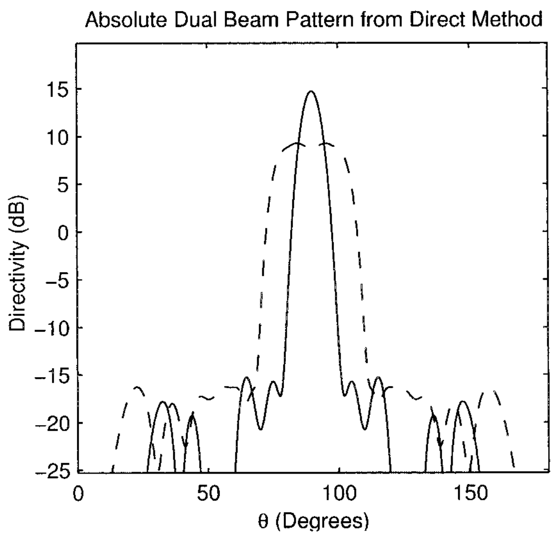

Figure 12 This figure verifies the pattern achieved by directly optimizing the element excitations

ing. The particle swarm was used to find solutions to a specific dual-beam array problem in two ways. First, the PSO optimized the Woodward–Lawson coefficients. Second, the PSO optimized the element excitation amplitudes and phases directly. Both methods provided acceptable solutions to the problem, but the second method was found to be more straightforward both conceptually and in practice.

In real-life applications, errors in power dividing networks and sampling error associated with binary phase shifters are inevitable, and practical arrays must be able to maintain acceptable performance in spite of these imperfections. The particle swarm-optimized reconfigurable array designs were found to be resistant to simulated variations in the excitation coefficients.

Future work with the particle swarm might extend to many different areas of antenna design and analysis. The PSO program developed at UCLA has the ability to be linked to nearly any numerical simulation program available, and is therefore capable of optimizing any structure that can be numerically simulated. In particular, multiple-beam array problems could be approached using more degrees of freedom than are utilized in the present work. For example, the element position and geometry could be optimized in addition to the array excitation to achieve even more complex multiple-beam patterns.

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THIN ABSORBING STRUCTURE FOR ALL INCIDENCE ANGLES BASED ON THE USE OF A HIGH-IMPEDANCE SURFACE

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ABSTRACT: *It is shown that thin mushroom layers (high-impedance surfaces realized as regular arrays of small patches at a small distance from a metal surface) can be used as radar-absorbing structures whose performance does not change with the incidence angle for TM-polarized waves. The key role of the vias connectors between the patches and the ground plane is explained, and potential performance demonstrated in examples.*
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Key words: *absorbers; RCS reduction; high-impedance surface; mushroom layer*

1. INTRODUCTION

The design of thin absorbing layers for radar cross section reduction is a challenging task, because the thickness reduction leads to a decrease of the bandwidth [1]. Another problem is that obliquely incident waves are absorbed much less effectively than normally incident plane waves. Indeed, imagine an absorbing layer excited by a plane wave whose tangential to the interface wavevector component is $\mathbf{k}_t$. If the absorber material has the material parameters ε and μ, the normal to the surface component of the propagation factor is $\beta = \sqrt{k^2 - k_t^2}$, where $k = \omega\sqrt{\varepsilon\mu}$. For plane waves coming from free space (parameters denoted as ε_0, μ_0, $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$, $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$) at an angle θ the tangential propagation factor is $k_t = k_0 \sin\theta$. Thus, the electrical thickness of the layer $|\beta|d$ decreases if the incident angle increases. Due to the same reason, the resonance frequency of Salisbury absorbers (resistive sheets located quarter-wavelength apart from metal bodies) is different for different incidence angles: the electrical thickness of the spacing between the sheet and the conductor is proportional to $\cos\theta$.

In this paper we describe an absorbing layer that does not suffer from this drawback, and has the same performance for wide ranges of the incidence angles.

