Hindawi Publishing Corporation
Shock and Vibration
Volume 2014, Article ID 318380, 5 pages
http://dx.doi.org/10.1155/2014/318380

*Research Article*

# Electromagnetic Wave Absorbing Composites with a Square Patterned Conducting Polymer Layer for Wideband Characteristics

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Received 11 January 2013; Accepted 19 September 2013; Published 6 April 2014

Academic Editor: Gyuhae Park



The applications of electromagnetic- (EM-) wave-absorbers are being expanded for commercial and military purposes. For military applications in particular, EM-wave-absorbers (EMWAs) could minimize Radar Cross Section (RCS) of structures, which could reduce the possibility of detection by radar. In this study, EMWA composite structure containing a square periodic patterned layer is presented. It was found that control of the pattern geometry and surface resistance induced EMWA characteristics which can create multiresonance for wideband absorption in composite structures.

## 1. Introduction

*1.1. Periodic Patterns for Radar Absorbing Structures (RAS).* An electrically conductive medium is used as an EM-wave reflector and shielding structure. When the conductive surface is engraved, DC can always be conducted, but in the case of AC, there is a specific region where the EM wave cannot be transmitted or reflected. In the frequency range of interest, periodic patterns such as EM wave filters are considered frequency selective surfaces.

There are various methods and equations to verify the characteristics of the pattern layer; however, a computer simulation using FEM was assumed to be an effective tool to verify the accuracy of the equations. When the square array pattern is located in free space, the approximate equation for the resonance characteristics is as follows [1]:

$$Y_{\text{ind}} = (-j)\left(\nu - \frac{1}{\nu}\right)\frac{\left[A/C + (1/2)(A/\lambda)^2\right]}{\ln \csc\left((\pi/2)(\delta/A)\right)}, \nu = \left(1 - 0.41\frac{\delta}{A}\right)\left(\frac{\lambda}{A}\right), \quad \delta = \frac{A-C}{2}. \tag{1}$$

Total transmission occurs at

$$\frac{\lambda}{A} = 1 - 0.41\frac{\delta}{A}. \tag{2}$$

$A$ and $C$ mean the size of unit cell and $\lambda$ is the wavelength. From the Babinet principle, the grid type and patch type have the same resonance point, with opposite filter characteristics. The equation assumes the medium of frequency selective surface (FSS) is a metallic material like perfect electric conductor (PEC) of an infinitely thin film. When we design the periodic pattern for a radome, this equation is useful. but the equation assumes a free-space boundary. When a dielectric slab is added to the FSS layer, the real characteristics of the periodic pattern are changed. In general, the degree of change depends on the dielectric properties and the resonance frequency moves to the low frequency range [2].

The high impedance surface is different from the lossy surface; the periodic pattern is usually made by metal. The pattern controls only the reactive part of the impedance, and the layer is assumed to be thicker than the skin depth. As a result, control of the pattern thickness cannot affect the EM characteristics of the filter.

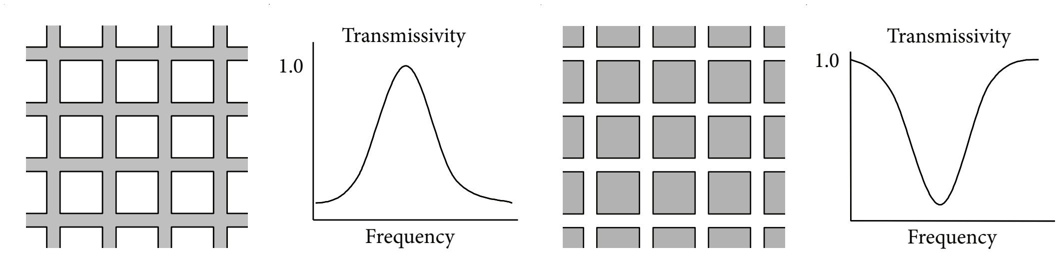



Figure 1: Inductive and capacitive screen.

