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Kazemzadeh, Alireza; Karlsson, Anders

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Alireza Kazemzadeh and Anders Karlsson

Alireza Kazemzadeh and Anders Karlsson
{Alireza.Kazemzadeh,Anders.Karlsson}@eit.lth.se

Department of Electrical and Information Technology
Electromagnetic Theory
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

Abstract

Design procedures of Jaumann and circuit analog absorbers are mostly formulated for normal angle of incidence. Only a few design methods considering oblique angle of incidence are published. The published methods are restricted to single resistive layer circuit analog absorbers or multilayered Jaumann absorbers with low permittivity spacers. General design procedures are developed in this paper for multilayered Jaumann and capacitive circuit absorbers. By expanding the scan and frequency compensation techniques to multilayered structures, Jaumann absorbers with outstanding performances are designed. A capacitive circuit absorber is presented with a stable frequency response up to 45°for both polarizations, having an ultra wide bandwidth of 26 GHz.

1 Introduction

Absorbers are mounted on the surface of objects to reduce their radar cross sections. Dielectric absorbers are suitable candidates for reduction of specular reflections of large metallic objects. The simplest type of absorber called Salisbury screen [6] is formed by a single homogenous resistive sheet placed $\lambda/4$ (at absorption frequency) in front of the perfectly conducting ground plane. By increasing the number of the resistive sheets, $\lambda/4$ apart from each other (Jaumann Absorber) larger bandwidths are achieved [4, 5]. Further improvement of the bandwidth is possible by replacing homogeneous resistive sheets with lossy band-stop frequency selective surface (FSS) sheets. This results in a complex sheet admittance that by proper design increases the bandwidth. Such absorbers are referred to as circuit analog absorbers [8–10]. In a recent publication we proposed the capacitive circuit absorber, a modification to the circuit analog absorber method that not only simplifies the design procedure but also leads to new applications [7]. One of the new applications is the design of ultra wideband absorber for oblique angle of incidence. This particular feature is explained and demonstrated in this paper.

Jaumann and circuit analog absorbers are mostly investigated for normal angle of incidence. This simplifies the design procedure since the variation of the frequency response at oblique angles of incidence is not considered. Moreover, if symmetric array elements are used (e.g. crossed dipoles [10]) the frequency response becomes polarization insensitive at normal angle of incidence. The situation is totally different when the absorber is designed for oblique angles of incidence. The frequency response shifts up in frequency and becomes polarization dependent [9, 10]. These unwanted features should be compensated as much as possible if the absorber is going to operate under large scan angles (usually up to 45°) and different polarizations. Therefore, the designer faces constraints and requirements that are not present in the design of conventional absorbers. This complicates the design problem such that previous investigations described in literatures, preferred to consider only special cases that are simpler to solve.

For the Jaumann absorber Chambers and Tennant have proposed a method of design based on genetic algorithm optimization [3]. It is a powerful approach that results in large bandwidths in comparison to the other published designs [9, 10].

Since the designs are based on genetic algorithm optimization and many degrees of freedom exist in a multilayered absorber, they limit the number of optimization variables. To speed up the optimization, the permittivity of the dielectric layers are considered to be very low (foam or honeycomb material) and fixed in their designs [3]. For normal angle of incidence foam or honeycomb materials are used extensively in wideband absorbers but they are not optimal choices for designs considering large scan angles. Munk *et al* have explained and demonstrated that high permittivity dielectric layers are essential for scan and frequency compensations and increase of bandwidth [9, 10]. This paper modifies the Chambers and Tennant's approach by suggesting a very accurate model for the equivalent impedance of a resistive sheet embedded in dielectric cover. It is shown that when proper dielectric layers are used, a two layered Jaumann absorber can offer almost the same bandwidth as the three layered optimized design of Chambers and Tennant [3].

The design approach of Munk *et al* has magnificent compensation features but is limited to single resistive layer absorbers with moderate bandwidths (at most $f_{\mathrm{H}}/f_{\mathrm{L}} \approx 2.7$) [9, 10]. If larger bandwidths are desired, the number of frequency selective surfaces must increase. Accurate modeling of the frequency selective surfaces (FSS) over a large bandwidth for different angles of incidence and polarizations, is a challenging problem. The variation of the resonant frequency, the bandwidth, the harmonic and anti-resonance frequencies with respect to polarization and angles of incidence must be considered in the model [7, 8, 10]. In addition, the process of finding proper FSS elements that are able to match the ground plane to the free space over a large bandwidth for different polarizations and incident angles is complicated. This paper provides a design tool for multilayered ultra wideband capacitive circuit absorbers [7]. These absorbers are designed by low-pass FSS elements instead of band-stop resonating arrays and consequently do not suffer from the harmonics and anti-resonance problems that occur in circuit analog absorbers [9, 10]. An absorber is presented possessing the largest bandwidth among the published designs [1, 2, 8–10]. It is also shown that in contrast to Munk's approach [9, 10] it is possible to have a wider range of selections for the permittivity of the dielectric layers in multilayered absorbers. This is essential in some applications where the mechanical and thermal properties of the absorbers are important.

2   The Design Method of Munk *et al* for Single Resistive Layer Absorbers.

The design of single resistive layer Jaumann and circuit analog absorbers are investigated by Munk *et al* in [9, 10]. Since the number of resistive layers has been limited to one, it is expected that their approach cannot be applied to the general case of multilayered absorbers without modification. The significance of their investigation is the illustration of the important role that dielectric layers play in the performance of the absorber, when oblique angle of incidence is considered. They have introduced brilliant compensation techniques that are extended to multilayered absorbers in the following sections.