2. HIGH-IMPEDANCE MUSHROOM SURFACES FOR OBLIQUELY INCIDENT WAVES

The proposed design is based on the use of a certain feature of high-impedance surfaces realized as so-called mushroom layers:

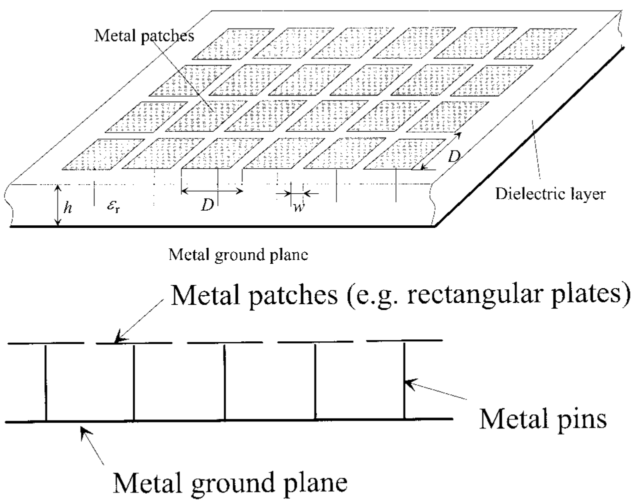

Figure 1 A high-impedance surface realized as an array of patches over a ground plane. Near the working frequency the thickness of the layer is much smaller than the wavelength. Also the patch array period is considerably smaller than the wavelength

arrays of patches connected to the ground plane by thin vias connectors [2], as shown in Figure 1.

Let us briefly consider the equivalent surface impedance and the reflection properties of high-impedance surfaces in the form of mushroom layers for obliquely incident plane waves. Here we should distinguish between two polarizations of the incident field, considering plane waves propagating along one of the crystal axes (Fig. 2).

The input impedance seen by the incident wave can be found as a parallel connection of the effective grid impedance of the patch array and the input impedance of the substrate laying on the ground plane. For an array of patches located at an interface between free space and a dielectric with the relative permittivity ε_r at frequencies well below the array resonances the grid impedance is capacitive:

$$Z_g^{TE} = \frac{\eta_0}{j\alpha(\varepsilon_r + 1)\cos^2\theta} \tag{1}$$

for TE polarized excitation, and

$$Z_g^{TM} = \frac{\eta_0}{j\alpha(\varepsilon_r + 1)} \tag{2}$$

for TM waves. Here, θ is the incidence angle and α is the grid parameter:

$$\alpha = \frac{k_0 D}{\pi} \log\left(\frac{2D}{\pi w}\right), \tag{3}$$

see, for example, [3].

If the incident field is TE polarized (Fig. 2), the external electric field is orthogonal to the wires, and the total current induced in the pins is zero. This means that we can consider the space between the patches and the ground as an isotropic dielectric slab, ignoring the vias connectors. If absorption is provided by a resistive sheet positioned on top of the patch array and grounding pins are missing, this is in fact the well-known circuit analog absorber. In the classical design (for example, in [4]) the array usually has a parallel resonance near the working frequency, in order to increase the bandwidth. Recently, the same system as an absorber was considered in [5], where the patch array was capacitive, and the goal was to reduce the layer thickness.

To analyze this absorber's performance for obliquely incident waves, we write the equivalent surface impedance of the substrate at the position of the patch array:

$$Z_s^{TE} = j\omega\mu \frac{\tan \beta h}{\beta} \approx j\omega\mu h, \tag{4}$$

where the approximate result is for thin slabs with $|\beta|h = |k|h \cos \theta \ll 1$. The input impedance of the whole structure is a parallel connection of Z_g^{TE} and Z_s^{TE}, given by

$$Z_{\mathrm{inp}}^{TE} = \frac{Z_g^{TE} Z_s^{TE}}{Z_g^{TE} + Z_s^{TE}}. \tag{5}$$

Because for TE plane waves the wave impedance is $\eta_0/\cos \theta$, the reflection coefficient reads

$$R^{TE} = \frac{Z_{\mathrm{inp}}^{TE}\cos \theta - \eta_0}{Z_{\mathrm{inp}}^{TE}\cos \theta + \eta_0}. \tag{6}$$

If there are no vias connections, it is easy to see that the result for TM-polarized incidence is exactly the same as that given by Eq. (6) for TE excitation. Thus, if there are no vias connectors, for very oblique incidence the reflection coefficient always tends to -1, because $Z_{\mathrm{inp}}^{TE}\cos \theta \to 0$ if $\theta \to \pi/2$.