*1.2. Advantage of Periodic-Pattern-Layered RAS (PPRAS).* One of the basic models for RAS is the Salisbury absorber, which uses a specific resistive sheet with a low dielectric spacer. The resonance peak can be controlled by the thickness of the spacer. As the thick spacer in the Salisbury absorber is its main demerit, many efforts have been made to reduce the thickness. The principle of impedance-matching with $\lambda/4$ thickness is that the maximum electric field is located at that point, and the resistive screen dissipates the energy of the electric field. Since the resistive sheet should not reflect the entire incident EM wave, it should have a free-space impedance of 377 Ω/sq. and be located at distance $\lambda/4$ from the PEC back-layer. This means that the Salisbury absorber has to be of minimum thickness and the resistivity of the screen should have a constant value.

The attempt to broaden the bandwidth of the Salisbury absorber involved multilayers of resistive screen, and the effort to minimize its thickness involved the study of highly dielectric materials [3]. However, such materials generally reduce the mechanical properties of the RAS and are costly to synthesize. Even if these kinds of materials do reduce the thickness, the bandwidth remains relatively narrow.

Another way to reduce the thickness is by application of a periodic pattern layer. Based on the $\lambda/4$ resonance, the engraved periodic patterns on the screen could reduce the total thickness of the RAS. In other words, this can move the resonance peak to a lower frequency range. The advantages of using such a pattern layer are reduction of thickness and the peak tuning of the RAS. Additionally, the loss control of the pattern is capable of changing the EM wave absorbing characteristics of the RAS. Because the pattern layer contains inductance (L) and capacitance (C) in the single layer, the filter characteristics of L and C are totally different. From the equivalent circuit theory, the combination of L and C could make a simple RF filter. As the number of elements increases, the order increases and the system shows good filter characteristics. These characteristics may be demerits of the RF circuit but, fortunately, these same characteristics are merits for the EM-wave-absorber. For example, a fractal pattern array with unit cells of various scales can be assumed to be a high-order system in filter design. The essence is that these high-order characteristics can be generated by the single layer pattern, not by the multilayered RAS.

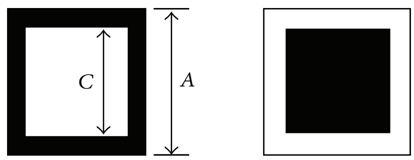



Figure 2: Unit cell of infinite array (inductive grid, capacitive patch).

## 2. PPRAS Design and Fabrication

*2.1. Design of the Composite Substrate.* The target frequency of the RAS designed in this research was X-band. Based on the target frequency, the Ku-band was included for ultrawide-band RAS. A RAS which could cover both bands is useful for air-stealth technology. In the first step, the RAS for X-band was designed with a thin substrate to verify the thickness reduction effect. The design of the substrate thickness was the main concern, because the thickness determines the target frequency range. For the Salisbury absorber in X-band, the thickness of the air spacer ($\varepsilon_r = 1.0 - j0.0$) is 7.5 mm, and glass/epoxy ($\varepsilon_r = 4.2 - j0.002$) is about 3.5 mm.

