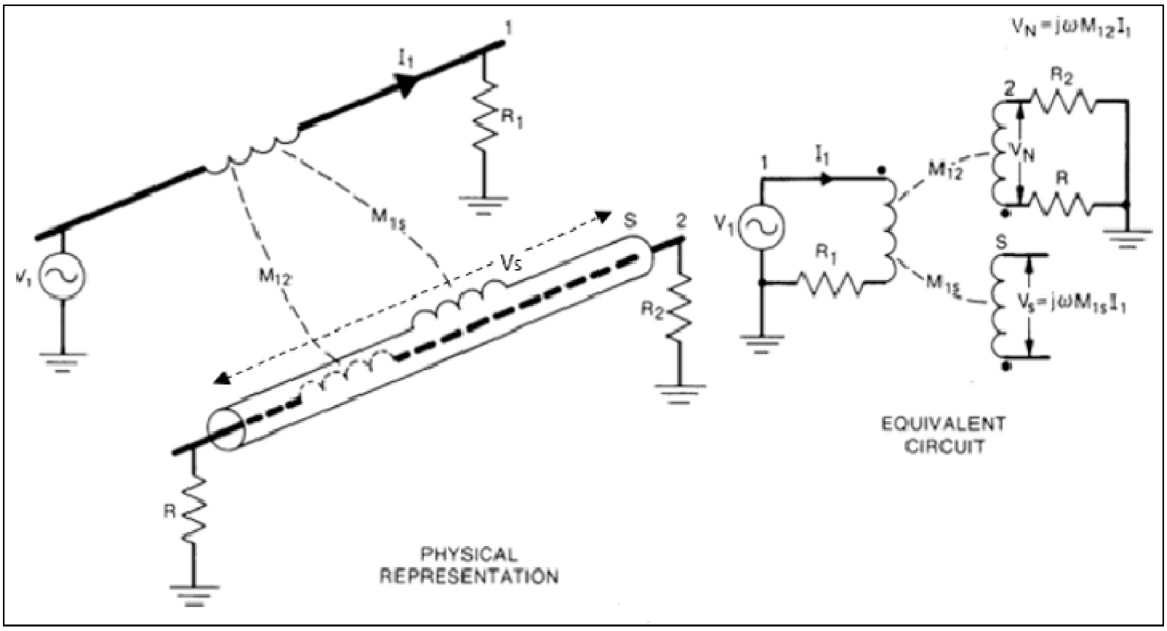

Figure 2: Pictorial representation of the physical significance of the proposed equivalent circuit

3. Ultra-Narrowband and Narrowband Configuration

The difference between HIS absorbers made up of metallic or resistive FSSs are clarified through a numerical example.

In Fig. 3a the dielectric and the ohmic resistance of the FSS impedance are compared with the real part of the substrate input impedance for a HIS absorber comprising a simple cross shaped FSS.

The substrate is a commercial FR4. The curves obtained through the approximate relations are compared with those obtained by using Method of Moments simulations [9]. In the case of metallic FSS the dielectric resistor is much higher than the ohmic resistor while in the case of resistive FSS losses introduced in the periodic pattern make the ohmic resistor predominant. The use of metallic FSSs forces the choice of the substrate thickness for obtaining, according to relation (6), a value of the real part of the HIS input impedance close to the free space impedance at the resonance.