If vias connectors are present, the result for the TM-polarized incident field is dramatically different [6]. An array of thin conducting pins between the patch array and the ground can be viewed as a slab filled by a wire medium [7]. In this medium, two eigenwave solutions exist. One is the TM mode of the wire medium, which is exponentially decaying, because the operational frequency is below the equivalent plasma frequency and the effective permittivity is negative [8, 9]. The field of this mode is concentrated near the upper surface, and its influence can be neglected when absorption in the substrate is considered. The only important solution in the space between the patch array and the ground is the propagating TEM wave in the multi-conductor transmission line, formed by the vias wires between the patch array and the ground plane. Its propagation factor has two components. One is orthogonal to the patch array plane, and it is equal to the

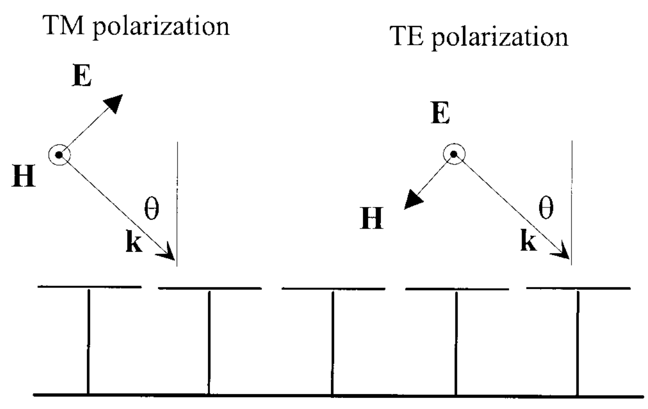

Figure 2 TM and TE plane waves incident on a mushroom layer. Note that the electric field of the TE-polarized incident wave is orthogonal to the vias connectors

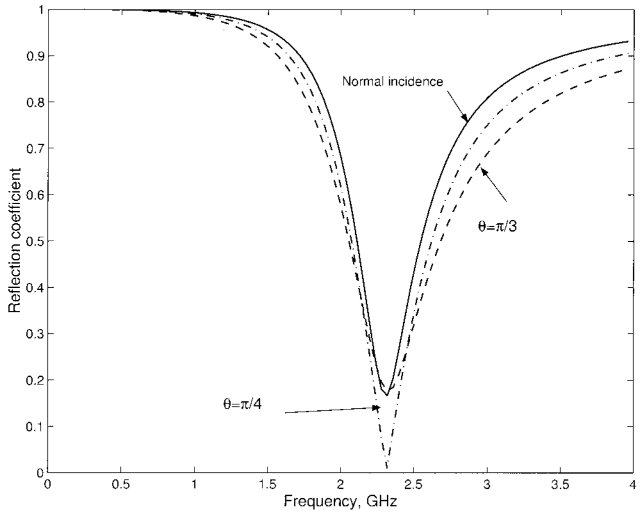

Figure 3 Absolute value of the reflection coefficient as a function of frequency for linearly polarized incident plane waves on a mushroom layer printed on a lossy dielectric substrate. θ is the incidence angle in radians. TM (vertically) polarized incidence

wave number in the substrate dielectric. The other one is tangential to that plane and naturally equal to the tangential component of the wave number of the incident wave. Electric and magnetic fields of this mode are orthogonal to the wires and their ratio (wave impedance) for the case of thin pins is approximately the same as in the filling dielectric. This is because the electric polarization of thin wires in the transverse direction is small, and the averaged quasistatic magnetic field of the wire currents is zero due to the symmetry of the problem.

Thus, we see that the surface impedance seen by a TM-polarized incident wave at the input plane of the wire grid is simply the same as that of a TEM transmission line section of the length equal to the layer thickness for all incidence angles. In other words, due to the presents of pins the surface impedance does not depend on the incidence angle:

$$Z_s^{TM} = Z_s^{TE} = j\omega\mu \frac{\tan kh}{k} \approx j\omega\mu h. \tag{7}$$

Note here that the equivalent surface impedance of the dielectric slab on a metal surface does depend on the incidence angle as $\cos^2\theta$, if the wave is TM polarized. The input impedance of the whole structure is the parallel connection of this surface impedance and the grid impedance of the patch array Z_s^{TM} (2), and it is given by Eq. (5) after replacing indices TE by TM:

$$Z_{\text{inp}}^{TM} = \frac{Z_g^{TM} Z_s^{TM}}{Z_g^{TM} + Z_s^{TM}}. \tag{8}$$

Finally, the reflection coefficient for the TM polarization is

$$R = \frac{Z_{\text{inp}}^{TM} - \eta_0 \cos\theta}{Z_{\text{inp}}^{TM} + \eta_0 \cos\theta} \tag{9}$$

In this case, because Z_g^{TM} does not depend on θ, and for thin substrates also Z_s^{TM} is approximately the same for all incidence angles due to the effect of the vias connectors, the resonance frequency of the structure is approximately the same over all incidence angles.