The schematic of a single resistive sheet/FSS layer absorber is shown in Fig. 1. According to the design method of Munk *et al*, each dielectric layer and the resistive element have specific roles in the performance of the absorber. The first dielectric layer (ϵ_1 in Fig. 1) is responsible for frequency compensation. Upward shift in frequency is a general characteristic of the absorber response at oblique angles of incidence [9, 10]. Proper selection of the permittivity of the first layer ($\epsilon_r = 2.5$ in Munk's design) can stabilize the frequency response. The second dielectric layer (ϵ_2 in Fig. 1) is used for increasing the bandwidth and scan compensation. A proper selection of its permittivity is done according to the following relation [8–10]:

$$\epsilon_r \approx 1 + \cos(\theta_i) \tag{2.1}$$

where θ_i is the (maximum) angle of incidence in air. A $45°$ angle of incidence corresponds to $\epsilon_2 = 1.7$. The thicknesses of both layers (d_1, d_2, see Fig. 1) are selected slightly larger than a quarter of a wavelength. The only remaining parameters to be determined are the resistivity of the sheet, and in case of the circuit analog absorber, the shape and dimensions of the FSS unit cell element. This is done by synthesizing the required sheet admittance that matches the ground plane to the free space for the given values of the dielectric permittivities and thicknesses. The details of the broadband matching technique are explained in [8–10].

Since the absorbers of Munk *et al* are single resistive layer with few degrees of freedom, the role of each dielectric layer is predetermined. The permittivity of the layers cannot be selected arbitrarily, otherwise the performance degrades. The situation is completely different in multilayered absorbers. As our design examples demonstrate, there are some freedom in selection of the dielectric layers. This is essential in practical designs where the mechanical or thermal properties of the absorber are also important. The absorbers of Munk *et al* have at most relative bandwidths (f_H/f_L) of $2 - 2.7$ depending on polarization [9, 10]. To broaden the bandwidth ratio and stabilize it for different polarizations, more resistive layers are required. Systematic methods are presented in the following sections to design wideband multilayered absorbers for oblique angle of incidence.

3 Multilayered Jaumann Absorber for Oblique Angle of Incidence

The Jaumann absorber consists of several homogenous resistive sheets separated by dielectric layers. An example is shown in Fig. 2. By proper selection of the resistivity of the sheets and the thicknesses and permittivities of the dielectric layers, power can be absorbed from the incident wave over a frequency range [4, 5, 8]. The design of the absorber is usually done for normal angle of incidence. This section presents a general method of design for multilayered Jaumann absorbers with wideband frequency responses for oblique angle of incidence. First, the pioneering work of Chamber and Tennant is studied and the shortcomings of their approach is explained. Then, their method is modified by providing accurate model for the impedance of a resistive
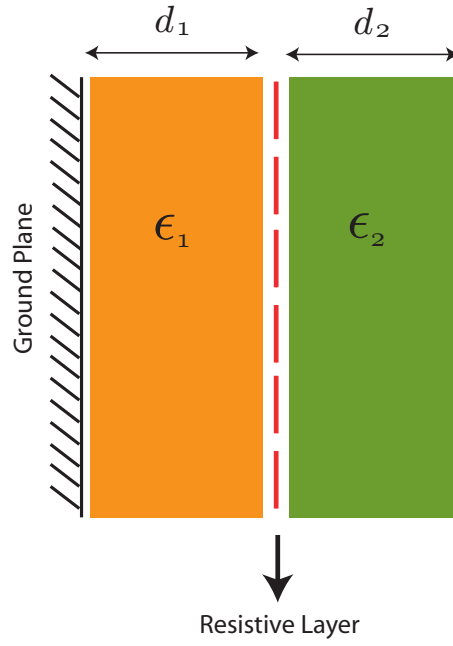
Figure 1: The schematic of a single resistive layer absorber. The resistive layer is a homogeneous sheet in the Jaumann absorber and a periodic array (FSS) in case of circuit analog absorber.
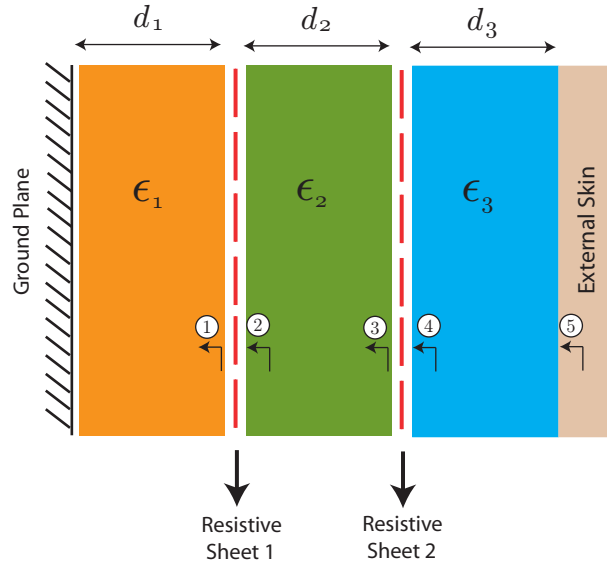
Figure 2: The schematic of a two resistive layer Jaumann absorber. The resistive sheets are embedded in thin dielectric covers not shown in the figure. The external skin is used in design No.2 ($\epsilon_r = 3$, Thickness $= 30$ mil)

sheet embedded in a dielectric cover. Different design examples are provided and important results are demonstrated by them.

3.1 Generalization of the Chamber and Tennat's Design Approach

Chambers and Tennant have proposed a method of design for oblique angle of incidence based on optimization [3]. They have published design examples that are the most wideband absorbers among the published papers [9, 10]. These large bandwidths have been achieved in the cost of using many resistive layers. This results in absorbers with large total thicknesses. It is proved in this section that more efficient designs are possible.

Since their approach is based on genetic algorithm optimization and there are many degrees of freedom in a multilayered absorber, they thought it would be helpful to minimize the number of unknown variables. Based on experience from wideband designs done for normal angle of incidence, Chamber and Tennat have considered the permittivities of the dielectric layers fixed, with values very close to unity (foams or honeycomb materials, $\epsilon_r \approx 1.1$). It was shown in the previous section that for oblique angles of incidence proper selection of the permittivity of the dielectric layers are vital for optimal performance of the absorber. The scan and frequency compensations require dielectric layers with higher permittivities than foams or honeycomb materials. It is illustrated that when proper dielectric layers are used, absorbers with fewer resistive sheets can offer the same bandwidths as the Chambers and Tennant's designs. This clearly demonstrates the important role the permittivity of the dielectric layers play in the performance of the absorber. Since the models proposed by Chambers and Tennant are not applicable to multilayered dielectric absorbers with arbitrary values of permittivity, a more general model is required.