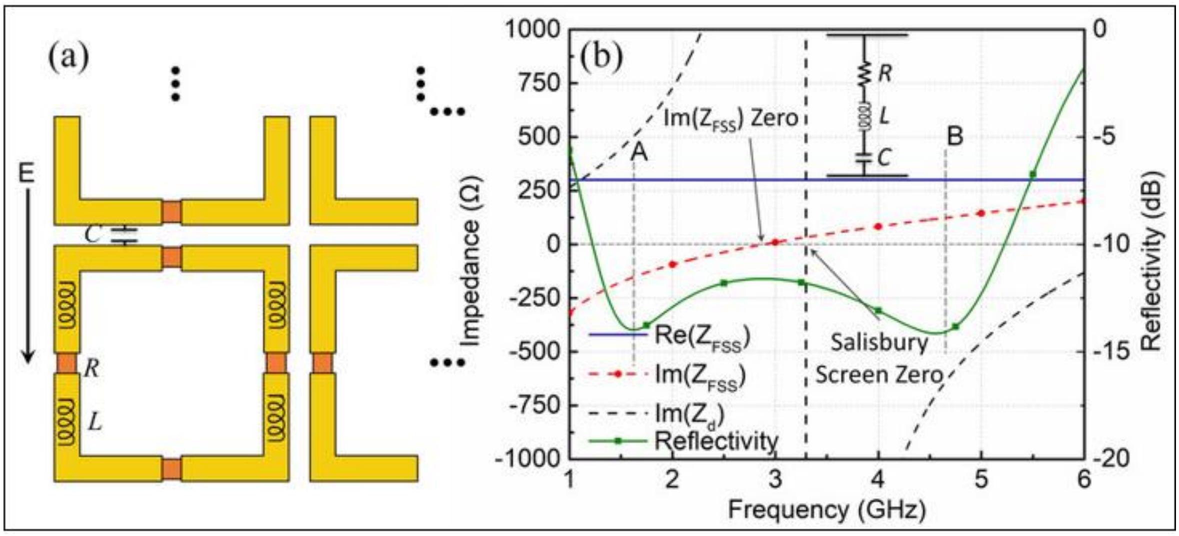

Figure 3: (a) Dielectric and ohmic components of the real part of the FSS impedance compared with the real part of the grounded substrate input impedance for absorbing structures comprising a metallic or a resistive FSS (b) Reflection coefficient of the HIS absorber comprising both metallic and resistive FSSs. Continuous line: MoM simulation, Dashed line: Transmission line model

The FSS element is the same in both cases but the periodicity of the metallic cross is slightly higher than the periodicity of the resistive cross in order to have absorption at the same frequency. The substrate thickness chosen for perfect absorption in the case of metallic cross is 0.5 mm while the substrate thickness for the resistive cross case is 1.6 mm. The lower substrate thickness increases FSS capacitance due to the influence of high-order Floquet modes. In the Fig. 3b the reflection coefficient of the thin absorber comprising a metallic and a resistive cross is shown. Due to the very small substrate thickness, the absorption bandwidth of the metallic absorber is ultranarrow. The use of resistive patterns introduces an additional degree of freedom in (6).

For this reason, the substrate thickness leading to a matching of the HIS input impedance with the free space impedance can be arbitrary selected. In order to maintain a perfect absorption at the resonance while the substrate thickness is increased, the surface resistance of the FSS needs to be enhanced (narrowband case).

The bandwidth of the absorber is directly proportional on the substrate thickness but, once the substrate thickness is fixed, the use of tightly coupled patch arrays allows to maximize the absorption bandwidth [14].

It is worth to point out the use of exotic elements is not necessary for obtaining a narrowband absorption. An optimal tuning can be simply obtained by Jerusalem cross element. More complex FSS elements are instead very useful for achieving wideband performance.

4. Bandwidth of Narrowband Absorbers

The bandwidth of the above-described narrowband absorbing configurations depends both on substrate properties and on FSS unit cell. Large substrate thickness leads to bandwidth enhancement but increased thickness is undesired in absorber design. For practical purposes it is useful to understand how to select FSS shapes in order to maximize or minimize absorption bandwidth, while the substrate geometrical and electrical properties are kept unchanged.

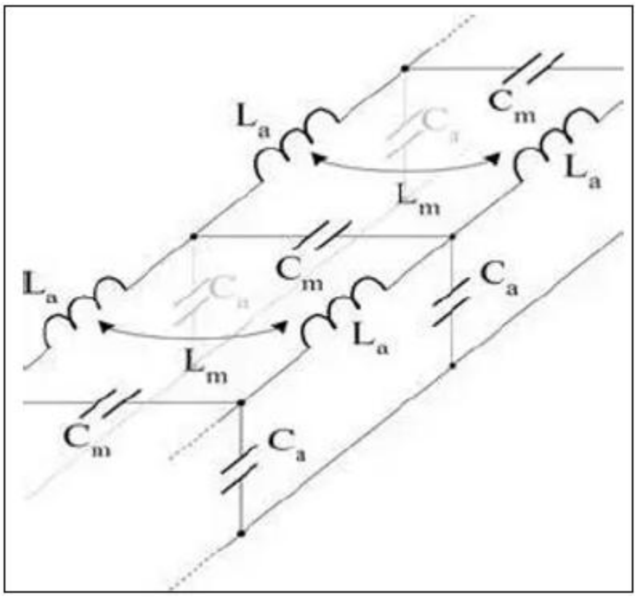

Figure 4: Equivalent transmission line of a high-impedance surface and its corresponding lumped circuit model allowing to correctly determine the bandwidth of the structure.

