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PATTERNED RESISTIVE STRIP LOADING FOR EDGE SCATTERING SUPPRESSION OF A FINITE WEDGE

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Abstract—Tapered resistive strip realized by patterning the constant resistive strip is used to suppress edge scattering of a finite wedge. The suppression effect is simulated and evaluated by the reduction in monostatic RCS (Radar Cross Section). This reduction is compared with the one which loaded by the ideal tapered resistive strip. The result indicating that patterning a constant resistive strip to create a gradient in sheet resistance is feasible. To verify this method of fabricating tapered resistive strip, patterned resistive strip with a proper gradient in sheet resistance is conducted and loaded on the wedge target for test. The gradient in sheet resistance used for test is obtained from the optimization. Resistive strip with this sheet resistance gradient renders a promising effect of edge scattering suppression. The test result shows a reduction of 20 dB for the geometric mean of monostatic RCS in the angular range of 45°. This value is close to the one of 23 dB in simulation.

1. INTRODUCTION

The scattering of electromagnetic (EM) waves by resistively loaded bodies has received much attention due to the desire to control the RCS of the targets. Study on the EM scattering of a wedge is important as wedge is a canonical target [1, 2]. For many applications, it is recommended to reduce the scattering from a wedge shape target. Scattering from the wedge faces can be solved by coating radar absorbing materials (structures) [3–5]. However, thinly coated absorbing materials cannot restrain edge diffraction from the wedge

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tip. This excites the scientific research interest in exploring effective RCS reduction methods for wedge tip scattering, in particular the one with resistive strip loading. Resistive strip is widely used in EM scattering suppression, especially for surface discontinuities like aperture and edge [6]. By providing a cushion at the discontinuity, resistive treatment may result in dramatic reduction of edge scattering. This makes it a promising treatment for controlling scattering from the wing and tail fin of aerial vehicle [7].

Resistive loading has been extensively studied both analytically and numerically [8–10]. Empirical expression of the backscattering from isolated resistive strip at grazing incidence is deduced based on Method of Moments (MoM) [11]. Angular uniform asymptotic expressions for the field scattered by a constant resistive strip of large electrical width is developed using Geometrical Theory of Diffraction (GTD) [12]. In the situation of tapered resistive strip at grazing incidence, an empirical expression for the rear edge contribution is also derived [13]. The study of resistive strip in the present of a scatterer is also widely documented. Three different solutions for TM scattering of resistive strip extended to a metallic half plane are developed [7]. One is based on MoM/Green function. The other two are approximate solutions, one of which is improved in the assumption of small resistive strip width whereas the other is developed in the case of large resistive strip extension. For a wedge shape target, a uniform asymptotic solution is developed by Rojas and Otero [14] for the scattering from an impedance wedge with resistive strip extended to the wedge tip using Uniform Geometrical Theory of Diffraction (UTD). According to their further work [15], the loading of exponential tapered resistive strip renders promising RCS reduction in most cases.

For the study of tapered resistive strip, it is assumed that the sheet resistance varies continuously along the strip. However, the realization of this ideal tapered resistive strip is technically difficult and costly. In the engineering perspective, it is desire to find a simple and low cost manner to realize tapered resistive strip that possessed similar properties as the ideal tapered one. In this paper, tapered resistive strip which based on geometry variation is realized using the matching method proposed in [16]. The primary purpose of this work was to validate the practicability of realizing gradient in sheet resistance by geometry variation. For this purpose, results of edge scattering suppression by the loading of the realized tapered resistive strip and ideal tapered one are compared. The scatterer considered is a finite metal wedge whose major scattering mechanism comes from edge scattering. For a better comparison, an optimization is processed to determine the sheet resistance distribution which results in effective RCS reduction. It is comprehensible, because with a promising reduction in RCS the difference between the effects of the two kinds of tapered resistive strips can be enhanced.

2. DESIGN

In our experiment, the target of interest is a finite metal wedge made of Aluminum, its primary scattering mechanism is edge scattering. The geometry and coordinate of the wedge target are depicted in Fig. 1. Fig. 1(a) is the target loaded by the ideal tapered resistive used for optimization, while Fig. 1(b) is the target loaded by realized tapered one (the patterned resistive strip) for validating its effect of edge scattering suppression. The target is illuminated by uniform plane wave of 6 GHz sweeping from $\varphi = 0°$ to $\varphi = 45°$, where φ is the included angle between the incident wave and the X axis in the XY plane. The angle of wedge tip is $\pi/6$, and the length of the wedge face is 200 mm. At the end of the wedge target is a contact semi-cylinder. Compared with the wedge of infinite dimension, this target include more scattering mechanisms such as curvature discontinuity scattering [17] and creeping wave in the shadow region. However, the major scattering still comes from the wedge tip under the considered incidence angular range of φ. And by considering a finite wedge, the number of unknowns decreases dramatically which is profitable for the Method of Moment (MoM). It should be mentioned that as resistive strip loading at the front edge hardly response to an H-polarized (magnetic vector parallel to the resistive strip edge in the Z axis direction) plane wave, E-polarized plane wave incidence is assumed here as shows in Fig. 1.

