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A Thin Electromagnetic Absorber for Wide Incidence Angles and Both Polarizations

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***Abstract*—A design for planar electromagnetic absorbers is presented. The performance of this absorber is maintained over a wide incidence angles and for both TE and TM polarization. The absorber is composed of a high-impedance surface comprising an array of patches over a grounded lossy dielectric slab perforated with metallic vias (wire medium). The main contribution of the paper is to demonstrate and practically use the presence of an additional resonance when the plasma frequency of the wire medium 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, through the derivation of simple and efficient analytical expressions, specifically derived for the problem at hand. We show that the presence of the vias influences the oblique incidence TM absorption, and when properly designed, the insertion of the vias into the absorber structure results in a bandwidth enlargement and higher absorption performance.**

***Index Terms*—Absorber, bandwidth enlargement, wide incidence angles, wire media.**

I. Introduction

CLASSICAL structures for electromagnetic absorbers include Jaumann, Salisbury, and Dallenbach absorbers [1] (see also [2], [3]). In Salisbury absorbers a resistive sheet is placed at a distance of $\lambda/4$ over the ground plane in order to generate losses to the incident field, whereas in Jaumann absorbers resistive sheets are stacked over each other at an approximate distance of a quarter wavelength distance (measured at the center frequency of the absorption band) generating a wider absorption band compared to the Salisbury absorber. In Dallenbach 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.

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Possibilities to enhance the performance of these absorbers have been widely studied. For instance, one may include chiral inclusions to the Dallenbach absorber's dielectric coatings and use the chiral resonance to enhance the absorption and enlarge the bandwidth of the absorber [4], or one can 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. What is common for all of the aforementioned absorption enhancement techniques, is that the widening of the absorption band is achieved by creating an additional resonance in the vicinity of the primary resonance, i.e., the $\lambda/4$-resonance of the grounded dielectric slab. Because of this, the thickness of the absorbers 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]. One can even connect resistors between the adjacent metallic parts of the capacitive sheet of the high-impedance surface [10], [11]. By increasing the overall thickness of the structure slightly, and exploiting two close resonances, a more wideband absorber can be designed by these techniques [12]. The drawback of these designs, especially the ones using lumped resistors, is the inherent difficult way of realizing the resistive sheet (the high cost of high frequency lumped resistors and the number of spot welding).

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 incidence angle was obtained by using metallic vias connecting the patches to the ground plane. The purpose was to use the extreme anisotropy of the wire medium formed by the metallic wires in the high-impedance surface favorably, and excite only the TEM mode in the array of vias treated as the wire medium slab. However, the analytical expressions in that paper for the grid impedance of the array of square patches were not accurate. In this paper we present a revised model which makes use of more accurate expressions for the surface impedance. More remarkably, by employing the proposed model, we show that vias can be used to increase the absorption band for the TM-polarized oblique incidence, by exploiting an additional resonance when the plasma frequency of the wire medium in the dielectric substrate is close to the original resonance of the high-impedance surface. Also, by using the above mentioned expressions we derive an efficient design methodology for this type of structures.

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, in terms of stable resonance frequency, is achieved by increasing the permittivity of the substrate. We will then consider high-impedance surfaces with vias in Section III and in Section IV we 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. 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 was derived. The surface impedance, $Z_{\rm inp}$, can be considered to be a parallel connection of the grid impedance of the patch array, $Z{\rm g}$ and the surface impedance of the grounded dielectric slab, $Z_{\rm s}$

$$Z_{\rm inp}^{-1} = Z_{\rm g}^{-1} + Z_{\rm s}^{-1}. \tag{1}$$

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

$$Z_{\rm inp}^{\rm TE} = \frac{j\omega\mu_0 \frac{\tan(\beta h)}{\beta}}{1 - 2k_{\rm eff}\alpha \frac{\tan(\beta h)}{\beta}\left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\rm r}+1}\right)}, \tag{2}$$