3. WIDE-ANGLE ABSORBER

For absorber applications, the most important conclusion from the above consideration is that the pins form a multi-conductor TEM transmission line that guides the power in the space between the metal ground and the patch array along the direction orthogonal to the metal surface. Since this is true for arbitrary TM-polarized incident fields, this means that if we now fill this volume by an absorbing dielectric material, absorption will not deteriorate at oblique incidence of waves. In addition to this advantage, there is also an advantage of a reduced thickness, as is pointed out in [5] for a system with an absorbing sheet over the patch array.

We have modeled this absorber with the use of an analytical model of mushroom layers [3]. A calculated example of the absorber performance is shown in Figure 3. The absorbing layer has the thickness of 3 mm and the relative permittivity of $9 - j2$. This material can be realized as, for example, a layered structure with intermitting layers of a microwave dielectric with a real permittivity of about 9 and graphite. On top of the layer a square patch array is printed (period 10 mm, gaps between patches 0.1 mm). The resonance absorption takes place near 2.3 GHz, that is, the absorbing layer thickness is only 1/50 of the free-space wavelength.

For TM-polarized incident waves the performance is extremely stable for all angles of incidence (see Fig. 3, in which the absolute values of the reflection coefficient are plotted for the normal incidence and the incidence angles equal to $\pi/4$ and $\pi/3$ rad). Note that the resonance frequency practically does not depend on the incidence angle. For the other polarization (TE), the performance is usual (illustrated in Fig. 4): the resonance frequency of the structure increases with increasing incident angle because the effective electrical thickness of the substrate decreases.

In fact, the presence of vias connectors brings the same performance advantage in the design of circuit analog absorbers [4, 5]. Here, the space between the patch array and the ground plane is lossless, and the absorption is due to a thin conductive layer positioned just on the array surface. This system can be analyzed in a very similar way. A thin conductive sheet is modeled as a sheet admittance $Y = \sigma d$, where σ is the material conductivity, and d is the layer thickness. This admittance is connected in parallel with the grid impedance (2) modeling the patch array. If the absorbing layer thickness d is small, as compared to the gaps

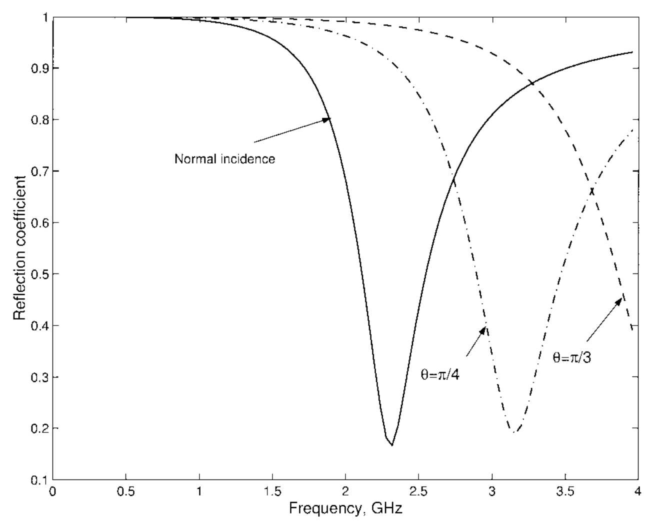

Figure 4 The same as in Fig. 3 for the TE (horizontally) polarized incidence. The same results also apply to the TM polarized incidence if there are no vias connectors

between patches w, we can assume that the array impedance does not change much, and write for the total admittance of the system "patch array + absorbing layer":

$$Y = \frac{j\alpha(\varepsilon_r + 1)}{\eta_0} + \sigma d. \tag{10}$$

It is convenient to express the result in terms of an equivalent grid parameter α that takes into account the conductive layer:

$$\alpha_{\rm eq} = \alpha - j\eta_0 \frac{\sigma d}{\varepsilon + 1}. \tag{11}$$

Replacing α by $\alpha_{\rm eq}$ in Eqs. (1) and (2), we find the reflection coefficient for this absorber as well.