Consider the schematic of a two resistive layer Jaumann absorber as shown in Fig. 2. It is well-known that the dielectric layers in a homogenous stratified medium can be modeled by equivalent transmission lines [11]. The length and the intrinsic impedance of the equivalent transmission lines are functions of polarization and angle of incidence. The free space surrounding the structure is also modeled by a port with proper impedance [11]. For the dielectric layer (d_j, ϵ_j) the equivalent transmission line length (l_j) and intrinsic impedance (Z_j) are obtained as follows:

$$\cos(\theta_j) = \sqrt{(1 - \sin^2(\theta_i)/\varepsilon_j)} \tag{3.1}$$

$$l_j = d_j \, \cos(\theta_j) \tag{3.2}$$

$$\text{TE Polarization:} \quad Y_j = \sqrt{\epsilon_j} \, Y_0 \, \cos(\theta_j) \tag{3.3}$$

$$\text{TM Polarization:} \quad Z_j = \frac{Z_0}{\sqrt{\epsilon_j}} \, \cos(\theta_j) \tag{3.4}$$

In the above formulas Z_0 and Y_0 are the free space intrinsic impedance and admittance, respectively. The angle θ_i is the angle of incidence and $\cos(\theta_j)$ is the direction cosine in layer j, calculated from the Snell's law [11]. For the equivalent port impedance one can use the above formulas with $\epsilon = 1$. This results in $Y_p = Y_0 \cos(\theta_i)$ for TE polarization and $Z_p = Z_0 \cos(\theta_i)$ for TM. To complete the absorber analysis, an accurate model for the resistive sheets is required. Chambers and Tennant suggest the following relations between the sheet resistivity R_s (Ω/Sq) and the equivalent resistance R (Ω) for different polarizations [3]:

$$\text{TE Polarization:} \quad R = R_s \cos(\theta_i) \tag{3.5}$$

$$\text{TM Polarization:} \quad R = R_s / \cos(\theta_i) \tag{3.6}$$

These relations are valid if and only if the reference impedance (for calculating the reflection/transsmission coefficient) is selected to be the free space intrinsic impedance. In other words, the equivalent port impedance is assumed to be fixed and equal to Z_0 in their approach. This is in conflict with Eqs. 3.3 and 3.4 for which the port impedance is a function of incident angle and polarization. To resolve the conflict two important questions must be answered. Why equations 3.5 and 3.6 do not result in perceptible errors in Chambers and Tennant's designs? and How can these equations be generalized to multilayered structure with arbitrary values of permittivity?

Consider the equivalent circuits of Fig. 3. Simple calculations show that the two circuits result in the same reflection/transmission response. If a single layer resistive sheet is considered in free space, each of the equivalent circuits of Fig. 3 can be used to model its frequency response. The parameter 'A' in Fig. 3 is equal to $\cos(\theta_i)$ for TM polarization and $1/\cos(\theta_i)$ for TE polarization. The relations of Chambers and Tennant (Eqs. 3.5, 3.6) correspond to the equivalent circuit model (b) in Fig. 3 with fixed port impedance. In multilayered structures with only low permittivity layers this model does not result in a perceptible error, but it can not be used in a general design with arbitrary permittivities. Therefore, the model with variable port impedance is used (part (a) in Fig. 3) in this paper. Consequently, Eqs. 3.5 and 3.6 are no longer valid for the equivalent impedance of the resistive sheets and new accurate relations must be proposed. From now on, the homogenous resistive sheets, and later the periodic square arrays of the capacitive circuit absorbers, are all embedded in dielectric covers, see Figs. 4 and 10. It is usually a requirement from the fabrication points of view, but it also simplifies the modeling of the resistive sheets (both homogenous and periodic patterns) significantly. Without the dielectric cover the equivalent impedance model has a complicated dependence on polarization and angle of incidence for periodic arrays, which makes modeling almost impossible. For homogenous resistive sheets embedded in a dielectric cover, the sheets can be modeled by the equivalent circuit in Fig. 4. The transmission line length (l_c) and the intrinsic impedance (Z_c) of the equivalent circuit model, are calculated by Eqs. 3.1-3.4. The resistance $R(\Omega)$ in this case has a simple relation to the sheet resistivity $R_s(\Omega/Sq)$. They are identical for different angles of incidence and polarizations. It
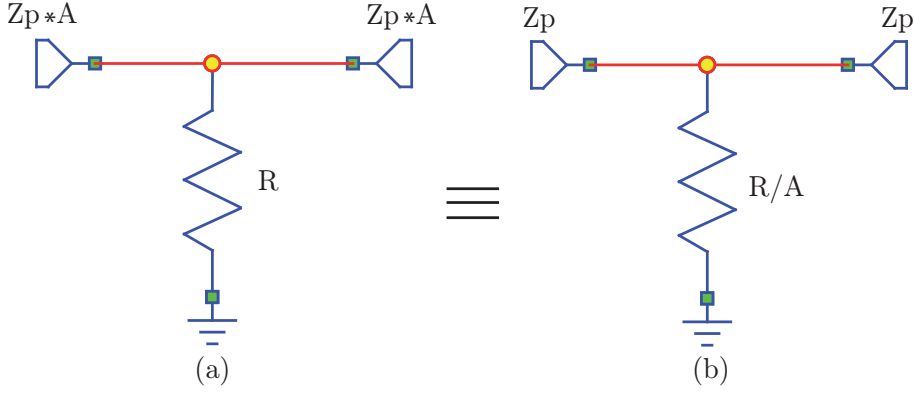
Figure 3: Equivalent circuits models of a single homogeneous resistive sheet surrounded by free space. Only circuit (a) can be used in a general multilayered absorber. The circuit (b) has been used by Chambers and Tennant and is accurate with only low permittivity spacers.

	$d_1(\,\mathrm{mm})$	$d_2(\,\mathrm{mm})$	$d_3(\,\mathrm{mm})$	$d_4(\,\mathrm{mm})$
Design No.1	5.6	4.7	6.4	Not applicable
Design No.2	5.5	5.1	4	0.76

Table 1: The thicknesses of the dielectric layers for the Jaumann absorbers

is simply the generalization of the circuit model of part (a) in Fig. 3 for a single homogenous resistive sheet in free space, to the multilayered dielectric structures.