$$Z_{\rm inp}^{\rm TM} = \frac{j\omega\mu_0 \frac{\tan(\beta h)}{\beta}\left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\rm r}}\right)}{1 - 2k_{\rm eff}\alpha \frac{\tan(\beta h)}{\beta}\left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\rm r}}\right)}, \tag{3}$$

where $\beta = \sqrt{k_0^2\varepsilon_{\rm r} - k_{\rm t}^2}$ is the normal component of the wave vector in the substrate, h is the height of the grounded dielectric substrate, $k_{\rm eff} = k_0\sqrt{\varepsilon_{\rm eff}}$ is the wave vector in the effective host medium (please see [14] for more details), $\varepsilon_{\rm eff} = (\varepsilon_{\rm r}+1)/2$ is the effective relative permittivity of the host medium, $\varepsilon_{\rm r}$ is the relative permittivity of the substrate, and θ is the incidence angle. Further, α is the *grid parameter* for electrically dense ($k_{\rm eff}D \ll 2\pi$) array of ideally conducting patches

$$\alpha = \frac{k_{\rm eff}D}{\pi}\ln\left(\frac{1}{\sin\left(\frac{\pi w}{2D}\right)}\right) \tag{4}$$

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 $\tan(\beta h)/\beta \approx h$.

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

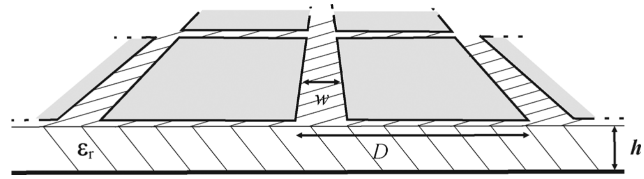


Fig. 1. Proposed absorbing structure. The dielectric substrate with relative permittivity $\varepsilon_{\rm r}$ may include metallic vias.

$$Z_{\rm s}^{\rm TE} = Z_{\rm s}^{\rm TM} \approx \frac{j\omega\mu_0 h}{1 - 2k_{\rm eff}\alpha h} \tag{5}$$

which clearly is not a function of the incidence angle. By increasing the losses in the substrate (this would affect the terms $k_{\rm eff}$ and α), 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 a limited bandwidth. If we write (5) in the lumped-element form, we have the following expressions for the effective inductance and capacitance

$$L_{\rm eff} = \mu_0 h, \tag{6}$$

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

The losses of the surface (due to the lossy substrate) are taken into account in the complex value of the relative permittivity ($\varepsilon_{\rm r} = \varepsilon_{\rm r}' - j\varepsilon_{\rm r}''$). One can also describe these losses at the resonance 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:

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

Furthermore, from the above expressions we can see that, although the increase of relative permittivity diminishes the dependence of the incidence 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 for TM-polarized incident plane waves.

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 can prevent the charges from accumulating on the tips of the vias and, 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 the spatial dispersion in the wire medium and neglect it in our analysis. 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]

$$\varepsilon_{\rm n} = \varepsilon_{\rm r}\left(1 - \frac{k_{\rm p}^2}{k_0^2\varepsilon_{\rm r}}\right), \tag{9}$$

where the "plasma wave number" is given by

$$k_{\rm p} = \frac{1}{D\sqrt{\frac{1}{2\pi}\ln\frac{D^2}{4r_0(D-r_0)}}}. \tag{10}$$

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])

$$Z_{\rm inp}^{\rm TM} = \frac{j\omega\mu_0 h\left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\rm n}}\right)}{1 - 2k_{\rm eff}\alpha h\left(1 - \frac{\sin^2(\theta)}{\varepsilon_{\rm n}}\right)}. \tag{11}$$

For the TE polarization the incident electric field is orthogonal to the vertical vias and hence does not excite them. Therefore, the vias have no effect on the response of the absorber for the TE-polarized incident fields and we still have (2) for this polarization.