The scattering can be calculated by using the Electric Field Integral Equation (EFIE), thus the scattered electric field can be expressed as

$$\vec{E}^s = -j\omega\vec{A}(\vec{r}) - \nabla\Phi = \frac{\mu_0}{4\pi}\int_S \vec{J}\,\frac{e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|}dS' - \nabla\frac{1}{4\pi\varepsilon_0}\int_S \nabla_S\cdot\vec{J}\,\frac{e^{-jk|\vec{r}-\vec{r}'|}}{-j\omega\,|\vec{r}-\vec{r}'|}dS' \quad (1)$$

where J is the surface current density, $k = \omega\sqrt{\mu_0\varepsilon_0}$ is the wave number and S is the surface of the target. According to the electric field boundary condition $\vec{n} \times (\vec{E}^i + \vec{E}^s) = 0$ on metal surface, the relation between incident field E^i and scattered field can be written as

$$\vec{n} \times \vec{E}^s = -\vec{n} \times \vec{E}^i \quad (2a)$$

For the resistive boundary condition, tangential electric field is continuous across a resistive strip and proportional to the surface

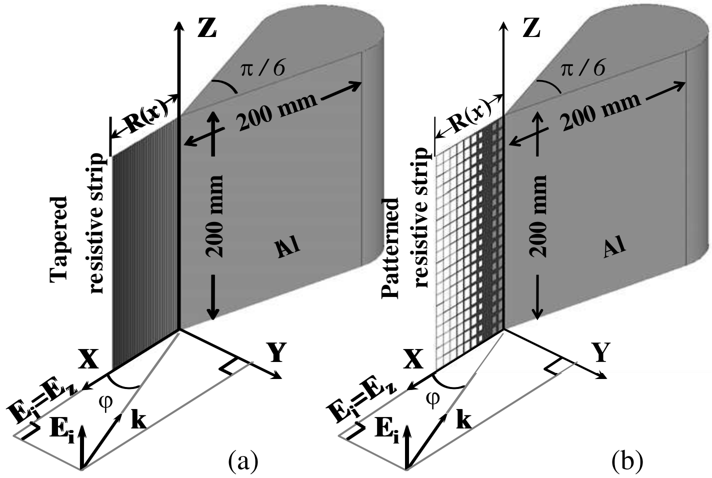

Figure 1. Geometry and coordinate of the target (a) loaded by ideal tapered resistive strip for numeric simulation. (b) Loaded by real tapered resistive strip for test.

current density on the strip. Thus

$$\begin{aligned} \vec{n} \times \left(\vec{E}_{+}^{i} + \vec{E}_{+}^{s}\right) - \vec{n} \times \left(\vec{E}_{-}^{i} + \vec{E}_{-}^{s}\right) &= 0 \\ \vec{n} \times \vec{n} \times \left(\vec{E}_{+}^{i} + \vec{E}_{+}^{s}\right) = \vec{n} \times \vec{n} \times \left(\vec{E}_{-}^{i} + \vec{E}_{-}^{s}\right) &= -R\vec{J} \end{aligned} \tag{2b}$$

where $\vec{E}_{+}^{i,s}$ and $\vec{E}_{-}^{i,s}$ means the electric field at positive and negative side of the resistive strip. R is the sheet resistance of the resistive strip surface.

MoM is applied to solve the problem by using the RWG basis function which is fully discussed in Ref. [18]

$$\vec{f}_n(\vec{r}) = \begin{cases} 0.5 l_n \vec{\rho}_n^{\,+} / \Omega_n^{+}, & r \text{ in } T_n^{+} \\ 0.5 l_n \vec{\rho}_n^{\,-} / \Omega_n^{-}, & r \text{ in } T_n^{-} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

T_n^{+} and T_n^{-} are two adjacent triangular patch, and l_n is the length of the edge between them. $\Omega_n^{\pm}$ is the area of triangular $T_n^{\pm}$. $\vec{\rho}_n^{\,\pm}$ is defined with respect to the free vertex of $T_n^{\pm}$. By using the Galerkin's method of choosing testing functions, the MoM impedance matrix Z can be written as

$$Z_{mn} = l_m \left[j\omega \left(\vec{A}_{mn}^{+} \cdot \frac{\vec{\rho}_m^{\,c+}}{2} + \vec{A}_{mn}^{-} \cdot \frac{\vec{\rho}_m^{\,c-}}{2} \right) + \Phi_{mn}^{-} - \Phi_{mn}^{+} \right] \tag{4}$$

where

$$\vec{A}^{\pm}_{mn} = \frac{\mu_0}{4\pi}\int_S \vec{f}_n(\vec{r}\,')\frac{e^{-jk\left|\vec{r}^{\,c\pm}_m-\vec{r}\,'\right|}}{\left|\vec{r}^{\,c\pm}_m-\vec{r}\,'\right|}dS' \tag{5}$$

$$\Phi^{\pm}_{mn} = \frac{1}{j4\pi\omega\varepsilon_0}\int_S \nabla'_s\cdot\vec{f}_n(\vec{r}\,')\frac{e^{-jk\left|\vec{r}^{\,c\pm}_m-\vec{r}\,'\right|}}{\left|\vec{r}^{\,c\pm}_m-\vec{r}\,'\right|}dS' \tag{6}$$

$\vec{\rho}^{\,c\pm}_m$ is the vector between the free vertex and the centroid of $T^{\pm}_n$, and $\vec{\rho}^{\,c-}_m$ directed toward the free vertex while $\vec{\rho}^{\,c+}_m$ directed away from it. $\vec{r}^{\,c\pm}_m$ is the vector from the coordinate origin to the centroid of $T^{\pm}_n$.