3.2   Design Examples, Explanations and Comparisons

The whole absorber of Fig. 2 can now be modeled by equivalent circuits for both polarizations and different angles of incidence. There exists no restriction on the permittivities of the layers. This enables us to look for optimal permittivities of the layers for scan and frequency compensations and bandwidth increase. Two different designs are presented. The aim is to demonstrate that there might be more than one solution, when multilayered absorbers are considered. This valuable result permits the designer to take other physical properties of the absorber into consideration besides the electrical properties. Also it shows that the design approach suggested by Munk et.al [9, 10] is not general and it is applicable only to single resistive layer absorber.

Both of the designs are two resistive layer Jaumann absorbers. The schematic of the absorbers are the same (see Fig.2) except that the external skin (Thickness = 30 mil, $\epsilon_\mathrm{r} = 3$) is used in the second design. The thicknesses and permittivities of the spacers and sheet resistivity values of the designs are tabulated in Tables 1-3. All the resistive sheets are embedded in dielectric covers with thickness $T_\mathrm{c} = 0.2\,\mathrm{mm}$ and permittivity $\epsilon_\mathrm{c} = 3.2$ (see Fig. 4). The frequency response of the absorbers are shown in Figs. 5 and 6.

Despite the employment of different dielectric layers in the designs, the absorbers
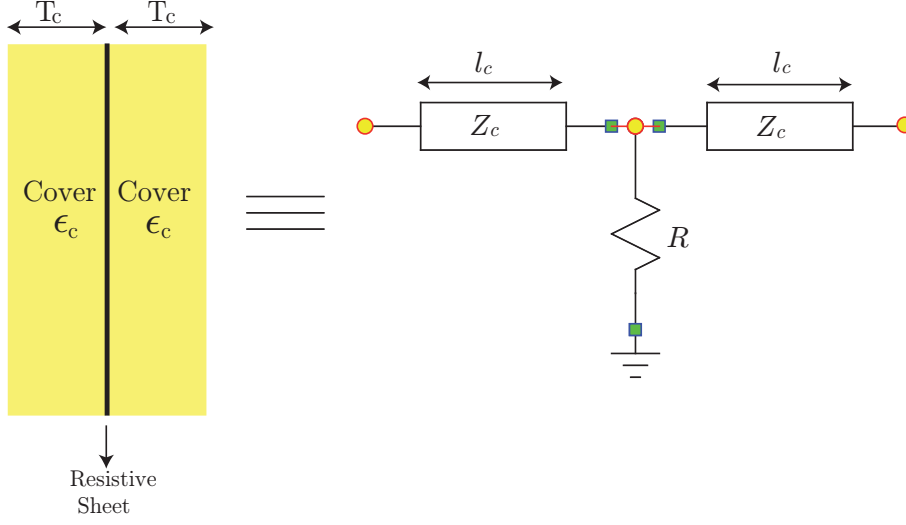
Figure 4: The schematic of the resistive sheet embedded in a thin dielectric cover and its accurate equivalent circuit model. l_c is the equivalent length (function of angle of incidence) and Z_c is the equivalent impedance (function of both polarization and angle of incidence).

	ϵ_1	ϵ_2	ϵ_3	ϵ_4
Design No.1	1.7	2	1.6	Not applicable
Design No.2	1.8	1.9	1.3	3

Table 2: The permittivities of the dielectric layers for the Jaumann absorbers

	$R_{s1}(\Omega/Sq)$	$R_{s2}(\Omega/Sq)$
Design No.1	189	648.5
Design No.2	196	710

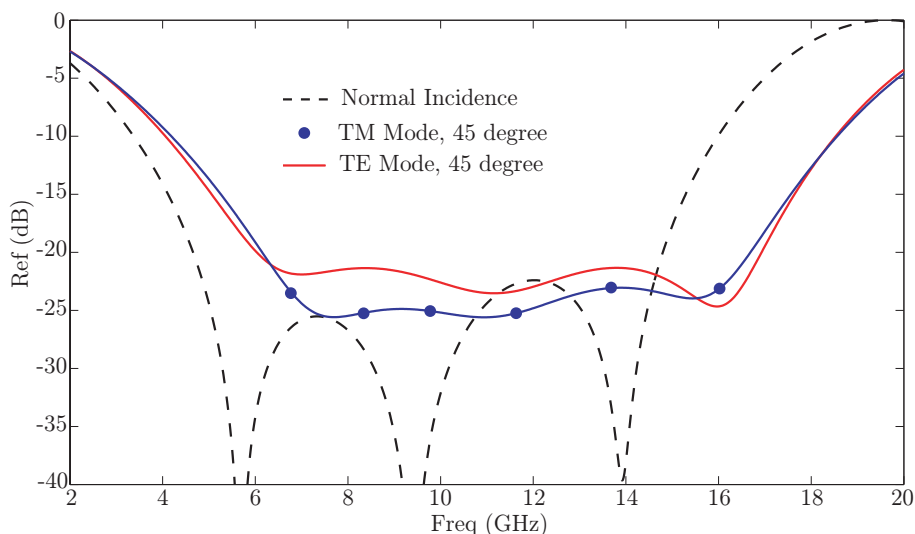**Table 3**: The resistivity of the sheets for the Jaumann absorbers
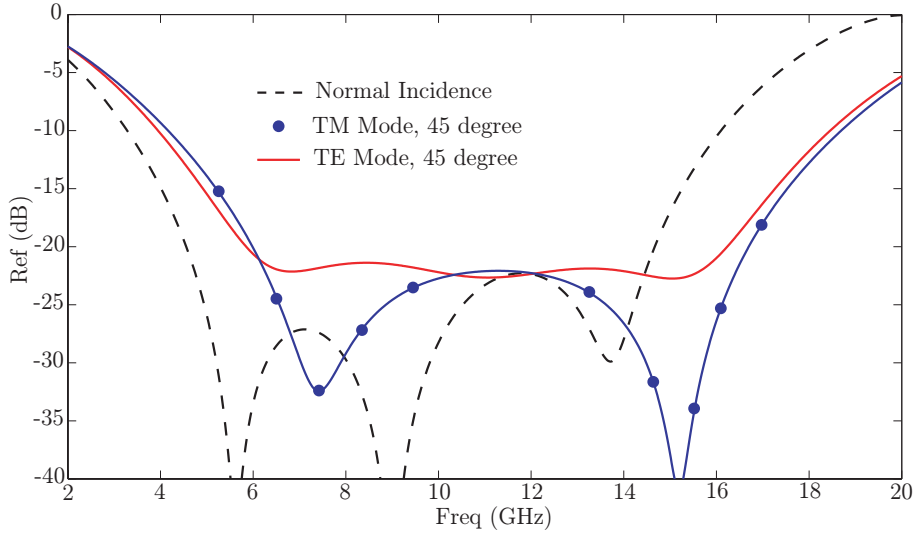
Figure 5: The frequency response of the Jaumann absorber (design No.1) for normal and oblique angles of incidence 45°.(Full-wave simulation)

