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Design of Thin RC Absorbers Using a Silver Nanowire Resistive Screen

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Abstract

A resistive and capacitive (RC) microwave absorber with a layer thickness less than a quarter of a wavelength is investigated based on closed-form design equations, which are derived from the equivalent circuit of the RC absorber. The RC absorber is shown to have a theoretical 90% absorption bandwidth of 93% when the electrical layer thickness is 57° (about $\lambda_0/6$). The trade-offs between the layer thickness and the absorption bandwidth are also elucidated. The presented formulation is validated by a design example at 3 GHz. The RC absorber is realized using a silver nanowire resistive rectangular structure with surrounding gaps. The measured 90% absorption bandwidth with a layer thickness of $\lambda_0/8$ is 76% from 2.3 GHz to 5.1 GHz in accordance with the theory and EM simulations. The presented design methodology is scalable to other frequencies.

Key Words: Absorption Bandwidth, Capacitive Screen, Design Equations, Resistive Sheet, Thin Absorber.

I. INTRODUCTION

As various applications in the area of communication, medicine, and defense, among others, are being developed and deployed rapidly, the demand for microwave absorbers is also increasing. Microwave absorbers are used for anechoic chambers [1], mobile phones, EMI/EMC problems, stealth air planes [2], and other applications. Particularly, they are required to minimize the hazards of EMP attacks.

The current commercial absorbers are usually made of ferrite materials, which are expensive and bulky. To replace these materials, many other types of absorbers have been introduced and developed. Recent advancements in metamaterial research have opened the possibility for metamaterial absorbers (MA) [3–5]. The literature shows that MAs can be realized very thinly, but their bandwidth is still narrow. Thus, a double layer may have to be used [5].

A conventional absorber is the Salisbury screen [6]. The Salisbury screen is made of a 377-Ω resistive film placed at a distance of quarter wavelength above a conducting plane. The thickness of the absorber is relatively thick at low frequencies because of the required spacing of $\lambda/4$, but its bandwidth is still not satisfactory. To achieve a wide-bandwidth absorption property, a multi-layer structure was also studied [7]. Although the bandwidth is excellently enhanced with a multilayer, the complexity and the considerable absorber size are always troublesome. A single layer is always preferable because of its simple and compact geometry, and its performance is comparable with that of the multi-layer. Single-layer reactive screens usually modeled by a lumped series RLC resonator have also been examined with results of much wider bandwidth than those of Salisbury screens [8, 9]. Especially in [10], simple closed-form solutions for the RLC absorbers with a layer thickness of $\lambda/4$ were derived from the impedance match and zero susceptance

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(or reactance) slope conditions for broadband design. With this method, complete absorption at and near a design center frequency can be achieved, and the 99% absorption bandwidth is about 54% (enough to cover the whole X-band) when an air or Styrofoam layer is used. The same design methodology was extended to absorbers with a layer thickness less than a quarter of a wavelength, but it was found to be not as effective as in the case of the quarter wavelength layer.

In this paper, the absorbers with a layer thickness less than a quarter of a wavelength are designed using a resistive and capacitive (RC) screen. The reason why the capacitive RC screen is employed is that the impedance of the layer, which has a thickness less than a quarter of a wavelength, is inductive. Convenient design equations are derived using a proper equivalent circuit. The provided design equations are useful for synthesizing any particular absorber at a specific frequency, and they also give us physical insight into the bandwidth trade-offs between the thick and thin absorbers. Particularly, the bandwidths of the RC absorbers are compared with those of the metamaterial-type absorbers. Finally, for the validity of the formulation, an RC absorber made of a silver nanowire (AgNW) resistive film is designed at 3 GHz, fabricated, and measured. Comparisons and discussions are then conducted.

