A Thin Electromagnetic Absorber for Wide Incidence Angles and Both Polarizations

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Abstract—In this paper a planar electromagnetic absorber is introduced whose performance is maintained over a wide change of the incidence angle for both TE and TM polarization. The absorber comprises an array of patches over a grounded dielectric slab, with clear advantage in terms of manufacturability. It is shown that a high value of the relative permittivity of the substrate is essential for the operation of the absorber. The main contribution of the paper is to demonstrate and practically use the presence of an additional resonance of high-impedance surfaces when the plasma frequency of the wire medium comprising metallic vias in the dielectric substrate is close to the original resonance of the high-impedance surface. The presence of the vias between FSS and the ground plane is discussed both for the case of a high-permittivity absorber and for a low permittivity one. The radius of the vias influences the oblique incidence TM absorption, and when properly designed, the insertion of the vias result in bandwidth enlargement and higher absorption.

I. INTRODUCTION

Classical structures for electromagnetic absorbers include Jaumann, Salisbury, and Dällenbach absorbers [1] (see also [2], [3]). In Salisbury absorbers a resistive sheet is placed at a distance of λ/4 over the ground plane in order to generate losses to the incident field. In Jaumann absorbers a resistive sheets are stacked over each other at an approximate distance of a quarter wavelength (measured at the center frequency of the absorption band) distance generating a wider absorption band compared to the Salisbury absorber. In Dällenbach absorber the structure is similar to the previous ones, with the exception that no resistive sheets are used, but the incident power is dissipated in lossy homogenous dielectric materials layered on top of each other over a ground plane.

Possibilities to enhance the performance of these absorbers have been widely studied. For instance, one may include chiral inclusions to the Dällenbach absorber’s dielectric coatings and use the chiral resonance to enhance the absorption and enlarge the bandwidth of the absorber [4]. One can also use complex fractal geometries in a similar way [5]. In [6] a frequency selective surface (FSS) was used on top of a grounded dielectric substrate to widen the absorption band. In all of the aforementioned absorption techniques, the widening of the absorption band is achieved by creating an additional resonance in the vicinity of the primary resonance, the λ/4-resonance of the grounded dielectric slab. In these cases the thickness of the absorber remains still considerably large.

Artificial impedance surfaces, or high-impedance surfaces, have been used to create electrically thin electromagnetic absorbers. These absorbers relate closely to the Salisbury absorber: the resonance is achieved by using the properties of the high-impedance surface and the absorption by a separate resistive sheet [7]. The resistive sheet can be realized by using commercially available resistive materials on top of the capacitive sheet or between the metallic parts of the capacitive sheet [8], [9], or by connecting resistors between the adjacent metallic parts of the capacitive sheet of the high-impedance surface [10], [11]. The drawback of these designs, especially the ones using lumped resistors, is the inherent difficult way of realizing the resistive sheet (i.e., the high cost of high frequency lumped resistors and the number of spot welding). Slightly increasing the overall thickness and exploiting two close resonances, a more wideband absorber can be designed by these techniques [12].

In [13] a simple way of realizing the absorption behavior was introduced: one simply needs to add losses to the grounded dielectric substrate. Further, in [13] the stability with respect to the TM-polarized incident angle was obtained using metallic vias connecting the patches to the ground plane. However, the analytical expressions in that paper for the grid impedance of the array of square patches were not accurate. In this paper we will show that with the revised expressions, angular stability also for the TE-polarized incident fields is achieved with sufficiently high values of relative permittivity of the substrate. As a matter of fact, no vias are needed for electrically thin substrates in order to realize angular stability. Furthermore, we will show that the vias can be used to increase the absorption band for the TM-polarized oblique incidence.