have almost equal bandwidths. The possibility of applying a high permittivity external skin ($\epsilon_r = 3$) to the second design without degrading the performance is remarkable. According to the Munk's formulation it is unattainable. This is expected since Munk's approach is optimal if and only if single resistive layer absorbers are considered. In multilayered absorbers the whole structure takes care of the frequency and scan compensations. If a layer must have a certain value of permittivity or thickness (for example the external skin in the second design), the values of other layers and the resistivity of the sheets can be adjusted to compensate for the deteriorations introduced by the selection. The rule of thumbs of the Munk's approach are optimal for single layer absorbers, but the ideas can be extended and used in multilayered absorbers. For example it can explain why our two resistive sheet absorbers have the same bandwidth as the three resistive sheet, genetic algorithm optimized absorber of Chambers and Tennant [3]. Their absorber is made of low permittivity spacers only ($\epsilon_r = 1.1$) while in our designs dielectric layers are optimized to increase the bandwidth and to perform the scan and frequency compensations with fewer number of resistive sheets. The freedom in selecting the dielectric layers is also important from the application point of view. One application Chambers and Tennant are aiming for, is to suppress the waves entering aircraft engine ducts [3]. Due to high thermal and pressure shocks in the engine ducts, the mechanical and thermal properties of the absorber are important. This can not be fulfilled only by foams or honeycomb material used in Chambers and Tennant's designs.

3.3 A Detailed Illustration of the Wideband Matching Technique

In multilayered absorbers the broadband matching of the ground-plane to free space is a complicated process. It must be done not only for the normal angle of incidence
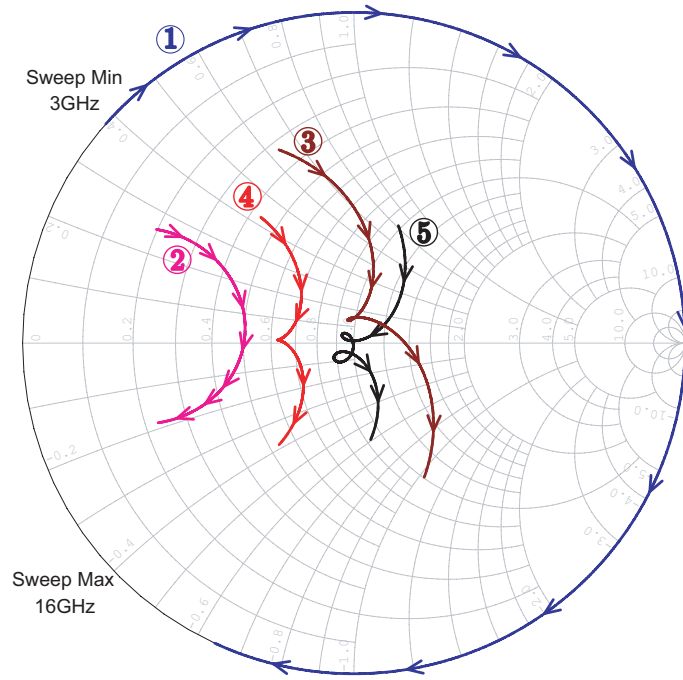
Figure 6: The frequency response of the Jaumann absorber for the design No.2 with external skin ($\epsilon_{\mathrm{r}} = 3$, Thickness = 30 mil).(Full-wave simulation)

but also for different polarizations at oblique angle of incidence, simultaneously. In addition in multilayered absorbers, there are more steps of impedance transformation and addition of sheet admittances to perform, compared to the single resistive layer absorbers [9, 10]. It is instructive to have a look at the matching steps of a multilayered absorber at normal and oblique angles of incidence. For this purpose the Jaumann absorber of the first design (the one without the external skin) is selected. The matching phases that absorber goes through are illustrated step by step in Smith charts. Three cases, the normal angle of incidence and the frequency response for the TE/TM polarizations at 45° (angle of incidence), are considered. The Smith charts of Figs. 7-9 represent the reflection coefficient at each step of the matching process. The circled numbers in Figs. 7-9 correspond to the reflection coefficient seen at the locations marked in Fig. 2.

4   Capacitive Circuit Absorber for Oblique Angle of Incidence

Homogenous resistive sheets are employed in Jaumann absorbers. If these sheets are replaced by proper lossy frequency selective surfaces, the complex admittance of the sheets can increase the bandwidth. Circuit analog absorbers are one class of FSS based absorbers, designed by band-stop resonating arrays [8–10]. Another important subgroup of FSS based absorbers are capacitive circuit absorbers [7]. In this class of absorbers the resonating elements are replaced by low-pass FSS arrays. This has several advantages and leads to new applications as explained in a recent publication [7]. Another new application of the proposed method is the ultra wideband absorber for oblique angle of incidence. This particular feature of the capacitive circuit absorber is explored in this section. It is explained why