II. Design of Thin Microwave Absorbers

The proposed absorber is composed of an RC screen and a conducting plane separated by a distance of less than a quarter of a wavelength. Fig. 1 shows the equivalent circuit of the RC absorber, where η_0 is the intrinsic impedance of air (377 Ω) and η_1 is the intrinsic impedance of the layer between the conducting plane and the RC screen. h is the layer thickness, and θ_0 is the electrical length of the layer given by βh, where β is the propagation constant in the layer. The RC screen can be modeled by a series connection of a resistor with R_0 and a capacitor with C_0. Y_{in} is the input admittance. The admittance Y_0 of the RC screen at an angular design center frequency ω_0 is given by

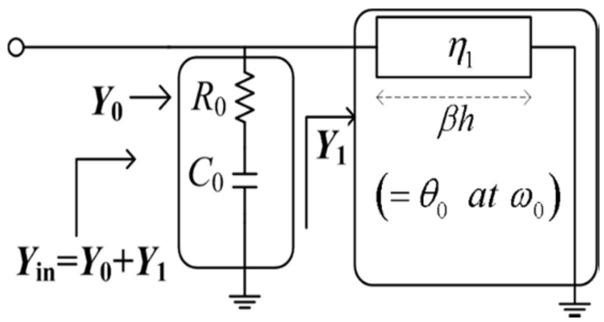


Fig. 1. Equivalent circuit of the proposed absorber with definitions of Y_0 (of the RC screen) and Y_1 (of the shorted transmission line).

$$Y_0 = \frac{1}{R_0 + \dfrac{1}{j\omega_0 C_0}} = \frac{(\omega_0 C_0)^2 R_0 + j\omega_0 C_0}{1+(\omega_0 C_0 R_0)^2}, \tag{1}$$

and the admittance Y_1 of the layer when its electrical length is θ_0 is given by

$$Y_1 = -j\frac{1}{\eta_1}\cot(\theta_0). \tag{2}$$

For the input admittance match of the absorber to free space, we require

$$Y_{in} = Y_0 + Y_1 = \frac{1}{\eta_0}. \tag{3}$$

By separately equating the real and imaginary parts of (3), we obtain the unique solutions of R_0 and C_0 expressed as

$$R_0 = \frac{\eta_0}{1+\left(\dfrac{\eta_0}{\eta_1}\right)^2 \cot^2\theta_0} \tag{4}$$

and

$$C_0 = \frac{1+\left(\dfrac{\eta_1}{\eta_0}\right)^2 \tan^2\theta_0}{\eta_1\omega_0\tan\theta_0}. \tag{5}$$

Fig. 2 illustrates the required circuit values of R_0 and C_0 as a function of the electrical thickness θ_0 of the layer when $\eta_1 = \eta_0 =$ 377 Ω and the design center frequency f_0 is assumed to be 3 GHz. As θ_0 increases from 0° to 90°, R_0 monotonically increases from 0 Ω to 377 Ω. However, C_0 is symmetric about $\theta_0 = 45°$ and goes to infinity as θ_0 goes to 0° or 90°. These observations indicate that when θ_0 goes to 90°, the screen is practically reduced to the conventional Salisbury screen. More discussions