The rest of the paper is organized as follows: we study first high-impedance surfaces without vias and show that the angular stability of the absorbers is achieved by increasing the permittivity of the substrate. We will then consider high-impedance surfaces with vias and we will discuss the possibility to enlarge the absorption band by using the effect due to the vias favorably. For comparison we will discuss high-impedance surfaces with both high- and low values of the relative permittivity.
II. SURFACE IMPEDANCE OF THE ABSORBER WITHOUT VIAS

The absorber structure is illustrated in Fig. 1(a). The patch array over the grounded dielectric slab has a capacitive response that, in conjunction with the inductive response of the grounded dielectric slab, forms a resonant circuit. The patch array comprises electrically small square metallic patches, so that the structure is nearly isotropic. This type of artificial impedance surfaces has been studied in our earlier work [14], in which the surface impedance for the structure illustrated in Fig. 1(a) was derived. The surface impedance of the impedance surface, \( Z_{\text{imp}} \), can be considered to be a parallel connection of the grid impedance of the patch array, \( Z_g \) and the surface impedance of the grounded dielectric slab, \( Z_s \):

\[
Z_{\text{imp}}^{-1} = Z_g^{-1} + Z_s^{-1}. \tag{1}
\]

For the structure illustrated in Fig. 1 the surface impedances for TE and TM polarization read, respectively,

\[
Z_{\text{TE}}^{-1} = \frac{j\omega\mu_0 \tan(\beta d)}{1 - 2k_{\text{eff}} \tan(\beta d) \left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\text{r}} + 1}\right)}, \tag{2}
\]

\[
Z_{\text{TM}}^{-1} = \frac{j\omega\mu_0 \tan(\beta d) \left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\text{r}} + 1}\right)}{1 - 2k_{\text{eff}} \tan(\beta d) \left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\text{r}} + 1}\right)}. \tag{3}
\]

where \( \beta = \sqrt{k_{\text{eff}}^2 - k_0^2} \) is the normal component of the wave vector in the substrate, \( d \) is the height of the grounded dielectric substrate, \( k_{\text{eff}} = k_0 \sqrt{\varepsilon_{\text{eff}}} \) is the wave vector in the effective host medium (please see [14] for more details), \( \varepsilon_{\text{eff}} = \frac{\varepsilon_{\text{r}} + 1}{2} \) is the effective permittivity of the host medium, \( \varepsilon_{\text{r}} \) is the relative permittivity of the substrate, and \( \theta \) is the incident angle. Further, \( \alpha \) is the grid parameter for electrically dense \( (k_{\text{eff}} D \ll 2\pi) \) array of ideally conducting patches:

\[
\alpha = \frac{k_{\text{eff}} D}{\pi} \ln \left(\frac{1}{\sin \left(\frac{\pi w}{2d}\right)}\right), \tag{4}
\]

where \( D \) is the period of the structure (see Fig. 1) and \( w \) is the gap between the adjacent patches. A more accurate approximation for the grid parameter can be found in [15]. For electrically thin substrates we can simplify \( 2 \) and \( 3 \) by using the approximation \( \frac{\tan(\beta d)}{\beta} \approx d \).

We see that all angle-dependent terms in \( 2 \) and \( 3 \) have the relative permittivity of the substrate (see also [16]), \( \varepsilon_{\text{r}} \), in the denominator. This means that by increasing the permittivity of the substrate we can diminish the effect of the incident angle to the surface impedances. For relatively high values of \( \varepsilon_{\text{r}} \) the expressions \( 2 \) and \( 3 \) for the surface impedance both reduce in case of electrically thin substrates to

\[
Z_{\text{TE}}^{-1} \approx j\omega\mu_0 d \frac{1}{1 - 2k_{\text{eff}} \alpha d}, \tag{5}
\]

which clearly is not a function of the incident angle. By increasing the losses in the substrate (this would affect the terms \( k_{\text{eff}} \) and \( \alpha \)), the high-impedance surface structure could be used as an absorber that has a stable operation with respect to the incidence angle.

