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Thin Wideband Absorber with Optimal Thickness

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Abstract

The known methods for designing nonmagnetic absorbers usually aim for either the reduction of total thickness or increase of absorption bandwidth by sacrificing the other parameter. The conventional circuit analog absorbers aim for large bandwidths whereas the newly proposed meta-material or optimized geometry designs try to reduce the thickness of the absorber. By the aid of the capacitive circuit absorber approach, an optimal method for designing thin absorbers with practical bandwidths is proposed. An absorber is designed for the whole radar X-band with total thickness about $\lambda/10$. It is shown that the absorber thickness is satisfactorily close to the theoretical limit. The effect of mutual coupling on the performance of thin absorbers are investigated and some techniques for reducing the mutual couplings are suggested.

1 Introduction

Two parameters are usually important in the design of an absorber, the absorption bandwidth and the total thickness of the design. The ideal situation for a design is to achieve the largest bandwidth with the minimum possible thickness. Simultaneous optimization of the total thickness and the absorption bandwidth is not an easy task and the published designs usually succeed in achieving one goal by sacrificing the other. For achieving large bandwidths, conventional design methods such as Jaumann [1, 2] and circuit analog absorbers [8–10] have been introduced. These absorbers are made of resistive layers separated from each other by dielectric spacers that are quarter of a wavelength thick at the mid-frequency. It is known that for obtaining large bandwidths a few resistive/dielectric layers are required. Consequently large bandwidths are achieved in cost of considerable thicknesses. Recent investigations have concentrated on low profile absorbers that are thinner than a quarter of wavelength. The designs are usually called ultra thin absorbers and use meta-material ideas or optimized geometries of frequency selective surfaces (FSS) to match the ground plane to free space [3, 4, 6, 7]. Unfortunately these absorbers have very narrow bandwidths which jeopardize their practicality [9, 10].

The capacitive circuit absorber approach is capable of fulfilling both of the contradictory goals [5]. A systematic method for designing wideband thin absorber with optimal thickness is presented. First, by the aid of the physical bound introduced by Rozanov [11] a meaningful relationship between bandwidth and total thickness of an absorber is established. It is shown that for a given frequency response, the total thickness of a nonmagnetic absorber cannot be less than a theoretical limit. Then a two layer thin absorber is designed for the whole radar X-band frequency interval (8-12 GHz). It is shown that the total thickness of the absorber is very close to the minimum possible thickness dictated by the theoretical limit.

2 The relation between total thickness and absorption frequency response

A basic rule of absorber design is that wider bandwidth requires larger thickness, but is there any physical relation between these quantities? Rozanov has shown that for any metal backed absorber under normal incident illumination, the infinite integral of natural logarithm of the reflection coefficient is bounded from above under certain conditions [11]. The conditions are very general and include all linear, passive, time invariant and causal materials. Therefore, all the meta-material or optimized geometries and FSS based absorbers are included in this general category. The physical bound is expressed by the following relation:

$$\left| \int_0^\infty \ln |R(\lambda)| d\lambda \right| \leq 2\pi^2 \sum_i \mu_{s,i} d_i \quad (2.1)$$

In the above equation R is the reflection coefficient, λ is the wavelength in free space and $d_i, \mu_{s,i}$ are the thickness and the static permeability of the i th layer of the multilayered slab. For a nonmagnetic absorber the above equation can be rearranged into the following form:

$$d \geq \frac{\left| \int_0^\infty \ln |R(\lambda)| d\lambda \right|}{2\pi^2} \quad (2.2)$$