If the absorbing layer thickness d is comparable or thicker than the gap width w, the gap capacitance is affected by the layer, and in formulas (1) and (2) one should replace $(\varepsilon_r + 1)$ by $(\varepsilon_r + \varepsilon_a)$, where $\varepsilon_a \approx -j\sigma/(\omega\varepsilon_0)$ is the relative permittivity of the absorbing layer. The total grid impedance of the patch array together with the absorbing layer becomes (TM incidence):

$$Z_g^{TM} = \frac{\eta_0}{j\alpha[\varepsilon_r - j\sigma/(\omega\varepsilon_0)] + \eta_0\sigma d}. \tag{12}$$

Figures 5 and 6 illustrate the influence of vias wires on the performance of circuit analog absorbers. In this example, all the geometrical parameters are the same as above. The difference is that the substrate is lossless, with $\varepsilon = 2.4$, and on the patch surface a thin conducting layer is located. The conductivity of the layer material is 500 S/m, and the layer thickness is $d = 0.02$ mm (Eq. (11) was used in calculations). Similarly to the case when the absorption occurs in the volume between the patch array and the ground, the vias connectors make the resonant frequency of the structure practically independent from the incidence angle, if the incident field is TM polarized. If the field is TE polarized or there are no vias connectors, the resonance frequency increases with increasing incident angle (Fig. 6).

4. CONCLUSION

In conclusion, a study of high-impedance mushroom surfaces at oblique incidence of plane waves of different polarizations reveals an important role of vias connectors for the power absorption of obliquely incident TM-polarized waves. Due to the existence of a TEM mode that travels in the direction orthogonal to the metal ground plane and whose propagation factor does not depend on the incidence angle, the absorber performance is exceptionally stable for all incidence angles. The resonance frequency, at which the reflection is very much reduced, is approximately independent from the incidence angle. This system also allows a substantial reduction of the layer thickness.

For the other possible polarization (TE), the vias connectors do not bring any advantage, and the resonance frequency of the absorber increases at oblique incidence, which is a common feature for known radar absorbing coverings of similar type. This is because the incident electric field is orthogonal to the metal vias connectors and does not induce any current there. "Magnetic conductors" used as vias connectors would solve this problem, but, unfortunately, they are not easy to realize.

Thus, the analyzed new structure allows us to design thin absorbers for TM waves that are functional for practically all incidence angles.

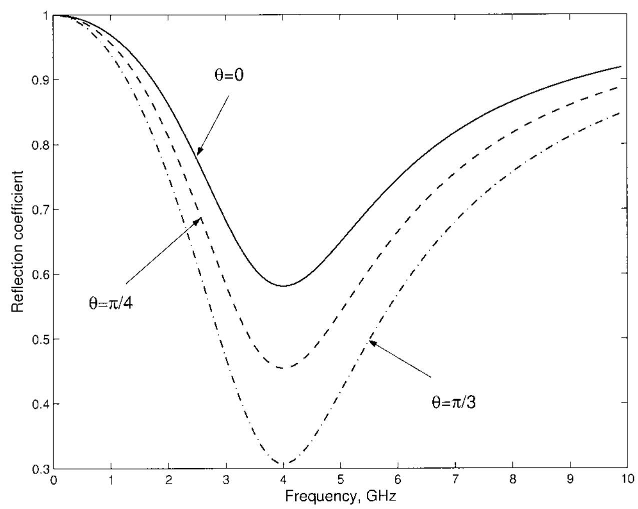

Figure 5 The absolute value of the reflection coefficient as a function of frequency for linearly polarized incident plane waves on a circuit analog absorber with vias connectors. θ is the incidence angle in radians. TM (vertically) polarized incidence

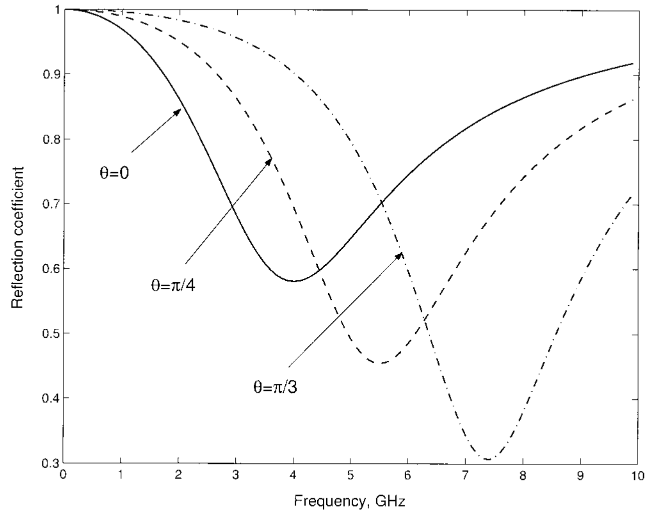

Figure 6 The same as in Fig. 5 for TE (horizontally) polarized incidence

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