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 a uniaxial slab, the normal component of the propagation constant for the TM-polarized field reads (see e.g., [18])

$$\beta_{\rm TM}^2 = k_0^2\varepsilon_{\rm t}\mu_{\rm t} - k_{\rm t}^2\frac{\varepsilon_{\rm t}}{\varepsilon_{\rm n}}, \tag{12}$$

where $\varepsilon_{\rm t}$ and $\mu_{\rm t}$ are the tangential components of the relative permittivity and relative permeability, respectively. In our case $\varepsilon_{\rm t} = \varepsilon_{\rm r}$ and $\mu_{\rm t} = \mu_0$. We see that in the vicinity of the plasma frequency of the wire medium ($\varepsilon_{\rm n} \to 0$), 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 $\varepsilon_{\rm r}$ at low and high frequencies ($\varepsilon_{\rm n} \to -\infty$ and $\varepsilon_{\rm n} \approx \varepsilon_{\rm r}$, respectively) the surface impedance should behave similarly to (5). 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 ($\varepsilon_{\rm n} \to -j\varepsilon_{\rm r}''$) 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 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 and Validation

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, $h = 3$ mm, and $\varepsilon_{\rm r} = 9(1 - {\rm j}0.222)$. 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 using Ansoft's High Frequency Structure Simulator (HFSS) [21]. The simulation results agree very well with our analytical results and the resonance frequency of the structure is little affected by the change of the incidence angle, as expected.

With the following examples we wish to demonstrate that by including vias into the substrate of the high-impedance surface it is possible to widen the absorption band by using the plasma resonance. However, in order to take full advantage from the proposed technique, the high-impedance surface structure together with the plasma resonance should be designed properly. In this design work we have made use of the expressions (2), (3), and (11).

For the first example the parameters of the impedance surface are the same as in Fig. 2. The radius of the vias, r_0, is changed in order to show the effect of the plasma resonance of the wire medium to the bandwidth of the absorber with respect to the reference case without vias. In Fig. 3(a) and (b) the power reflection factors are plotted for the TE and TM polarization for the incidence angle of 60°, respectively, and with the values of 0.01 mm and 0.05 mm for the radius of the vias. The analytical results in Figs. 3(a) and (b) have been verified using CST Microwave Studio [22]. We can see that the absorption bandwidth is increased in Fig. 3(b) as compared to the reference case of the same structure without the vias. Moreover, in order to improve the situation the most, the plasma frequency should lie close to