The proposed high-impedance surface absorber is a resonant structure and it suffers from the same characteristic features as other resonators, that is from narrow bandwidth. If we write \( 5 \) in the lumped-element form, we have the following expressions for the effective inductance and capacitance:

\[
L_{\text{eff}} = \mu_0 d, \tag{6}
\]

\[
C_{\text{eff}} = \varepsilon_0 (\varepsilon_{\text{r}} + 1) \frac{D}{\pi} \ln \left(\frac{1}{\sin \left(\frac{\pi w}{2d}\right)}\right). \tag{7}
\]

The losses of the surface (due to the lossy substrate) are taken into account in the complex value of the relative permittivity \( (\varepsilon_{\text{r}} = \varepsilon_{\text{r}}' - j\varepsilon_{\text{r}}'') \). One can also describe these losses with an effective resistor that would be connected between the adjacent patches of the capacitive grid. The conductance of the resistor can be calculated from the above expression for the effective capacitance, and it reads:

\[
G_{\text{eff}} = \omega\varepsilon_0 \varepsilon_{\text{r}}'' \frac{D}{\pi} \ln \left(\frac{1}{\sin \left(\frac{\pi w}{2d}\right)}\right). \tag{8}
\]

Furthermore, from the above expressions we can see that, although the increase of relative permittivity diminishes the dependence of the incident angle, this also increases the effective capacitance and hence narrows the bandwidth. By increasing the height of the substrate, the bandwidth of the absorber can be somewhat increased, but increasing the height is not desirable. Another possibility is to connect the patches to the ground plane by metallic vias and increase the absorption band by using the effect of these vias.

III. ABSORBER WITH VIAS

Let us now consider high-impedance surface absorbers in which the metallic patches have been connected to the ground plane by vias. In [13] this case was considered in order to diminish the angle-dependency from the absorber for TM-polarized incident fields. However, in this paper we employ a different approach: we use the high-permittivity substrate to diminish the angle-dependency for both polarizations in the case of electrically thin slabs, and use the vias to enhance the absorption and to widen the absorption band.

If the metallic patches are not connected to the wires of the wire medium layer, electric charges accumulate on the tips of the vias, and the wire medium is spatially dispersive even for electrically thin slabs [17]. For the absorber applications we wish to suppress the spatial dispersion in the wire medium in order to use it in the proposed design for an additional resonance. By connecting large (compared to the via diameter)
metallic patches to the tips of the vias, we prevent the charges to be accumulated on the tips of the vias. Instead, the charges spread over the metallic patches. In addition, we need to have electrically thin slab of wire medium so that the phase variation along the vias is minimum. With these two conditions fulfilled, we can suppress and neglect the spatial dispersion. In this case we model the wire medium slab as a grounded uniaxial material slab [18], [19] whose normal component of the relative permittivity is calculated using the local approximation (without spatial dispersion) [18]:

\[
\varepsilon_n = \varepsilon_r \left(1 - \frac{k_p^2}{k_0^2\varepsilon_r}\right),
\]

where the plasma frequency can be calculated using the quasi-static approximation [18]:

\[
k_p = \frac{1}{D} \sqrt{\frac{1}{2\pi} \ln \frac{D^2}{4r_0(D-r_0)}}
\]

(10)

Here \(r_0\) is the radius of the vias. We can make use of the artificial plasma resonance and widen the absorption band of the high-impedance surface by choosing the plasma frequency of the wire medium slab to lie close to the high-impedance surface resonance. In the case of an electrically thin wire medium slab (except the very proximity of the plasma frequency), the surface impedance of the high-impedance surface reads for the TM polarization (see also [19]):

\[
Z_{\text{imp}}^{\text{TM}} = \frac{j\omega\mu_0d\left(1 - \frac{\sin^2(\theta)}{\varepsilon_n}\right)}{1 - 2k_{\text{eff}}\omega d\left(1 - \frac{\sin^2(\theta)}{\varepsilon_n}\right)}
\]

(11)

For the TE polarization we still have (2).