Figure 7: The frequency response of the Jaumann absorber circuit model (design No.1) at normal angle of incidence. The circled numbers correspond to the reflection coefficient seen at the locations marked in Fig.2.
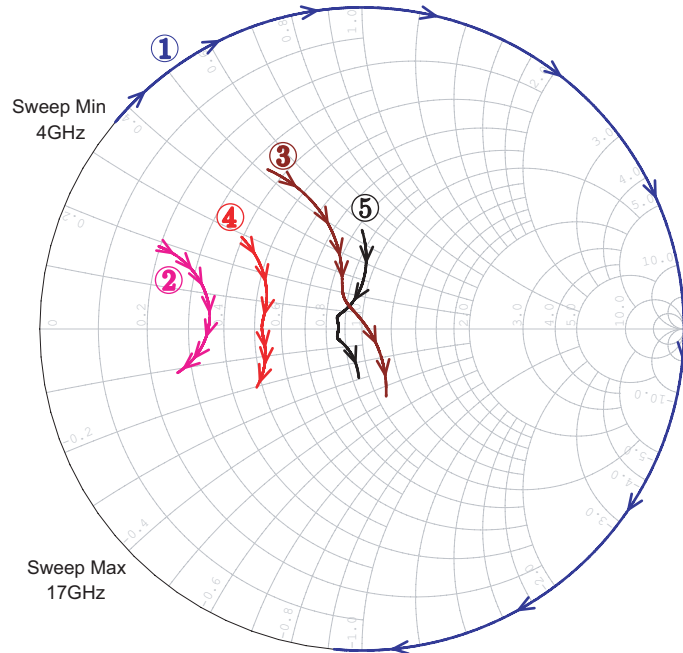
Figure 8: The frequency response of the Jaumann absorber circuit model (design No.1) for TE polarization, oblique angles of incidence 45°. The circled numbers correspond to the reflection coefficient seen at the locations marked in Fig.2.
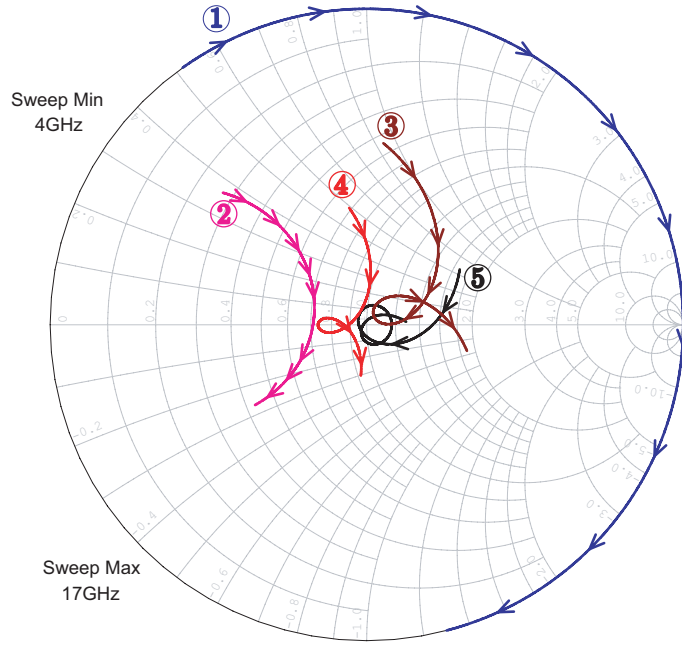
Figure 9: The frequency response of the Jaumann absorber circuit model (design No.1) for TM polarization, oblique angles of incidence 45°. The circled numbers correspond to the reflection coefficient seen at the locations marked in Fig.2.

circuit analog absorbers are not proper candidates for ultra wideband designs under oblique angles of incidence and how to overcome the difficulties by capacitive circuit approach.

4.1 Resonating FSS Elements, Difficulties and the Alternative Solution

The main problem with the resonating structures is the harmonics of the fundamental resonance and the anti-resonance effects that limit the bandwidth of the absorber [9, 10]. By replacing the resonating elements by low-pass arrays this unwanted feature disappears in the whole frequency range of interest [7]. Moreover, the design of multilayered absorber capable of handling normal and oblique angles of incidence for both polarization is a complicated problem. It can not be done unless accurate models for the behavior of the equivalent impedance of the FSS elements are available. The equivalent impedance of the periodic array is a function of polarization and angle of incidence. For the resonating structures the resonating frequency and the bandwidth vary with angle of incidence and polarization. Also the harmonic and the anti-resonance frequencies are slightly shifted by polarization and incident angle [7]. Thus it is very complicated to provide an accurate circuit model of resonating FSS elements for a large bandwidth and scan angle. Fortunately, the square patch element used for synthesizing the low-pass RC elements of the capacitive circuit absorbers [7] does not suffer from the mentioned problems and can be modeled accurately for a wide range of angles of incidence at both polariza-

$\Theta(\deg)$	$R_{\mathrm{TE}}(\Omega)$	$C_{\mathrm{TE}}(\mathrm{pF})$	$R_{\mathrm{TM}}(\Omega)$	$C_{\mathrm{TM}}(\mathrm{pF})$
0	114	0.121	114	0.121
15	114	0.125	113.5	0.125
22	114.7	0.126	113.5	0.125
30	116	0.121	114	0.121
37	117	0.122	114	0.121
45	118	0.127	114	0.126
52	118.5	0.127	114	0.126
60	119.5	0.129	114	0.126

Table 4: The resistance (R) and the capacitance (C) values of the circuit model for the square patch FSS at different angles of incidence and polarizations. ($\epsilon_{\mathrm{c}} = 2.3, T_c = 0.2\,\mathrm{mm}, a = 4.3\,\mathrm{mm}, w = 4.1\,\mathrm{mm}, R_{\mathrm{s}} = 100\,\Omega/\mathrm{Sq.}$)

tions. This permits us to simulate accurately the behavior of the absorber by circuit models, for different incident angles and polarizations. An ultra wideband absorber is designed by the method.