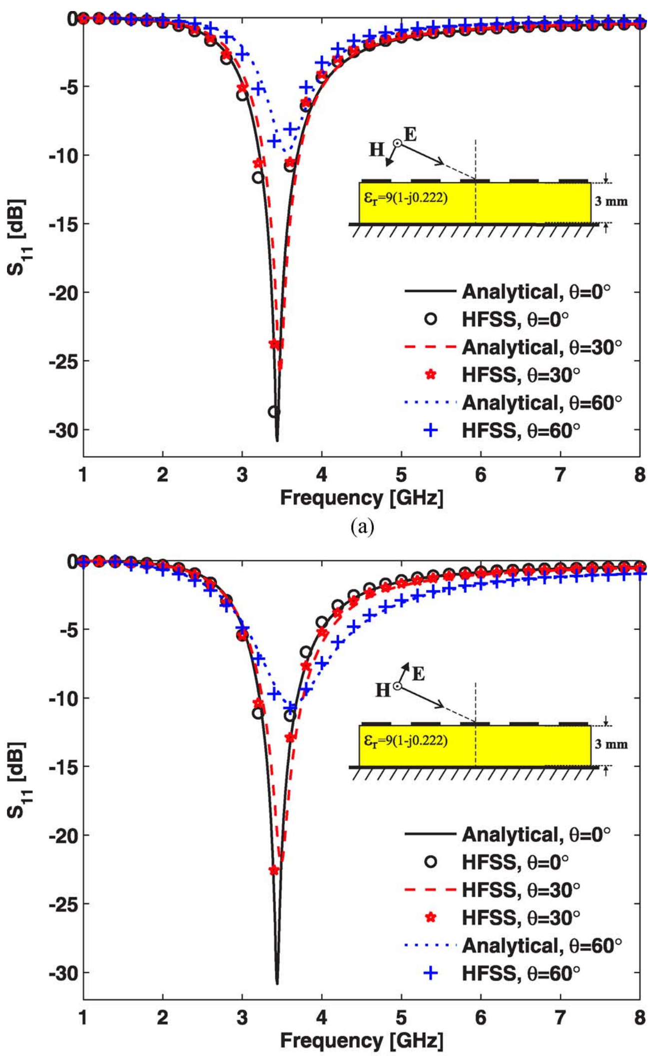


Fig. 2. Power reflection factors for the incidence angles of 0°, 30°, and 60° for (a) TE and (b) TM polarization. The parameters of the absorber are the following: $D = 5$ mm, $w = 0.1$ mm, $h = 3$ mm, and $\varepsilon_r = 9(1 - j0.222)$.

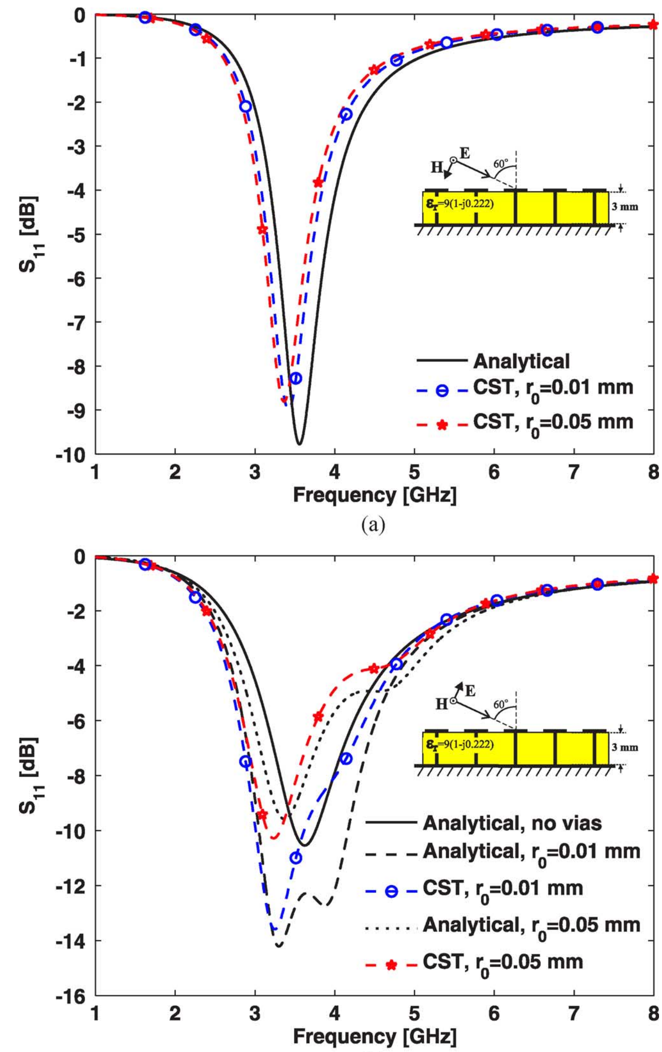
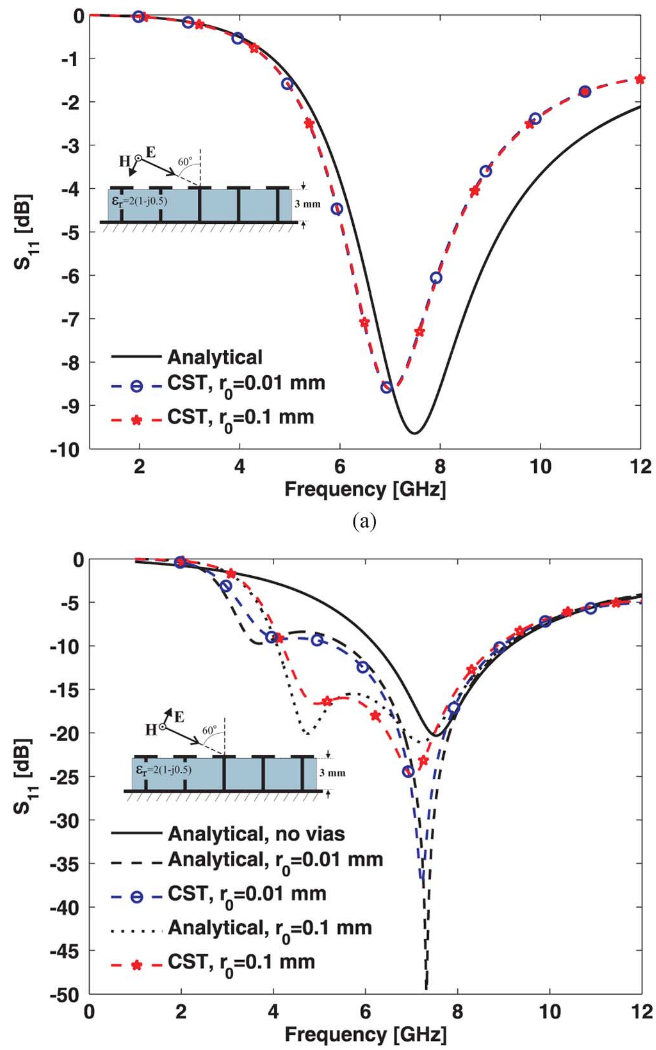