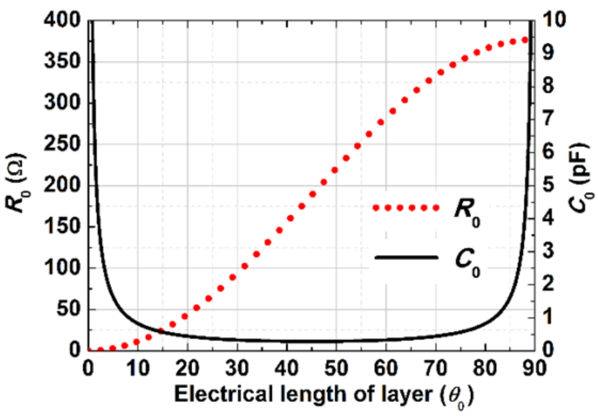
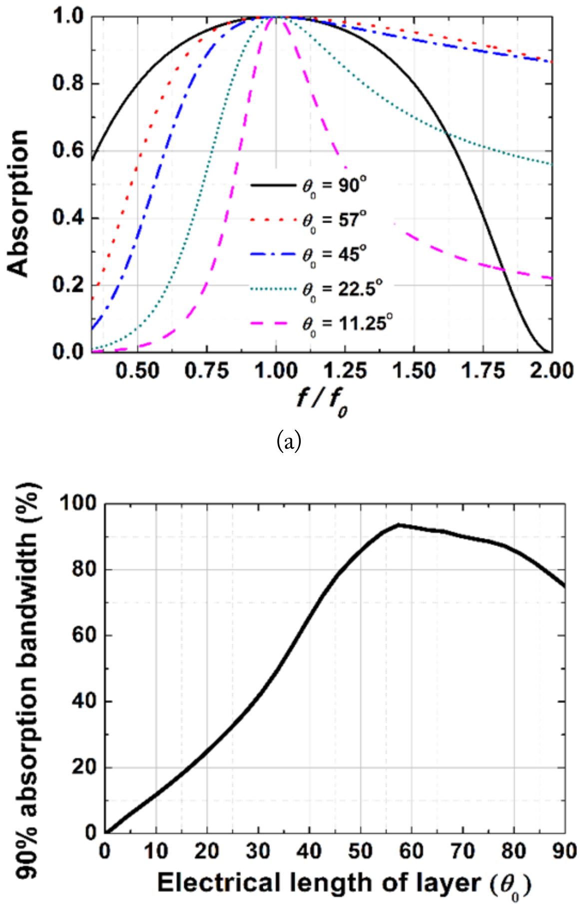


Fig. 2. Required circuit values of R_0 and C_0 as a function of the electrical thickness θ_0 of the layer when $\eta_1=\eta_0=377$ Ω and the design center frequency is 3 GHz.



(a)

(b)

Fig. 3. Absorption and 90% absorption bandwidth of RC absorbers when $\eta_1 = \eta_0 = 377\ \Omega$. (a) Absorptions as a function of normalized frequencies for different layer electrical lengths (θ_0). (b) 90% absorption bandwidth depending on the electrical length of the layer.

will follow later.

Fig. 3(a) shows the absorptions ($=1-|S_{11}|^2$) as a function of normalized frequency f/f_0 for different θ_0 of 11.25°, 22.5°, 45°, 57°, and 90°. Each absorber has a perfect absorption at the design center frequency as expected. Note that although C_0 depends on f_0 as shown in (5), Fig. 3(a) holds true for any f_0. In Fig. 3(b), the 90% absorption bandwidths are plotted as a function of θ_0. As the absorption characteristics are not symmetric, especially near $\theta_0 = 45°$, the fractional bandwidths are been calculated on the basis of the center frequencies. One notable observation is that as θ_0 increases from 0°, the bandwidth increases only up to about 57° but decreases beyond that. The 90% absorption bandwidth is shown to have a maximum of about 93% when θ_0 is about 57°. Thus, the RC absorbers are not recommended with a layer thickness larger than 57°.

Fig. 4 illustrates a unit structure of the RC absorber with dimensions determined at a design frequency of 3 GHz using EM simulations for the case of $\eta_1 = \eta_0 = 377\ \Omega$ and $\theta_0 = 45°$ ($h = 12.5$ mm $= \lambda_0/8$). The unit of the RC screen consisting of a square resistive sheet and four gaps is placed above a conducting plane. Based on (4) and (5), R_0 and C_0 of the RC screen are 188.5 Ω and 0.28 pF, respectively. These required circuit values can be realized by surface resistance per square (R_s) and the gap. The determined values (a, l, R_s) using HFSS simulations are $a = 35$ mm ($0.35\ \lambda_0$), $l = 28$ mm, and $R_s = 110$ Ω/□. Table 1 summarizes the theoretically required values of R_0 and C_0 using (4) and (5), the obtained dimensions of the absorbers using EM simulations, the used surface resistance (Ω/□), and the 90% absorption bandwidths for different electrical lengths (θ_0) at 3 GHz. The terminal impedance Z_0 of the RC screen in Fig. 4 is evaluated after proper de-embedding using EM (HFSS) simulations. It denotes the impedance of the RC screen alone.