The above equation provides a useful relation between the total thickness of a nonmagnetic absorber (d) and its frequency response. It states that for a given absorption frequency response, the total thickness of the absorber cannot be less than a theoretical limit. By providing an accurate approximation of the desired frequency response, Eq. 2.2 can be used to estimate the minimum possible thickness of the corresponding absorber. This theoretical thickness is then used as a design objective. Experience has shown that a linear piecewise approximation of the frequency response in dB scale is a fair approximation for the frequency response of a nonmagnetic absorber. It is very similar to the Bode plots used in filter theory with the difference that the frequency is not in logarithmic scale. Therefore, the reflection coefficient can be expressed as a function of frequency as the following:

$$R(f) = \begin{cases} -R_0 \left(\frac{f-f_1}{f_2-f_1} \right) & f_1 \leq f \leq f_2 \\ -R_0 & f_2 \leq f \leq f_3 \\ R_0 \left(\frac{f-f_4}{f_4-f_3} \right) & f_3 \leq f \leq f_4 \\ 0 & \text{otherwise} \end{cases} \quad (2.3)$$

In the above equation, the R_0 is the average absorption level in the absorption band in dB scale (a positive number). The transition intervals are controlled by the f_1 and f_4 frequencies and should be selected in a way that they result in practical slopes for the frequency response. By mapping the frequency response of Eq. 2.3 into wavelength domain and using Eq. 2.2, the minimum possible thickness of the absorber can be calculated. In the next section an absorber is designed for the radar X-band (8 – 12 GHz). To define a design objective, the case with $f_1 = 6$ GHz, $f_2 = 8$ GHz, $f_3 = 12$ GHz, $f_4 = 16$ GHz and $R_0 = 22$ dB is considered throughout the paper. For the given values the minimum possible thickness is ≈ 2.8 mm.

3 Thin Absorber for the Radar X-Band

After defining the design goals and calculating the minimum possible thickness for the desired frequency response, it is time to propose a design that can fulfill them as close as possible. A two layer (number of periodic layers) capacitive circuit absorber [5] is able to meet the design goals successfully. All the previous publications on ultra thin absorber are single resistive layer designs [3, 4, 6, 7] and it is for the first time that a wideband two layer thin absorber is presented. Capacitive circuit absorber [5] is a modification of the circuit analog absorber [9, 10] approach that results in many advantages. The basic idea is to replace the band-stop resonating FSS elements of the circuit analog absorbers with low-pass FSS structures. The low-pass elements can be synthesized by simple geometries such as square patches [5]. The low-pass behavior of the square patch array has the advantage that its frequency response is not affected by harmonic and anti-resonance frequencies over a very large bandwidth, in contrast to the band-stop resonating elements used in circuit analog absorbers [5, 8–10]. The fact simplifies the modeling and design of the absorber significantly. It can be shown that the capacitive circuit absorber method is a more flexible approach that leads into new applications, impossible to be accomplished by circuit analog absorber method (some examples have been given in [5]). Among the new applications one is the wideband thin absorber with optimal thickness. An important advantage of the capacitive circuit method is that the distance between FSS layers can be much smaller than quarter-wavelength separations common in circuit analog absorbers [8–10]. When the distance between FSS layers are about a quarter of a wavelength, the mutual coupling between the periodic arrays is very low, in particular if they are embedded in dielectric covers [8–10]. Therefore, the equivalent circuit models of the circuit analog absorbers are very close to the actual frequency response of the synthesized absorber (cares must be taken into account about harmonic and anti-resonance frequencies). The situation is the same (or better owing to avoiding resonances) for thick capacitive circuit absorbers. In a thin absorber the total thickness of the design is in order of $\lambda/10$ or less. Consequently, the distance between the FSS layers and the distance between the first periodic layer and the ground plane are much smaller than quarter of a wavelength. Therefore, it is expected that the mutual coupling between layers can be high and destructive if they are not treated properly. There might be a perceptible difference between the frequency response of the equivalent circuit model and the actual full-wave response of the synthesized absorber. These facts and the potential of the capacitive circuit absorber method to handle the problem is illustrated in the following.