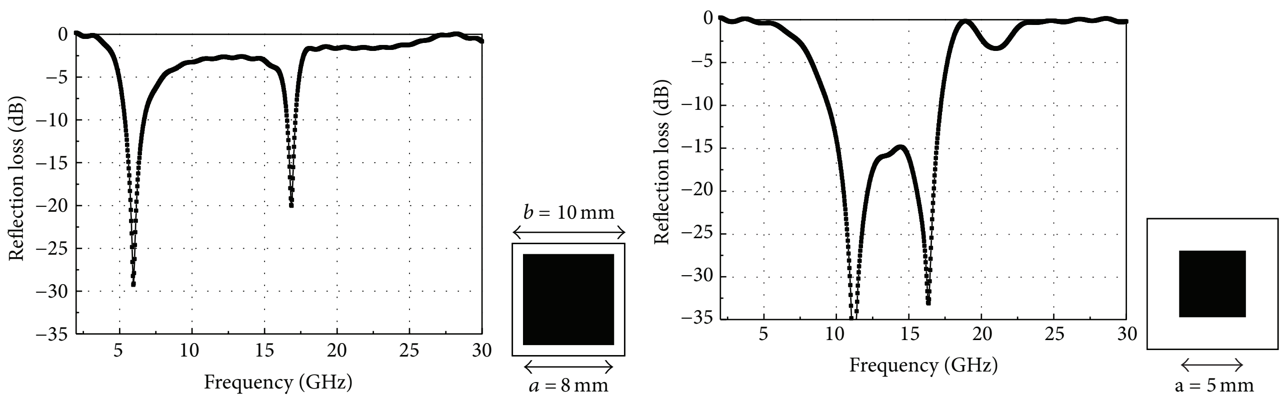
*2.2. Design of the Periodic Pattern Layer.* Through previous research on various patterns, the characteristics of each type could be verified. In this research, the square unit cell was adopted because of the simplicity of design and analysis to the various incidence angles. The square cell is divided into inductive (grid type) and capacitive (patch type) surfaces (Figure 1).

Basically, the dielectric substrate with PEC back plate has inductive characteristic and the capacitive pattern layer is effective for the RAS. According to the above consideration, square patch was used as unit cell, and the capacitance can be calculated by the following equation [4]:

$$Z_p = \frac{1}{j\omega C_p}, \quad C_p = \frac{(\varepsilon + 1)\,\varepsilon_0 D}{\pi} \log\left(\frac{2D}{\pi g}\right), \qquad (3)$$

where $D$ = array period and $d$ = gap between patches.

The size of unit cell, the gap between patches, and the thickness and permittivity of the dielectric substrate mainly control the inductance and capacitance of the pattern




(a) Width = 8

(b) Width = 5

Figure 3: Peak control: AMC absorber with Salisbury absorber.

layer, and the resonance frequency can be estimated from the variables (Figure 2). The resonance occurs when the imaginary part of impedance becomes zero.

From $Z = R + jX = R + j\omega L + 1/j\omega C$

$$X = \omega L - \frac{1}{\omega C} = 2\pi f L - \frac{1}{2\pi f C} = 0. \quad (4)$$

Resonance frequency $= 1/2\pi\sqrt{LC}$:

$$f_{\text{resonance}} = \frac{1}{2\pi\sqrt{\mu_0 h \cdot \varepsilon_0 D\left(\varepsilon_r + 1\right)/\pi \cdot \log\left(2D/\pi d\right)}}. \quad (5)$$

The approximate resonance point can be calculated from the above equation, and the more exact resonance frequency was deduced from computer simulation. Within reasonable boundary conditions, parameter sweep and optimization were performed. The approximate equation assumes the thickness of the conductive square patch is enough to generate L and C, and the target resonance frequency was set to 10.3 GHz.

*2.3. Expansion of Bandwidth.* The maximum electric conductivity of the synthesized conducting polymer (CP) was set and the surface resistance was controlled by varying the coating thickness. In the case of the CP, the thickness for a Salisbury resistive screen was 2 $\mu$m, and sheet resistance was 377 Ω/sq. When the coating layer exceeds this thickness, surface resistance decreases and conductivity increases. When the pattern layer is applied, the effective surface resistance should be considered. The unit cell with a 6 mm square pattern should have a 6 $\mu$m coating thickness to achieve the Salisbury resistive effect, as there was a 2 mm null-grid region. When the thickness exceeded 6 $\mu$m, L and C resonance was initiated, and the artificial magnetic conductor (AMC) characteristic was as if the thickness was more than 12 $\mu$m. In other words, the 6~12 $\mu$m range would be the transition thickness for the AMC absorber, and at 12 $\mu$m thickness, the increased conductivity of the patterns could generate L and C on the surface of the periodic layer. As a result, there was a combination of Salisbury and AMC absorption in the transition range of the coating thickness.

When we design the periodic pattern layer with coating thickness control, the resonance peaks from these two EM-wave-absorber effects can be tuned effectively. That is the essence of wideband RAS with peak control in the X- and Ku-bands.