Fig. 5 demonstrates the real and imaginary parts of Z_0 as a function of frequency based on circuit (Fig. 1) and EM simulations for the case of $\theta_0 = 45°$ at 3 GHz. The excellent ag-

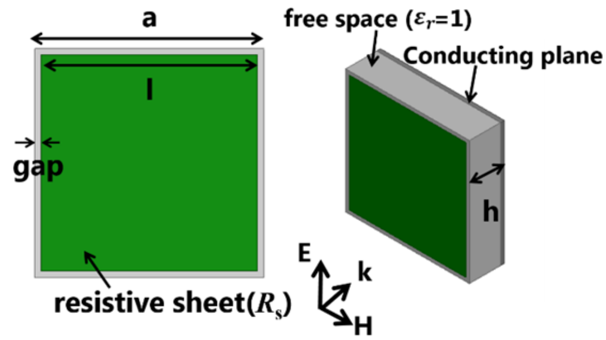


Fig. 4. Unit structure consisting of an RC screen and a conducting plane for the case of $\theta_0 = 45°$ at 3 GHz ($a = 35$ mm, $h = 12.5$ mm, $l = 28$ mm, and $\varepsilon_r = 1$).

Table 1. Designed absorber parameters and 90% absorption bandwidths for different air-spaced layer electrical lengths at 3 GHz

θ_0	R_0 (Ω)	C_0 (pF)	a (mm)	l (mm)	h (mm)	R_s (Ω/□)	90% absorption bandwidth (%)
90°	377	2298	35	35	25	377	75
57°	265	0.31	35	28.3	15.8	164	93
45°	188.5	0.28	35	28	12.5	110	76
22.5°	55.2	0.39	35	31	6.25	40	29
11.25°	14.34	0.74	35	33.6	3.12	9	13

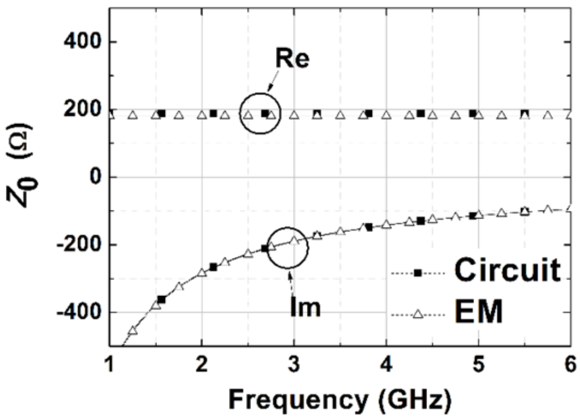


Fig. 5. Real and imaginary parts of the terminal impedance (Z_0) on the reference plane of the RC screen using EM and circuit (R_0= 188.5 Ω, C_0=0.28144 pF) simulations when f_0=3 GHz.

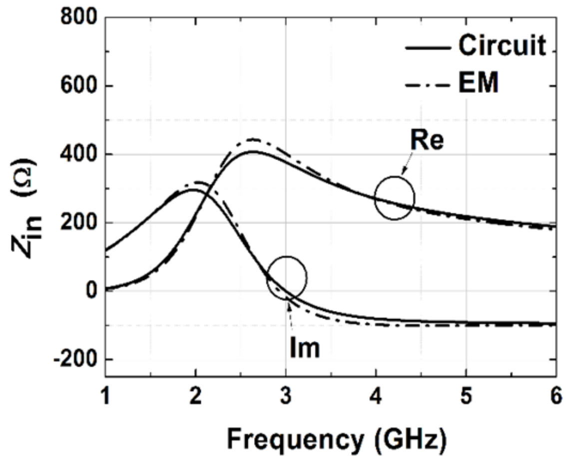


Fig. 6. Real and imaginary of Z_{in} using circuit and EM simulations.

reement implies that the required circuit values of R_0 and C_0 are well realized by the RC screen dimensions as summarized in Table 1.