4.2 Accurate, Wideband Model of Square Patch Periodic Array

Consider a periodic square patch array embedded in a dielectric cover as shown in Fig. 10(a). The array can be modeled accurately by the equivalent circuit model shown in Fig. 10(b). The periodic array is embedded in a dielectric cover to stabilize the R and C values of the equivalent circuit. Like before the equivalent length (l_c) and the intrinsic impedance (Z_c) of the transmission lines (see part(b) in Fig.10) are calculated from Eqs. 3.1-3.4. Fortunately, the R and C values of the equivalent circuit (when the square patch array is embedded in a proper cover) do not vary with angle of incidence. They fluctuate insignificantly around their values at normal angle of incidence for both polarizations (see the values in Tables 4-5). Therefore, with a very high accuracy, they can be considered constant in the absorber model. If necessary, final adjustments can be done in a full-wave simulation but experience has shown that the circuit models are sufficiently accurate. The stability of the R and C values of the equivalent circuit to changes of the incident angle is demonstrated in Tables 4-5. Two different widths are considered for a typical square patch array embedded in a dielectric cover.

4.3 An Ultra Wideband Design

A three layered capacitive absorber is designed by the above method. The schematic of the absorber is shown in Fig. 11. The first resistive sheet used in the absorber is a homogeneous resistive sheet and the rest are lossy periodic square patches. All the resistive sheets are embedded in similar dielectric covers, with the parameters $T_c = 0.2\,\mathrm{mm}$ and $\epsilon_{\mathrm{c}} = 2.3$ (see Figs. 4 and 10). The parameters of the dielectric layers used in the design (see, Fig. 11) are tabulated in Table 6. The dimensions of
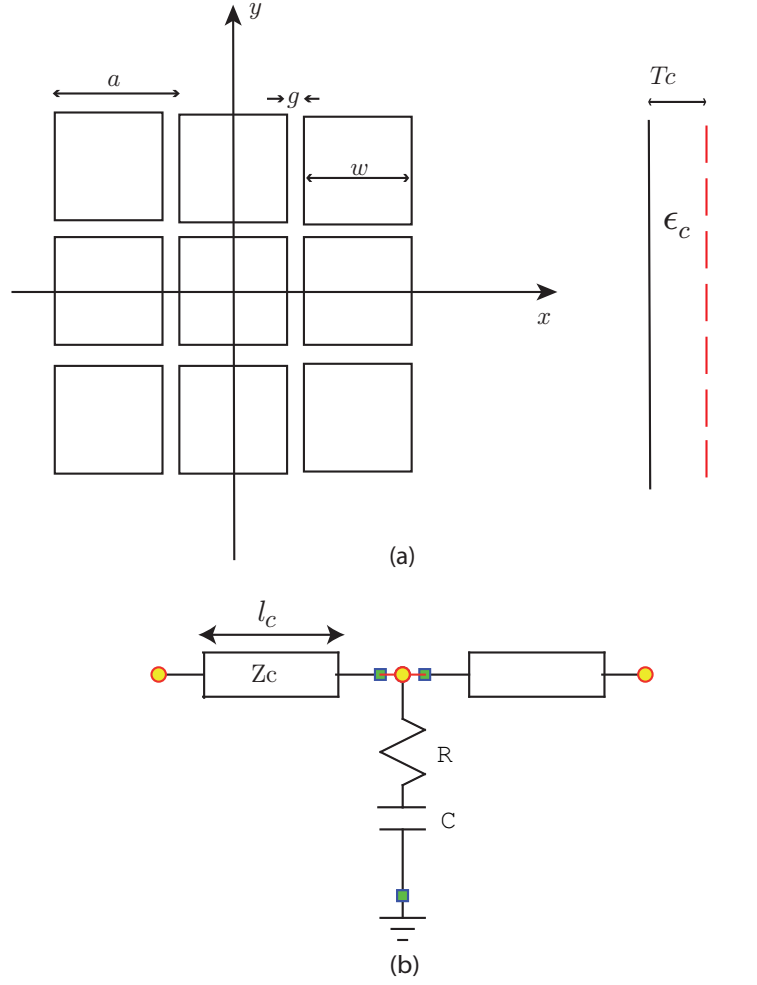
Figure 10: Square patch array and its circuit model, (a) the front and the side view of the FSS structure (b) The equivalent circuit model and its parameters.

$\Theta(\deg)$	$R_{\text{TE}}(\Omega)$	$C_{\text{TE}}(\text{pF})$	$R_{\text{TM}}(\Omega)$	$C_{\text{TM}}(\text{pF})$
0	134.5	0.0705	134.5	0.0705
15	134.5	0.07	134.5	0.0705
22	137	0.07	134.5	0.07
30	139.5	0.07	134.5	0.07
37	141	0.07	134.5	0.07
45	142	0.07	134.5	0.07
52	144	0.07	134.5	0.07
60	145	0.07	133	0.07

Table 5: The resistance (R) and the capacitance (C) values of the circuit model for the square patch FSS at different angles of incidence and polarizations. ($\epsilon_{\text{c}} = 2.3, T_{\text{c}} = 0.2\,\text{mm}, a = 4.3\,\text{mm}, w = 3.8\,\text{mm}, R_{\text{s}} = 100\,\Omega/\text{Sq.}$)
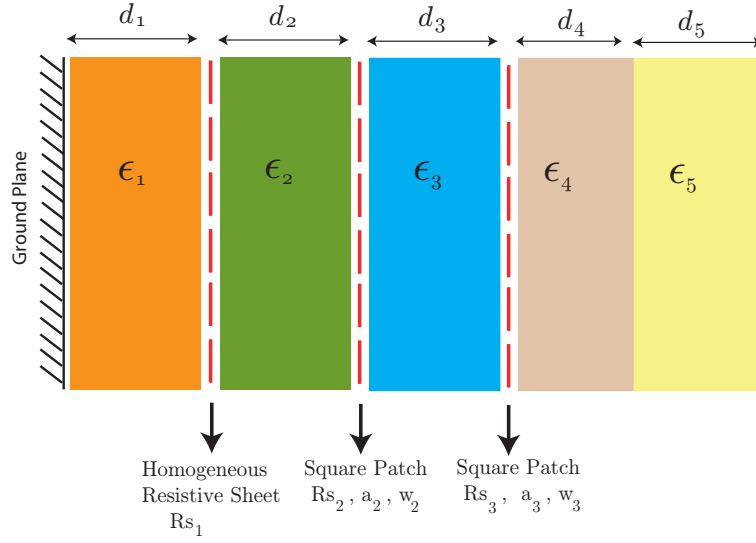
Figure 11: The schematic of the capacitive circuit absorber. The first resistive layer is a homogeneous resistive sheet but others are square patches with different resistivity and dimensions.