As the effective surface resistance was applied to maintain 377 Ω/sq., the pattern shape was functionless when the thickness was less than specified, whether the pattern existed or not. Clearly then, for the evaluation of the critical thickness, the transition thickness is important to be considered in the pattern design and conductivity of the coating material. When the unit cell has enough thickness to generate current using incident EM wave energy, the AMC characteristics are generated. If the pattern shape is effective in generating large amounts of L and C, the AMC resonance peak moves into the lower frequency range, and this means that the AMC peak location can be controlled. When the peaks of the Salisbury screen and the AMC are properly arranged for the specific frequency range, the combined dual peak can make the wideband absorption region within the single-layered PPRAS.

For the square pattern used in this research, as the size of a square increases, the capacitance also increases. As a result, the AMC peak moves to the lower frequency range, whereas the Salisbury peak remains in the original frequency region. When the size of a square decreases, the AMC peak moves to the higher frequency range located near the Salisbury resonance peak.

Figure 3 shows the location and movement of the AMC peak with variation of square size. In the first graph, the square size is large and the capacitance is also relatively large. The location of the AMC peak is near 6 GHz and Salisbury peak is at 17 GHz. In the second graph, the square size is smaller. The AMC peak moved to the right, but the Salisbury peak location remained fixed. As a result, the AMC peak and

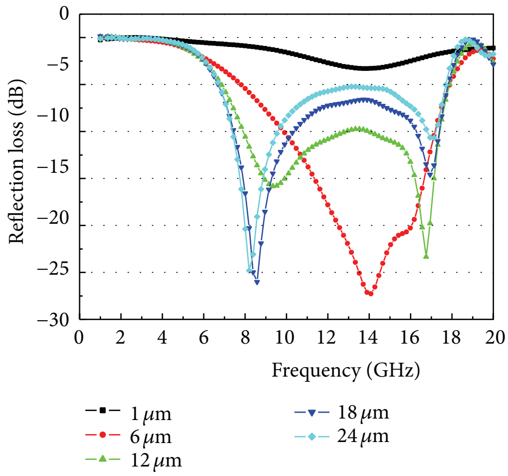



Figure 4: Simulation model: reflection loss change with different CP thickness.

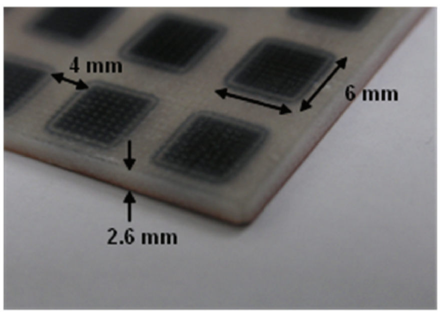



Figure 5: PPRAS composite.

Salisbury peak are combined in a specific frequency range. Generally, this kind of dual-peak control was achieved by control of the thickness of the multilayered RAS. The result of this multiple-peak control is expansion of the EM wave absorption bandwidth in the single-layered PPRAS.

The simulation model was designed for measurement of the S-parameter. The boundary condition was the TEM-mode plane wave. The back plate of the PPRAS was covered by PEC, and its transmission and reflection characteristics were simulated. The design was conducted with parameter sweep and optimization with CST-MWS. Based on the simulation result, we prepared an effective PPRAS model. The thickness of the substrate was 2.6 mm and the unit cell size was 6 mm with a 4 mm gap (Figure 5).

Figure 4 shows variation in the reflection loss with change in the thickness of the CP layer, while the other variables are fixed. Up to 6 $\mu$m, the AMC peak did not appear at the target frequency (left peak). When the thickness approached 12 $\mu$m, the single peak split into two peaks. When the thickness increased more than 12 $\mu$m, two clear peaks were present.

The coating thickness needed to establish this critical transition point is determined by the conductivity of the coating materials, and the CP paste synthesized in this study had the desired transition characteristics with a coating of 6–12 $\mu$m. If the thickness increased more than 12 $\mu$m, the peaks were totally separated.