The first step in the design of the absorber is to find an equivalent circuit model that can match the ground plane to the free space over the desired frequency interval. Then, the circuit model is synthesized by proper FSS elements and dielectric layers. If the separation between the FSS layers are large enough, the frequency response of the circuit model and the actual absorber are very similar. In our case where the total thickness of the absorber is only $\lambda/10$, cares must be take into account from the beginning in the circuit model. The mutual coupling between the FSS layers and the ground plane must be reduced as much as possible by proper techniques.

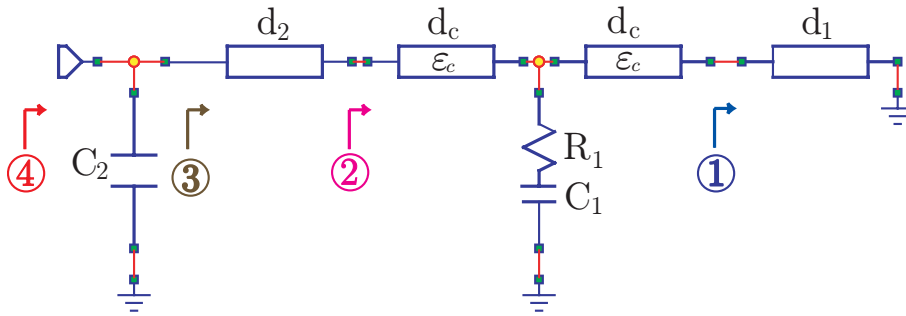


Figure 1: The schematic of the equivalent circuit model of the thin wideband absorber.

ϵ_c	d_1 (mm)	d_c (mm)	d_2 (mm)
1	0.8	0.2	1.9
3.8	0.8	0.2	1.9
ϵ_c	R_1 (Ω)	C_1 (pF)	C_2 (pF)
1	37.3	0.305	0.061
3.8	39.6	0.31	0.06

Table 1: The equivalent circuit model parameters for the thin absorbers accompanied with the permittivity of the corresponding dielectric cover used in the designs. Other dielectric layers have permittivity values equal to one.

The fact is illustrated by two different design examples. Both of the designs are two layer absorbers with circuit models that differs only in one parameter. It is shown that this small difference causes a large effect on the full-wave frequency response of the absorbers. The equivalent circuit model of the thin absorber is shown in Fig. 1. As seen from the equivalent circuit model, only low-pass elements are used to match the ground-plane to the free space impedance (the port symbol in Fig. 1). The first series RC circuit (R_1 and C_1 in Fig. 1) is embedded in a dielectric cover with permittivity ϵ_c and thickness d_c . The dielectric cover with proper permittivity results in significant advantages, one is the reduction of the mutual coupling effects. The best way to illustrate the mechanism is through examples. Two absorbers with the same circuit models are designed for the radar X-band with the only difference that the permittivity of the dielectric cover is varied between them (ϵ_c in Fig. 1). The values of the circuit parameters are tabulated for both designs in Table 3. As seen from the values, the two circuit models are very similar except they have different permittivity values for the dielectric cover. The variation of the permittivity of the dielectric cover has a minor effect on the frequency response of the circuit models. The fact can be seen clearly in Fig. 2 where the frequency responses of the two circuit models are compared. Both designs have the same total thickness of 3.1 mm which is practically close to the minimum possible thickness calculated in the previous section (2.8 mm). Therefore, as far as circuit models are considered the designs are almost identical.