In Fig. 6, the EM-simulated input impedance Z_{in} ($1/Y_{in}$) is compared with the circuit-simulated (or theoretical) impedance shown in Fig. 1, and the two impedances are shown to be in good agreement. The impedance behaviors for frequencies higher than 3 GHz are shown to be better for wideband characteristics than those for lower frequencies.

III. FABRICATION AND MEASUREMENTS

Fig. 7 shows a photograph of the fabricated RC absorber made of AgNW resistive film. The AgNW film with 110±4 Ω/□, produced by Cosmo AM&T (www.cosmoamt.com), was cut by a laser-cutting machine. The whole patterned film was then attached to a Styrofoam layer. The unnecessary part was detached later. One unit is composed of a square-shaped AgNW film, a Styrofoam layer of 12.5 mm ($\lambda_0/8$ at 3 GHz), and a conducting plane. The size of the unit is 35 mm × 35 mm (0.35 λ_0 × 0.35 λ_0 at 3 GHz).

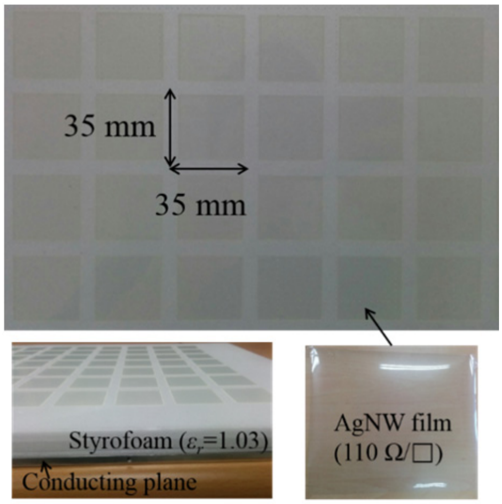


Fig. 7. Photograph of the fabricated RC absorber made of AgNW resistive film.

Fig. 8 presents the measurement setup to estimate the absorptions of the fabricated absorber with one horn antenna. The size of the fabricated absorber is 35 cm (10 units) × 25 cm (7 units). The measurements were conducted to change the distance between the standard horn antenna and the absorber from 3.5 cm to 23 cm. Although the absorber is placed somewhat in the near field, the following extraction procedures have been found to give closer results than the EM-simulation results [11].

Fig. 9 illustrates the measured reflection coefficients of the horn antenna in free space (S_{11} without the absorber), with the conducting plane (S_{11} with the conducting plane), and with the absorber (S_{11} with the absorber) as a function of frequency. The calibration method in [11] was used. The magnitude of the reflection coefficient referenced on the absorber surface under the condition of a normal plane wave incidence can be estimated using $|S_{11,\text{plane wave}}| = |S_{11}$ with absorber $|$ / $|S_{11}$ with conducting plane$|$.

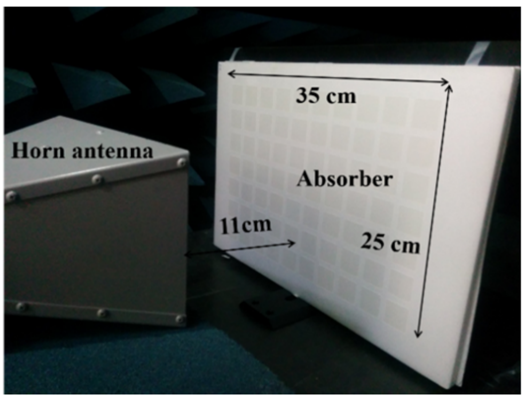


Fig. 8. Photograph of measurement setup for the fabricated RC absorber made of AgNW resistive film with one horn antenna.