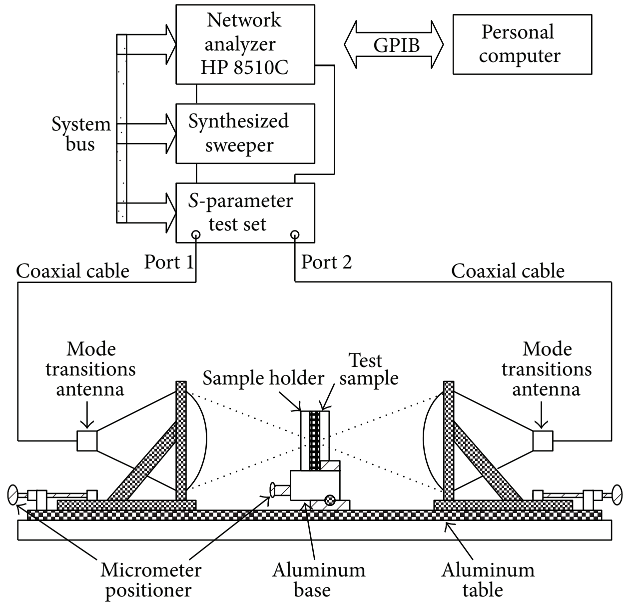



Figure 6: Free-space measurement system.

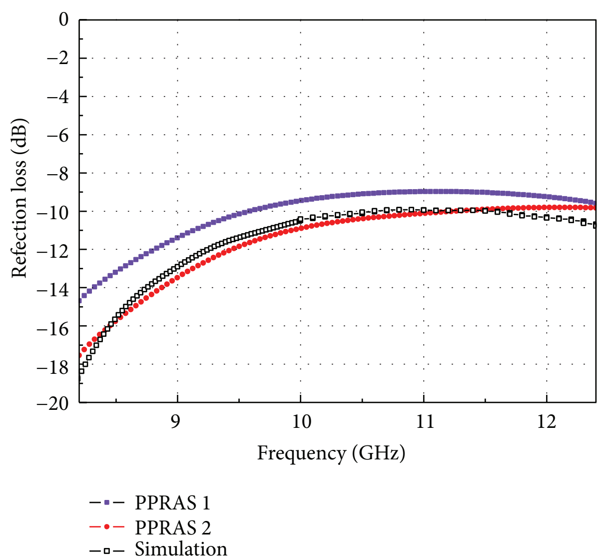



Figure 7: Reflection loss of the PPRA in X-band.

## 3. Results and Conclusion

The reflection loss of the PPRAS plate was measured in X-band. The free-space measurement system was used. In the experiment and simulation, transmission was prevented by a metal back plate. The relation between the incidence wave and reflection wave verified the absorption characteristics.

The measurement system is illustrated in Figure 6. Two spot-focusing horn antennas for X-band were located on a square aluminum plate (1.83 m × 1.83 m). The sample was located at the midpoint between the antennas. The specimen was a square plate (150 mm × 150 mm) and the antenna was connected to a network analyzer (HP 8510C). The designed PPRAS had 9.5 GHz bandwidth under −10 dB, and its X-band properties were measured. The S-parameters are shown in Figure 7.

The absorbers had about −10 dB absorption characteristics in the X-band, as designed. PPRAS 1 and 2 show similar traces as the simulation result and the result follows the initial design target. From the graph, we can expect that the first peak is located in the lower frequency range, and the second peak is located in the higher frequency range. As the S-parameter was measured only in X-band, we cannot confirm the exact location of the peaks. PPRAS 1 and 2 were two similar specimens, which were fabricated considering fabrication error. The disagreement of the graphs of the two specimens was caused by measurement errors, coating resolution, pattern uniformity, and various fabrication errors.

In this study, we designed PPRAS using a composite material. The PPRAS had a dual resonance peak in the layer with a single pattern, and the peak could be effectively designed and controlled to cover the X- and Ku-bands. As a result, we realized a thin, wideband RAS using PPRAS.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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