Let us discuss the validity of (11) in the absence of losses. The local and quasi-static model of the wire medium assumes that the phase variation along the normal direction of the uniaxial slab is minimum. For an uniaxial slab, the normal component of the propagation constant for the TM-polarized field reads (see e.g. [18]):

\[
\beta_{\text{TM}}^2 = k_0^2\varepsilon_t\mu_t - k_0^2\varepsilon_t\varepsilon_n
\]

(12)

where \(\varepsilon_t\) and \(\mu_t\) are the tangential components of the relative permittivity and relative permeability, respectively. In our case \(\varepsilon_t = \varepsilon_r\) and \(\mu_t = \mu_0\). We see that in the vicinity of the plasma frequency of the wire medium (\(\varepsilon_n \rightarrow 0\)), the normal component of the propagation constant (12) approaches infinity and invalidates our initial assumptions on the quasi-static field distribution along the normal direction within the uniaxial material slab. We see from (11) that in the case of relatively high values of \(\varepsilon_n\) at low and high frequencies (\(\varepsilon_n \rightarrow -\infty\) and \(\varepsilon_n \approx \varepsilon_r\), respectively) the surface impedance should behave similarly to (2). However, very close to the plasma frequency, the behavior of the surface impedance is very different.

When losses are taken into account, we see that in the vicinity of the plasma frequency (\(\varepsilon_n \rightarrow -j\varepsilon'_n\)) the normal component of the propagation constant (12) does not tend to infinity but to a certain complex value. By increasing the losses we can clearly avoid the singularity of (12) and therefore widen the validity region of the approximation in the vicinity of the plasma frequency. We cannot, however, determine the exact boundaries of validity and it is considered to be outside of the scope of this paper. We can hence conclude that (11) is valid for electrically thin substrates below and above a narrow frequency band in the very vicinity of the plasma frequency (see also [20]).

IV. NUMERICAL RESULTS

As an example of the performance of the absorbing layer, an artificial impedance surface with the following parameters is considered: \(D = 5\) mm, \(w = 0.1\) mm, \(d = 3\) mm, and \(\varepsilon_r = 9(1-j0.222)\). The power reflection factors are plotted in Fig. 2 for the normal incidence and for the angles of 30° and 60° for both TE and TM polarizations. The analytical results have been verified by full wave simulations done using Ansoft’s High Frequency Structure Simulator (HFSS) [21]. The simulation results agree very well with our analytical results have been verified by full wave simulations done using Ansoft’s High Frequency Structure Simulator (HFSS) [21].
results and the performance of the absorber is little affected by the change of the incidence angle, as expected. The resonance frequency remains the same for both TE and TM polarizations.

In the case of presence of vias, we wish to demonstrate the widening of the absorption band by using the plasma resonance. The parameters for the impedance surface are the same as in Fig. 2. The radius of the vias, \(r_0\), is changed in order to show that the widening is truly because of the plasma resonance. In Fig. 3(a) and (b) the power reflection factors are plotted for the TE and TM polarization for the incident angle of \(60^\circ\), respectively. The following values were considered for the vias: 0.01 mm and 0.05 mm. The analytical results in Figs. 3(a) and (b) have been verified using CST Microwave Studio [22].

For comparison, a low-permittivity example is considered as well. With this example we wish to demonstrate the dependency of the operation on the relative permittivity of the substrate. In addition, we wish to show that the bandwidth of the absorber can be enlarged by means of the plasma frequency of the wire medium and by choosing the parameters for the structure favorably. In Fig. 4(a) and (b) the power reflection factors are plotted for different via radiuses for an absorber with the following parameters: \(D = 10\) mm, \(w = 1.25\) mm, \(h = 3\) mm, and \(\varepsilon_r = 2(1 - j0.5)\).
The plasma frequency close to the resonance frequency of the absorber is given for the considered structure. We can clearly see in a frequency band from 6.8 GHz to 8.3 GHz. The parameters of the absorber are the following: \( D = 10 \text{ mm}, w = 1.25 \text{ mm}, h = 3 \text{ mm}, \varepsilon_r = 2(1 - j0.5) \), and \( r_0 = 0.1 \text{ mm} \).