Fig. 3. Effect of the vias to the power reflection factors for (a) TE and (b) TM polarization. The angle of incidence is 60°. For the TE-polarized case the analytical results are the same for different via radii and in the absence of vias. $D = 5$ mm, $w = 0.1$ mm, $h = 3$ mm, and $\varepsilon_r = 9(1 - j0.222)$.

the main resonance of the high-impedance surface, i.e., the resonance due to the structural dimensions of the impedance surface excluding the vias. As the results in Fig. 3 show, it is not predetermined that by including metallic vias into the structure the bandwidth of the absorber will be enlarged. Instead, the radius of the vias and the period of the lattice need to be chosen favorably in order to benefit from the vias the most, as shall be seen with the following example.

For comparison, a low-permittivity example is considered as well. With this example we wish to demonstrate that the bandwidth of the absorber can be enlarged considerably by means of the plasma resonance of the wire medium and by choosing the parameters for the structure favorably, as discussed in the previous paragraph. In Fig. 4(a) and (b) the power reflection factors are plotted for different via radii for an absorber with the following parameters: $D = 10$ mm, $w = 1.25$ mm, $h = 3$ mm, $\varepsilon_r = 2(1 - j0.5)$, and the incidence angle $\theta = 60°$. In Fig. 4(a) the difference between the simulation results is minimum and the simulated results concur with each other almost perfectly. It should be noted that here the substrates cannot be treated as electrically thin substrates nor is the patch array as electrically dense as in the first example (Figs. 2 and 3). According to the analytical model, for the TE-polarized fields the vias have no effect on the fields in the wire medium slab and the normal component of the wave vector in the host medium can be used. Fig. 5 shows the results for the second example in the absence of vias. Clear difference between the results for the TM-polarized case is seen when Figs. 4(b) and 5 are compared with each other. In Fig. 4(b) we see notable enlargement of the absorption band, with respect to the case of no vias, when the vias are included into the design. Furthermore, Figs. 5 and 6 show that the enlargement of the absorption band allows to maintain good absorption at the center frequency of the band for different incidence angles giving a clear practical benefit.