By using the equivalent circuit of Fig. 4, valid for lossless AISs, it is possible to derive physical bandwidth limits and to obtain guidelines for tailoring the operating bandwidth of the absorber. The impedance of the circuit reads:

5. Bandwidth Enlargement Techniques

Techniques to improve the matching bandwidth of subwavelength absorbers are based either on substrate properties modification or on the use of more complicated FSS element geometry.

6. Bandwidth Enlargement by Using Magnetic Substrates

The use of a magnetic substrate instead of an electric one is a simple strategy to improve the absorption bandwidth [11]–[13]. The effectiveness of this strategy can be demonstrated by simply inspecting the analytic expression of the grounded substrate inductance used in the previous sections.

6.1 Bandwidth Enlargement by Using Multi-Resonant Dipoles on the Same Unit Cell

One possibility to improve the absorption bandwidth is to use multiple resonances located close to each other. Multiples dipole elements can be used for enlarging absorption band. One method utilizes multiple resonating structures in each unit cell, exploiting the fact that resonators with different sizes resonate at different frequencies. If the resonance frequencies of the resonators are close enough the absorption band of the ultra-thin metamaterial absorber, the absorption band can be potentially enlarged. However, it has to be pointed out that this methodology works only if the surface resistance of each resonator in the unit cell is adequately controlled. The surface resistance of large elements must be higher than the surface resistance of small elements. As an example, the reflection coefficient of a Tri dipole unit cell arranged on both the incident planes is reported in Fig. 5. The length and the optimal surface resistances of the three dipoles are 5.1 mm, 3.9 mm, 3.3 mm and 4.5 Ω□-1, 3.0 Ω□-1, 0.05 Ω□-1, respectively. The dependence of the reflection coefficient on the surface resistance value of the smallest dipole element is highlighted in figure.

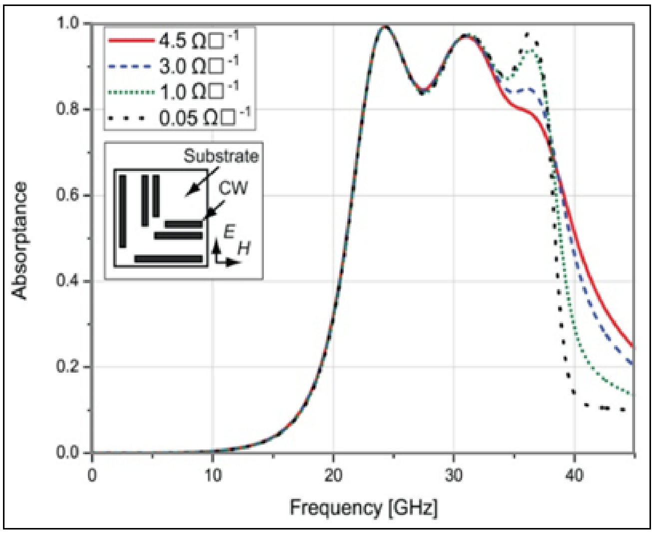

Figure 5

6.2 Bandwidth Enlargement by Using Single-Resonant Resonators Located on Separate Layers

Another technique proposed to enlarge the bandwidth of metamaterial absorbers is stacking the same resonator with different geometrical characteristics on multiple layers. In this way the coupling between closely spaced elements is reduced with respect to configurations where multi-resonant elements are located on the same layers. This disposition leads to a more complex multilayer structure which still preserves a considerable subwavelength profile. For instance in [18] a multi-loop absorber is proposed.