In Table I the plasma frequencies for different via radiuses \( |r| \) are compared to each other. In Fig. 6 the power reflection factors are plotted for different incident angles and in Fig. 7 the simulation results obtained using CST Microwave Studio for different incident angles are plotted in decibels. Considering \(-15\) dB to be the limit of good absorption, we find that in the case of vias for the oblique incidence of \( 60^\circ \) we fulfill this limit in a frequency band from 4.6 GHz to 8 GHz whereas without vias this band would range from 6.8 GHz to 8.3 GHz.

In Table II the plasma frequencies for different via radiiuse is given for the considered structure. We can clearly see the effect of the plasma frequency to the power reflection factors in Figs. 3 and 4. We can also see that by choosing the plasma frequency close to the resonance frequency of the host medium can be used. Fig. 5 shows the results for the same absorber in the absence of vias. Clear difference between the results for the TM-polarized case is seen when Figs. 4(b) and 4(c) are compared to each other. In Fig. 6 the power reflection factors are plotted for different incident angles and in Fig. 7 the simulation results obtained using CST Microwave Studio for different incident angles are plotted in decibels. Considering \(-15\) dB to be the limit of good absorption, we find that in the case of vias for the oblique incidence of \( 60^\circ \) we fulfill this limit in a frequency band from 4.6 GHz to 8 GHz whereas without vias this band would range from 6.8 GHz to 8.3 GHz.

In the presence of vias the absorption band can be enlarged and the absorption can be enhanced.

In Figs. 5 we see that the relative bandwidth of the absorption has been increased when compared to the results presented in Figs. 3. For the second example we have increased the operational frequency of the absorber approximately by a factor of two, lowered the permittivity of the substrate approximately by a factor of four, and kept the height of the structure the same. Because of this, the wave number for normal incidence in the uniaxial material slab, (12), remains roughly the same for both cases, as does the effective inductance (6). Simultaneously we have decreased the capacitance of the structure.

The increase of the relative bandwidth can be partially explained through the quality factor for a parallel resonant circuit. Although the losses in our case are high, the following expression for the bandwidth of parallel resonant circuits still holds qualitatively:

\[
BW = \frac{1}{Q} = G_{\text{eff}} \sqrt{\frac{L_{\text{eff}}}{C_{\text{eff}}}} = G_{\text{eff}} \omega_r L_{\text{eff}},
\]

where \( \omega_r \) is the angular resonance frequency of the circuit. However, this is not a fair comparison as the resonance frequencies of our example "circuits" are not the same.

In our second example in Figs. 4 the enlargement of the bandwidth is also partially due to the fact that in the case of lower permittivity substrates, the resonance frequency of the absorber shifts to higher frequencies as the incident angle grows. Together with the rather stable resonance caused by the stable plasma frequency of the wire medium, this leads to the case where the absorption band widens with the incidence angle, as shown in Fig. 6.

**V. Conclusions**

An electrically thin absorber for wide incidence angles and for both polarizations has been presented. The absorber is composed of a patch array over a grounded dielectric substrate.
TABLE I
THE PLASMA FREQUENCIES FOR DIFFERENT VIA RADIUSES.

| $r_0$ (mm) | $f_p$ (GHz) |
|-----------|-------------|
| 0.01      | 3.6         |
| 0.05      | 4.4         |
| 0.1       | 4.7         |
| 0.2       | 5.3         |

with or without vias. It has been shown that a relatively high value of the permittivity is needed for the substrate in order to have a stable operation of the absorber with respect to the incidence angle. The increase in the relative permittivity of the substrate leads to the decrease in the bandwidth of the absorber. It has been shown in this paper that the absorption band can be enlarged and the absorption enhanced for the TM polarization by using metallic vias to connect the metallic patches of the high-impedance surface to the ground plane.

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