In Table I the plasma frequencies for different via radii and lattice periods is given for the considered structures. We can clearly see the effect of the plasma frequency to the power reflection factors in Figs. 3–6. We can also see that by choosing



(a)

(b)

Fig. 4. Effect of the vias to the power reflection factors for (a) TE and (b) TM polarization. The angle of incidence is 60°. For the TE-polarized case the analytical results are the same for different via radii and in the absence of vias. The parameters of the absorber are the following: $D = 10$ mm, $w = 1.25$ mm, $h = 3$ mm, and $\varepsilon_r = 2(1 - j0.5)$.

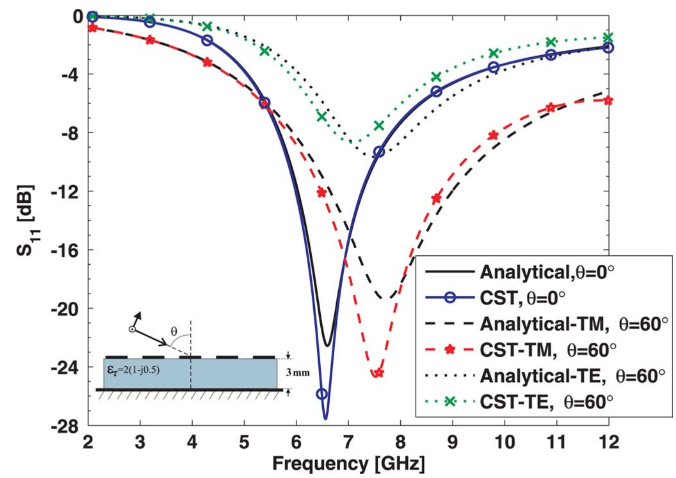


Fig. 5. Power reflection factors for the incidence angle of 60° for TE and TM polarization in the absence of vias. The parameters of the absorber are the following: $D = 10$ mm, $w = 1.25$ mm, $h = 3$ mm, and $\varepsilon_r = 2(1 - j0.5)$.

TABLE I
THE NORMALIZED PLASMA FREQUENCIES FOR DIFFERENT VIA RADII AND LATTICE PERIODS

r_0	D	ε_r	$f_p/\sqrt{\varepsilon_r'}$
0.01 mm	5 mm	9(1 - j0.222)	3.6 GHz
0.01 mm	10 mm	2(1 - j0.5)	3.6 GHz
0.05 mm	5 mm	9(1 - j0.222)	4.4 GHz
0.1 mm	10 mm	2(1 - j0.5)	4.7 GHz
0.5 mm	7.3 mm	2.65	8.6 GHz

the plasma frequency close to the resonance frequency of the impedance surface, the absorption band can be enlarged and the absorption can be enhanced.

At plasma resonance the current induced on the metallic wires equals in magnitude with the displacement current and is out of phase with it, and a more oblique angle for the incident field increases the magnitude of these quantities, i.e., the resonance becomes stronger. Indeed, in Fig. 6, where the power reflection factors for the second example are plotted for different incidence angles in the presence of vias, we see that as the incidence angle grows, the plasma resonance (at 4.7 GHz) becomes stronger and absorption is increased, as suspected. Although the change in the incidence angle does not affect the plasma frequency, it is possible that due to the spatially dispersive properties of the capacitive array, the additional absorber resonance occurring due to the plasma frequency in the absorber might be affected by the change of the incidence angle.

In [23] the reflection phase characteristics of similar mushroom-like high-impedance surface as here was studied. The authors of that paper noticed in their HFSS simulations that for the obliquely incident TM-polarized plane wave two resonances occur for the high-impedance surface. The simulation results were validated by measurements. The double-resonance phenomenon noticed in the reflection phase simulations by the authors of [23] occurs due to the plasma resonance of the wire medium, i.e., due to the same physical property of the mushroom structure that is used in this paper to enhance the performance of absorbers for TM-polarized incident fields. In order to validate our analytical model against the experimental results of [23], we have calculated the reflection phases in Fig. 7 for a high-impedance surface with exactly the same parameters as in the [23]. Following the notations in Fig. 1 these parameters read: $D = 7.3$ mm, $w = 0.3$ mm, $h = 1.5$ mm, $r_0 = 0.5$ mm, and $\varepsilon_r = 2.65$. The results in Fig. 7 agree well with the results presented in [23].