Table 2. Comparison of absorber characteristics with those of this work

Ref.	Structure	f_0 (GHz)	Layer (ε_r)	Unit size (mm^3)	Max absorption (%)	90% absorption bandwidth (%)	Bandwidth expected (%)
[12]	Jerusalem cross	5	Cardboard (1.69)	22×22×1.9 (λ/25)	≥99	4.9–5.1 (4)	12.5
[13]	Soft magnetic film	5	Vacuum (1)	25×25×5 (λ/12)	≥99	4.8–5.4 (12)	41
[14]	Squre ring	6.18	FR-4 (4.25)	10×10×1 (λ/24)	≥99	6–6.36 (6)	8.5
[15]	Split ring cross	11	FR-4 (5.7)	6×6×0.4 (λ/28)	≥99	10.6–11.4 (7)	5.7
This work	Square patch	3	Styrofoam (1.03)	35×35×12.5 (λ/8)	≥99	2.3–5.1 (76)	76

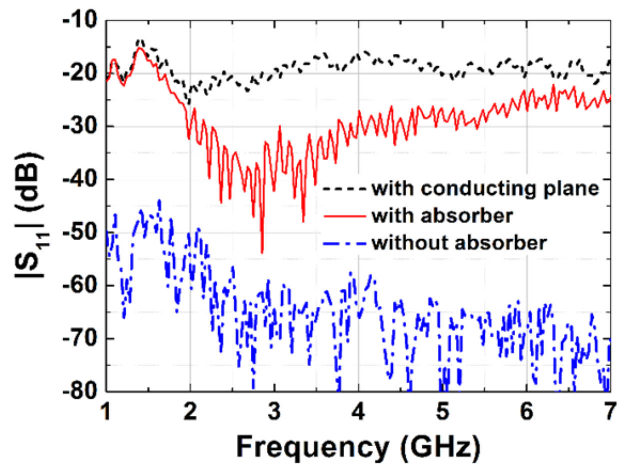


Fig. 9. Measured reflection coefficients of the horn antenna without the absorber, with the conducting plane, and with the absorber for the RC absorber at 3 GHz.

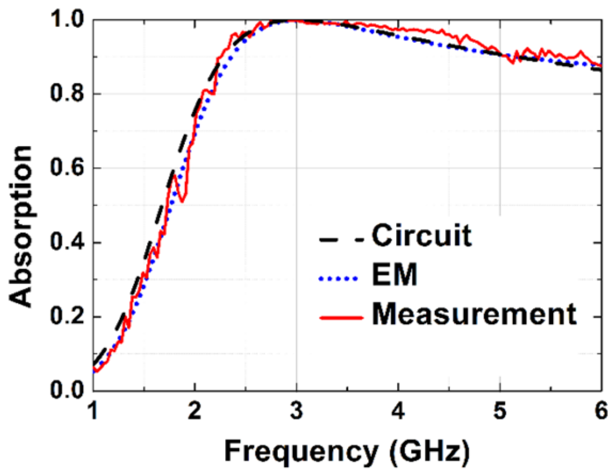


Fig. 10. Circuit-simulated/EM-simulated and measured absorptions ($=1-|S_{11}|^2$) as a function of frequency in the case of $f_0=3$ GHz and $\theta_0=45°$.

This estimation removes the effects of the used horn antenna and minimizes the effects of the used near-field measurements. The measured absorption is calculated using ($1-|S_{11,\text{ plane wave}}|^2$).

In Fig. 10, the measured absorption is shown to agree well with the theoretical (or circuit-simulated) and EM-simulated absorptions. The measured 90% absorption bandwidth is approximately 76% (2.3–5.1 GHz) with a complete absorption at the design center frequency of 3 GHz.

In Table 2, the absorption characteristics of the thin absorbers in [12–15] are compared with those theoretically expected by the proposed design method. Except for the case of [15] in which the measured bandwidth of 7% is wider than 5.7%, the bandwidth characteristics of the rest are shown to be at best comparable with or even far worse than those of the presented simple RC absorbers although diversified structures have been employed.

IV. CONCLUSIONS

An RC absorber with a layer thickness of less than a quarter of a wavelength has been examined from a simple equivalent circuit. Closed-form design equations have been derived and presented. The validity of the presented formulation has been demonstrated by a design example for the RC absorber at 3 GHz. The RC absorber has been designed, fabricated with AgNW resistive film, and measured. The absorber is shown to offer a 90% absorption from 2.3 GHz to 5.1 GHz (76%) with a layer thickness of 1/8 wavelength. The proposed design methodology is scalable to other frequencies.

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