7. Multi-Resonant FSS Absorbers

When metallic concentric loop elements are employed on the same periodic surface a multi-resonant absorption behavior can be achieved. As depicted in Fig. 6, a multi-loop FSS can be represented as a shunt connection of several series RLC circuits. The number of absorption peaks is related to the number of loops. As an example, the reflection coefficient of a five-loop unit cell is reported in Fig. 6.

Both the normal and oblique incidence response are reported to remark that the position of the resonance frequencies is nearly unaffected by the angle variation leading to a very stable absorption property.

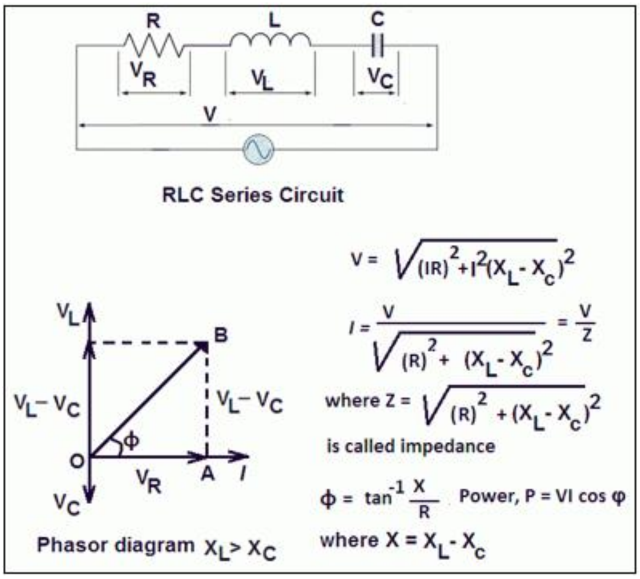

Figure 6

From a circuit point of view, angular stability of the absorption is achieved since the impedance of the thin grounded substrate is nearly unaffected by the variation of the incident angle and also the FSS impedance of thin loop elements is angularly stable [11].

It has to be noticed that the matching condition (perfect absorption) is different for the first resonance with respect to high order ones. It can happen that the real part of the input impedance associated with the first loop is larger than free space impedance and, at the same time, the real part of the input impedance associated with high order resonance is lower than free space impedance. In this situation, a decrease of the substrate thickness leads to an improved matching with free space for the first resonance but a suboptimal matching for higher order resonances. In relation to this, it is important to select a substrate with a suitable thickness and the proper amount of substrate losses to guarantee good absorption at all resonant frequencies.

7.1 Oblique Incidence Performance Improvement by Using Electric or Magnetic Plasmonic Resonances in the Substrate

As it is well known, a wire medium behaves as a plasma around at a certain resonance frequency dictated by the radius and the periodicity of the wires [11]–[13]. Moreover, when vias are loaded with metallic patches the spatial dispersion is suppressed [18] leading to a plasmonic resonance nearly independent on incident angle. Presence of vias can be therefore advantageously used to enlarge the absorption bandwidth at oblique incidence [15].

The proposed methodology consists in designing the wire medium formed by the array of vias so that the plasma resonance occurs in the vicinity of the HIS resonance. When the incident angle of the TM polarized waves is off from the normal direction, part of the electric field is aligned to shorting vias and an additional resonance is created in the absorption profile.

As the incidence angle grows the plasma resonance becomes stronger and absorption is increased.

The position of the resonance is determined by the radius of the vias and therefore can be shifted independently of the main AMC resonance. Its position can be efficiently estimated through a rigorous analytical approach [6], [7]. The typical behavior of the phase of the TM reflection coefficient of a AIS both for normal and oblique incidence is shown in Fig. 7.