In Fig. 4(a) and (b) 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.

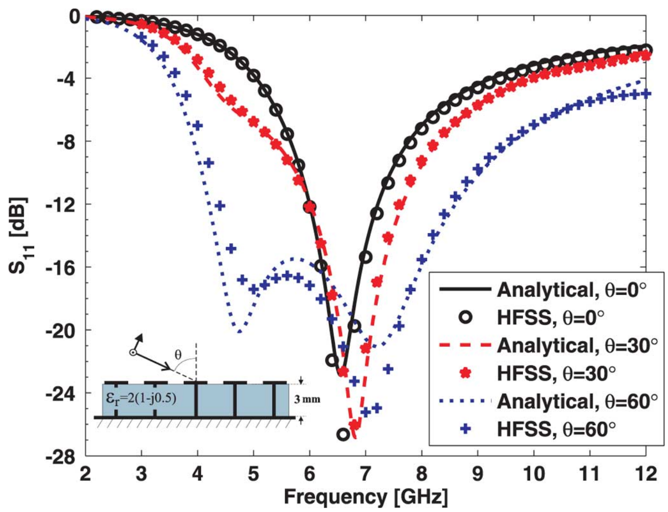


Fig. 6. Power reflection factors for different incidence angles for the TM polarization in the presence of vias. The parameters of the absorber are the following: $D = 10$ mm, $w = 1.25$ mm, $h = 3$ mm, $\varepsilon_{\rm r} = 2(1-{\rm j}0.5)$, and $r_0 = 0.1$ mm.

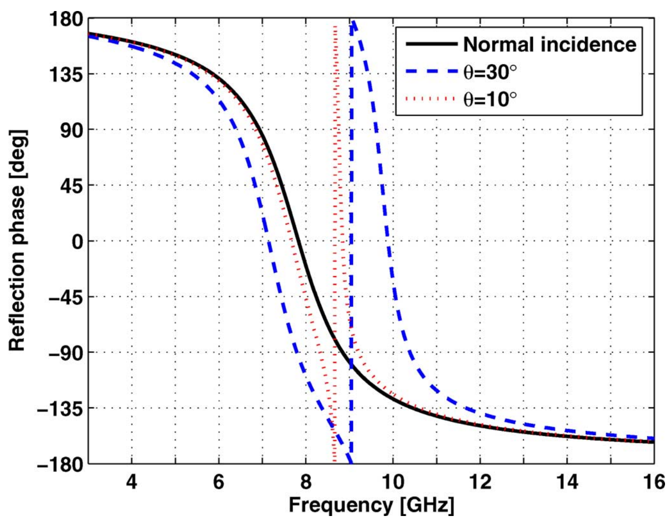


Fig. 7. Reflection phase according to the analytical model for a mushroom structure with the following parameters: $D = 7.3$ mm, $w = 0.3$ mm, $h = 1.5$ mm, $r_0 = 0.5$ mm, and $\varepsilon_{\rm r} = 2.65$ (see [23]).

Although the losses in our case are high, the following expression for the bandwidth of parallel resonant circuits still holds qualitatively

$$BW = Q^{-1} = G_{\rm eff}\sqrt{\frac{L_{\rm eff}}{C_{\rm eff}}} = G_{\rm eff}\omega_{\rm r}L_{\rm eff}, \qquad (13)$$

where $\omega_{\rm r}$ 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(a), (b) 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 incidence angle grows. Together with the 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. Conclusion

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 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. The evident limitation of this approach is that the vias have no effect on the TE polarization. However, in a practical environment, waves imping on the absorber with a random polarization. Therefore, the presented modification introduces an average lowering in the reflected power.

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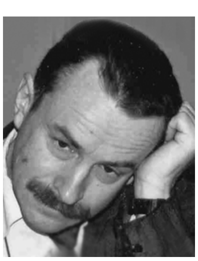

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