$d_1(\,\mathrm{mm})$	$d_2(\,\mathrm{mm})$	$d_3(\,\mathrm{mm})$	$d_4(\,\mathrm{mm})$	$d_5(\,\mathrm{mm})$
3.4	2.6	2.4	3.3	4

| ϵ_1	ϵ_2	ϵ_3	ϵ_4	ϵ_5
1.8	1.7	1.33	1.8	1.33

Table 6: The parameters of the dielectric layers used in the capacitive circuit absorber.

the square patches and the resistivity of the sheets (Ω/Sq) are given in Tables 7-8. It should be noted that the periodicity of the last square patch (a_3) is half of the fundamental spatial period of the absorber ($a_2 = 3.6\,\mathrm{mm}$). This is done to make the synthesis of the required capacitances possible.

The absorber has an ultra wideband frequency response, at least 26 GHz. The frequency response of the absorber at normal and oblique angle of incidence is shown in Fig. 12. The ability of the absorber to operate for such a wide range of angles of incidence (up to 45°) for both polarizations over its huge bandwidth is remarkable. Comparisons demonstrate that our design possesses the largest bandwidth among the published designs, keeping in mind that some of them are designed only for the simple case of normal incidence [1, 2, 8–10]. It is worth to mention that the total thickness of the absorber is only 16.9 mm.

$Rs_1(\,\Omega/\mathrm{Sq})$	$Rs_2(\,\Omega/\mathrm{Sq})$	$Rs_3(\,\Omega/\mathrm{Sq})$
134	285	370

Table 7: The resistivity of the sheets used in the capacitive circuit absorber.
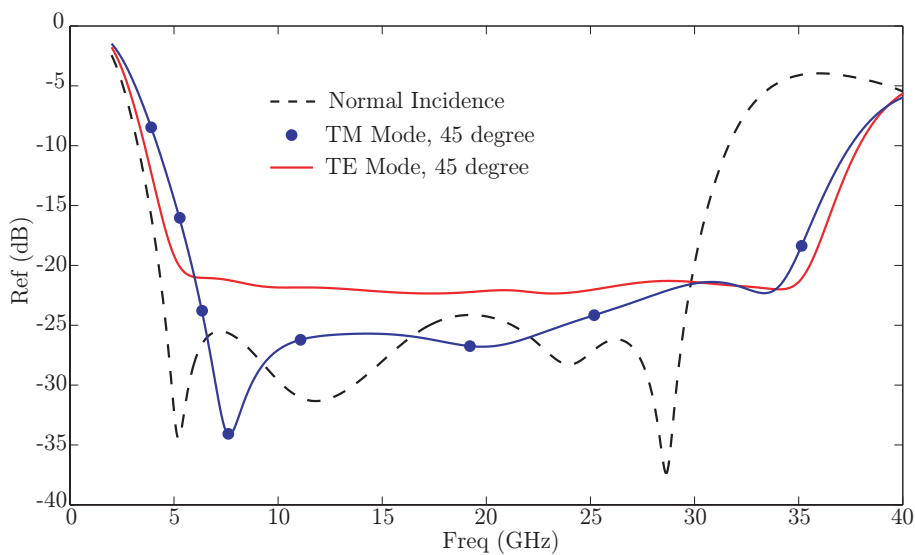
Figure 12: The frequency response of the capacitive circuit absorber at normal and oblique angle of incidence.(Full-wave simulation)

$a_2(\text{mm})$	$w_2(\text{mm})$	$a_3(\text{mm})$	$w_3(\text{mm})$
3.6	3.5	1.8	1.6

Table 8: The dimensions (periodicity (a), width (w)) of the periodic square patches. The fundamental spatial period of the absorber is $3.6\,\text{mm}$.

5   Conclusion

Design of an ultra wideband absorber operating for a large range of incident angles and different polarizations is a challenging problem. Usually the design of Jaumann and circuit analog absorbers are restricted to normal angle of incidence. Therefore, the variation of the frequency response with respect to incident angle and polarization are not taken into consideration in the design. No general methods have so far been described in the literatures although some specific cases have been investigated [3, 9, 10]. In case of multilayered Jaumann absorbers, only low permittivity spacers are used in the designs [3]. It is shown that according to scan and frequency compensation techniques, this is not a reasonable choice. The circuit analog absorbers of Munk *et al* are single FSS layer designs with moderate bandwidths [9, 10], that are not adequate for invisibility against modern radars operating at different frequency intervals. Therefore, a systematic method for achieving larger bandwidths with multilayered absorbers is proposed in the paper.

A general model of Jaumann absorber is provided. The model is applicable to arbitrary permittivities of the dielectric layers, leading to two vital advantages. First, from the scan and frequency compensation techniques [10], it is known that using only low permittivity spacers is not optimal for oblique angles of incidence. Second, there are applications where mechanical and thermal properties of the absorbers are important for the designer. This can not be fulfilled by foams and honeycomb

materials alone, as used in the Chambers and Tennant's designs [3]. Different designs of two resistive layer Jaumann absorbers are presented, possessing almost the same bandwidth as the three layered genetic algorithm optimized design of Chambers and Tennant [3], where the absorber consists of only low permittivity spacers. It is also shown that in contrast to the recipe of Munk *et al*, there are some freedom in selection of dielectric layers in multilayered design. This is also important from a practical point of view.

A three layered capacitive absorber is presented with an ultra wide bandwidth of 26 GHz. The absorber can operate at normal and oblique angles of incidence for both polarizations. It is explained that because of harmonics and anti-resonance effects [10] of the resonating elements such a large bandwidth is not achievable by circuit analog absorbers. By replacing the band-stop resonating FSS elements with low-pass periodic square patches, the problems associated with harmonics and anti-resonances are avoided. Also it is shown that the periodic square patch array has a special property that enables us to model it very accurately for a large scan angle. All these fascinating properties of square patches lead us to designs that are outstanding in comparison to the earlier published designs [1, 2, 8–10].

Acknowledgment

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