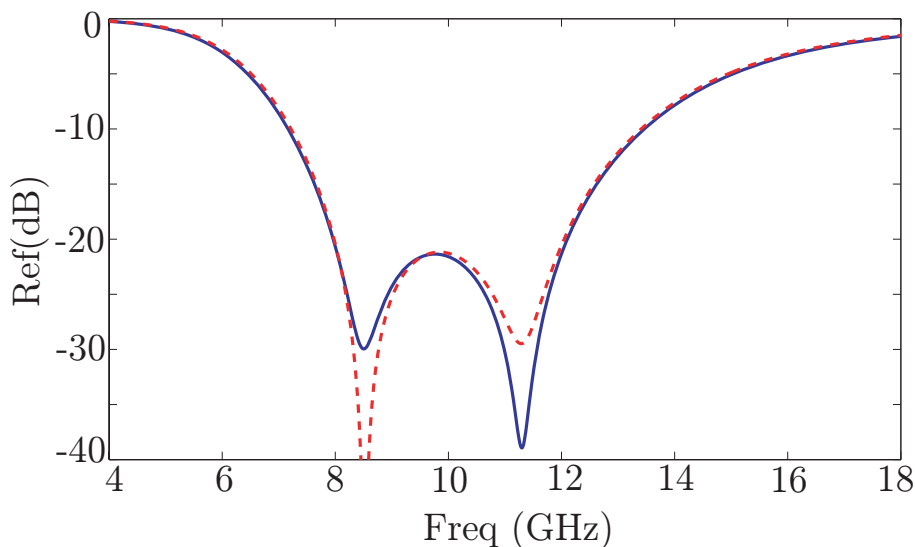


Figure 2: The comparison of the frequency response of the circuit models for the the two different permittivity values of the dielectric cover (ϵ_c). The solid curve is for the circuit model with $\epsilon_c = 3.8$

3.1 The Full-Wave Behavior of the Absorbers

It was shown that the two different designs have almost identical circuit model properties. The difference appears when the electromagnetic properties of the actual absorbers are considered. The circuit models of the previous section are synthesized by proper square patches (periodicity (a), width (w) and sheet resistivity (R_s)). The dimensions of the patches used in implementation of the absorbers are tabulated in the Table 3.1 with the corresponding dielectric permittivity of the cover used in the designs. The first obvious difference between the absorber structures is the size of the elements. In the design with high permittivity value for the dielectric cover, the periodicity of the arrays is almost half of the spatial periodicity of the design without an actual cover (since $\epsilon_c = 1$ in fact no cover exists). The reason becomes clear when considering that the square patches of the first layer in both designs are used to synthesize almost the same capacitance value (see the C_1 in Table 3). If one square patch is embedded in a high permittivity cover it results in larger capacitances in comparison to a coverless patch. Therefore, its size must be made smaller to result in the same capacitance value.

The essential advantage of having a proper dielectric cover is to control the level of mutual coupling between the periodic arrays and between the first layer and the ground plane. As seen from the Fig. 1 and the values of Table 3, the distance between the first periodic array to the ground is $1 \text{ mm} = \lambda/30$ and the distance between the two periodic arrays is $2.1 \text{ mm} \simeq \lambda/15$. From these values it is expected that the mutual coupling between the layers can be high. Consequently, the actual frequency response of the final absorber might be different from the circuit model response. For the design without an actual cover ($\epsilon_c = 1$) this difference is obvious. The destructive effect of high coupling between absorber components on its frequency response is

ϵ_c	a_1 (mm)	w_1 (mm)	a_2 (mm)	w_2 (mm)
1	12	11.9	6	5.4
3.8	6.8	6.6	3.4	3.3

Table 2: The parameters of the square patches used in the absorbers accompanied with the permittivity of the corresponding dielectric cover used in the designs.