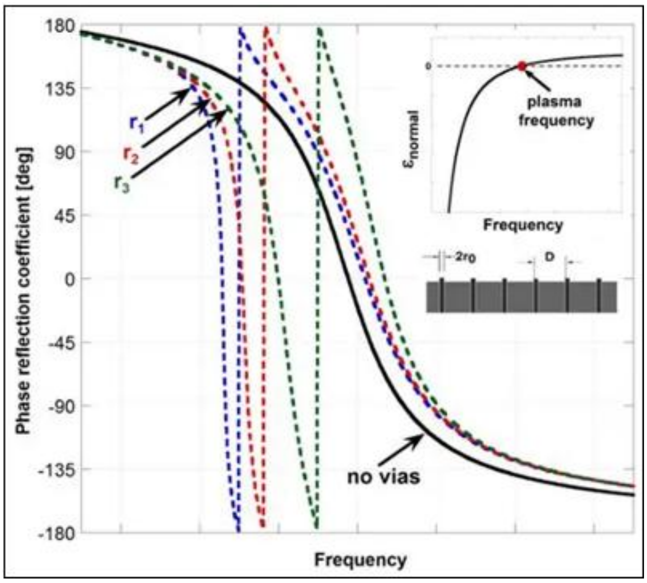

Figure 7

The figure highlights the effect of the vias radius: plasma resonance shifts towards lower frequencies as the vias radius is reduced. As an example of the performance of the absorbing layer, an artificial impedance surface with the following parameters is considered: D = 10 mm, L = 8.75 mm, d = 3 mm, εr = 2(1- j0.5) and r0=0.1 mm.

7.2 Promising Applications of FSS-Absorbers

FSS-based absorbers have proved to be a versatile structure that has been exploited in a very wide range of applications. One of the most investigated areas is related to stealth technology and more precisely to the reduction of the Radar Cross Section (RCS) of antennas.

Resistive periodic surfaces have been adopted for reducing the field scattered by a 2x2 patch array [1] by surrounding the antennas with the absorber. An absorbing selective Radom has been designed in [2] for allowing the in-band radiation of the enclosed antenna and, at the same time, the reduction of the scattered field in the out-of-band.

FSS-based absorbers have been tailored to enhance the stealth performance of a patch array antenna comprising a hybrid ground plane [3]. In this case, the insertion of an absorber placed below the selective transparent ground plane (fig 5) has doubled the low-RCS bandwidth of the antenna. In [5] a superstrate comprising a resistive periodic surface and parasitic metallic patches has been presented as a good trade-off for reducing the RCS of a slot array and improving the radiation properties of the antenna.

Another application of FSS-based absorbers that is lately gaining interest is related to the control of the signal propagation within an indoor environment. In particular, ultrathin absorbing panels [11] have been Signal propagation may also be controlled for security reasons, as described in [10] where a dual-layer absorb/transmit surface is designed for absorbing WLAN signals while passing mobile ones.

A very promising application of FSS-based absorbers is their employment in Thermophotovoltaic (TPV) systems. In TPV system the heat is converted into electricity by radiating thermal-generated photons able to generate electron-hole pairs in a low-bandgap photovoltaic medium and thus a current. In solar TPV systems the sunlight is collected via optical concentrators and it is then absorbed by a surface which is coupled with an emitter that radiates photons which impinges on a photovoltaic (PV) cell.

More in detail, photons with energy less than the bandgap of the PV converter cannot be absorbed to generate electron/hole pairs and are either reflected and lost or passes through the cell. Photons with energy above the bandgap can be absorbed, but the excess energy is lost, thus generating undesirable heating in the cell and reducing the efficiency.

In a TPV system it is advantageous to match the thermal emission with the most efficient conversion characteristics of the photovoltaic cell therefore it is of the utmost importance to control the emitter properties.

In this scenario, a selective emitter whose thermal radiation is much narrower than that of a blackbody at the same temperature would improve the system performance. FSS-based absorbers can play this role because they can be tailored to have sharp resonances with high absorption and thus, thanks to the Kirchhoff's law of thermal radiation, they can realize a high-Q emitter with high emissivity [15].

8. Conclusions

Properties of the electrically thin absorbers synthesized by employing opportunely designed high-impedance surfaces are discussed. The differences between an entirely metallic absorber, typically referred to as metamaterial absorber, and HIS absorbers comprising resistive FSSs are highlighted by recurring to a simple transmission line model. It is shown that dielectric losses are predominant for metamaterial absorbers while ohmic losses are the most influent in case of resistive losses. Techniques to improve the operating bandwidth or to design multi-resonant absorbers have been described. Properties and performance of single-layer and multi-layer absorbers have been also introduced. Manufacturing procedures of the described absorbing structures have been also presented. Finally, promising applications and open issues have been described.

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