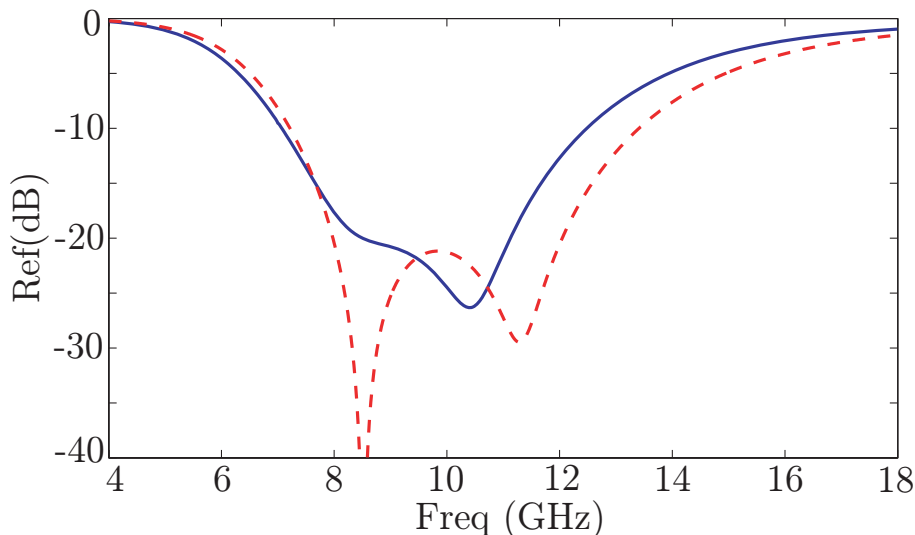


Figure 3: Comparison of the frequency response of the actual absorber with the equivalent circuit model used to construct it for the case of low permittivity dielectric cover ($\epsilon_c = 1$). The solid curve shows the full wave simulation (CST Microwave Studio).

shown in Fig. 3. A proper dielectric cover can concentrate the field distribution to the vicinity of the periodic array. Therefore, when the first periodic layer is embedded in a high permittivity dielectric cover ($\epsilon_c = 3.8$), the presence of the ground plane and the next periodic array do not influence its field distribution. As a result its equivalent impedance is not altered by the presence of the ground plane and the second periodic array. Moreover, by increasing the width to periodicity ratio of the second square patch (w_2/a_2) from 0.9 in the design with low permittivity cover to 0.97 in the design with high permittivity, the field distribution of the second array is more concentrated to the vicinity of the patches. Therefore, the coupling between the two periodic arrays is reduced one more time. All these effects together cause that the frequency response of the final design to be preserved in the transition from the circuit model to the actual absorber. Comparison of the frequency response of the circuit model and the full-wave simulation in Fig.4 verifies the fact.

3.2 Why Capacitive Circuit Absorber Method

Before ending this section it is important to explain why the circuit analog absorber approach cannot be used for thin wideband absorbers. The main reason is that

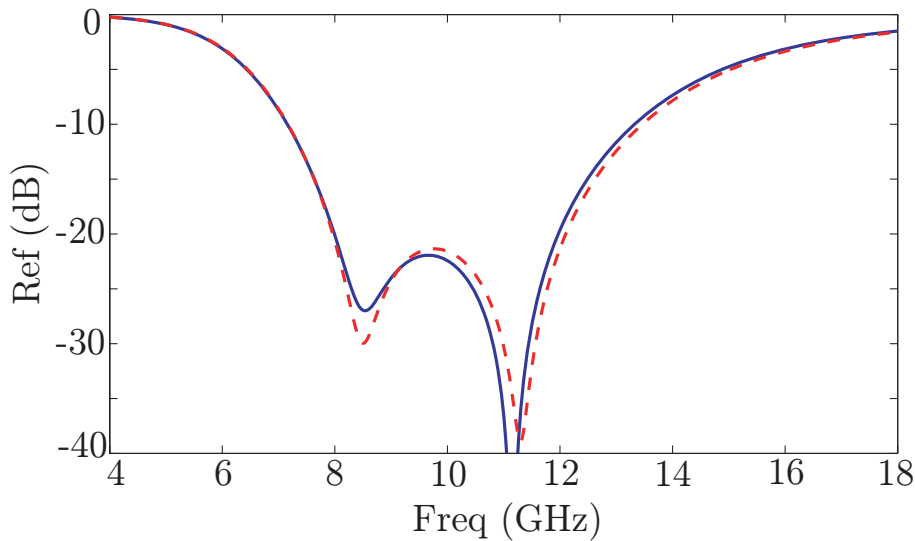


Figure 4: Comparison of the frequency response of the actual absorber with the equivalent circuit model used to construct it for the case of proper dielectric cover ($\epsilon_c = 3.8$). The solid curve shows the full wave simulation (CST Microwave Studio).

circuit analog absorber are optimal when they are used with quarter-wavelength spacers [8–10]. If the distance between layers are reduced then there are cases that circuit analog absorbers cannot handle. Consider the circuit model of the thin absorber. The thickness of the dielectric layers given in Table 3 are obviously much smaller than quarter of a wavelength ($d1/\lambda \approx 1/30$ and $d2/\lambda \approx 1/15$). For these small values of thickness ratios, the ground plane impedance remain inductive over the whole absorption frequency band. Consequently only capacitive loads are required for the matching and the extra inductances of the resonating elements of the circuit analog absorbers become redundant [5]. The fact can be shown clearly on a Smith chart by showing the different steps of the matching process. For this purpose the thin design with the proper dielectric cover is selected and the reflection coefficient at different stages of the matching process are plotted on a Smith chart, see Fig. 5. The numbers next to the curves correspond to the positions where the reflection coefficients are picked up in the circuit model of Fig. 1. It is obvious from the Smith chart that the impedances seen at stages 1 and 3 are inductive over the whole absorption frequency band. As mentioned it is due to the small values of the dielectric layer thicknesses used in the design.

4 Conclusion

By the aid of physical bound for a nonmagnetic absorber, the relation between the absorption frequency response and the total thickness is presented. An outstanding design method is proposed capable of making a balance between bandwidth and the thickness of an absorber. All previous investigations aim for one of these parameters by sacrificing the other one. For example the circuit analog absorbers provide broad

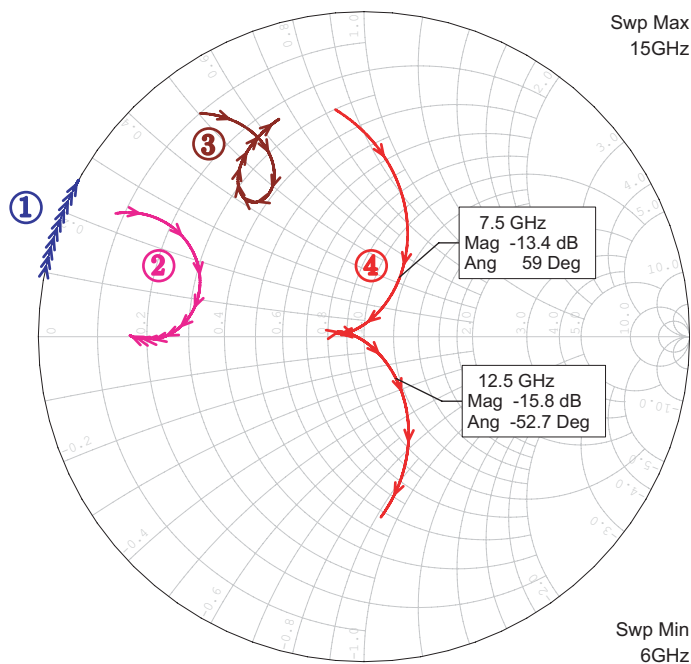


Figure 5: The reflection coefficient of the thin absorber at the different steps of the matching process. The numbers next to the curves correspond to the positions indicated by arrows in the circuit model of the absorber (see Fig. 1).

bandwidths in cost of large thicknesses [8–10] and the published ultra thin absorbers have very narrow bandwidths [3, 4, 6, 7]. By using the capacitive circuit method [5] a thin absorber is designed for the radar X-band with total thickness of 3.1 mm ($\approx \lambda/10$) and average absorption level of 22 dB. It is shown that the total thickness of the design is practically close to the minimum possible thickness given by the physical bound (2.8 mm). The effect of mutual coupling on the frequency response of the thin absorber is illustrated and some techniques are introduced to minimize it.

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