The numeric method described above is used to calculate the scattering properties of the target. For the optimization, resistive strips are loaded at the tip of the metal wedge as shows in Fig. 1(a). The loading width of the strips is 100 mm, which is two times the free space wavelength of the considered frequency. According to the study of Ref. [15], resistive strips are considered with the sheet resistance profile

$$R(x) = e^a \cdot e^{b\cdot x} \quad x \in \ [0, 100\,\mathrm{mm}] \tag{7}$$

where $R(x)$ is the sheet resistance of the strip in *ohms per square* ($\Omega/\square$), a and b are amplitude and exponential factors respectively, which shape the sheet resistance distribution of the loaded resistive strip, and x is the distance from the wedge tip (as shows in Fig. 1). When $b = 0$, the constant resistive strips are loaded on the target. Otherwise, the ideal tapered ones are loaded. For the comparison, promising performance of scattering reduction should be obtained, so factors a and b are optimized. Notes that the optimization is processed assuming the loading of ideal tapered resistive strip shown in Fig. 1(a) as sheet resistance follows Eq. (7). Based on the optimization, the effect of edge scattering suppression by loading the realized tapered resistive strip is evaluated by numerical simulation and test as shows in Fig. 1(b).

3. OPTIMIZATION OF RESISTIVE STRIP

To provide a clear comparison of the effect in edge scattering suppression by loading of the two kinds of tapered resistive strip, the difference in mono-static RCS reduction should be enlarged. This means, as the property of *Decibel*, comparison should be made in the situation that good mono-static RCS reduction is achieved. Thus factors a and b in Eq. (7) are optimized.

The optimization is processed by sweeping the factors a and b of Eq. (7) in a reasonable range $a \in [0, 6]$ and $b \in [0, 0.1]$, as shows in

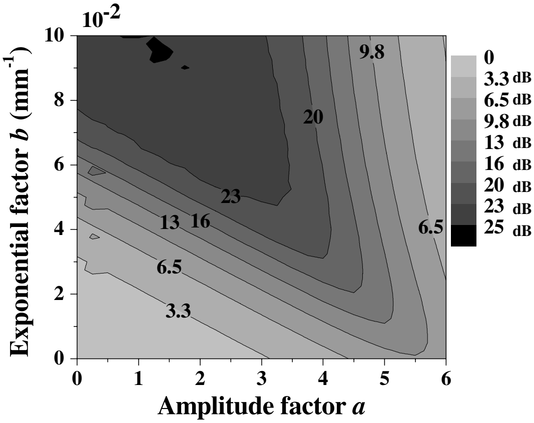

Figure 2. Geometric mean of mono-static RCS reduction in the incident range of $\varphi = 0°$ to $\varphi = 45°$ by loading of ideal tapered resistive trip (in *Decibel*).

Fig. 2. This makes the sheet resistance of the resistive strip sweep in an effective large range in engineering application perspective. For tapered resistive strip ($b \neq 0$), sheet resistance at the front portion of the strip varies from $1\,\Omega/\square$ ($b \to 0$, $a = 0$) to $22\,\mathrm{k}\Omega/\square$ ($b = 0.1$, $a = 0$). And sheet resistance of constant resistive strip ($b = 0$) varies from $1\,\Omega/(a = 0)$ to $400\,\Omega/\square$ ($a = 6$).

Performance of edge scattering suppression by the resistive loading is evaluated using the geometric mean of the mono-static RCS reduction in the considered incidental angular range ($\varphi = 0°$ to $\varphi = 45°$). The results are presented as contour map in *Decibel* and shown in Fig. 2. For constant resistive strips ($b = 0$), geometric mean of the best performance in mono-static RCS reduction is about 9.8 dB, which achieved by resistive strip loading with constant sheet resistance $244\,\Omega/\square$ ($a = 5.5$). For tapered resistive strip loading, a steady reduction of 23 dB is obtained, which is much better than the loading of constant resistive strip. One of the main reasons for using inhomogeneous materials is that they introduce more degrees of freedom than homogeneous materials which facilitate the control of the echo width of a scatterer. To validate the practicability of realizing gradient in sheet resistance by geometry variation, patterned resistive strip with sheet resistance property factor $a = 2.5$ and $b = 7 \times 10^{-2}\,\mathrm{mm}^{-1}$ is loaded on the scatterer for numeric simulation and test.

4. EXPERIMENTAL VERIFICATION

Patterning a constant resistive trip leads to alteration in the equivalent sheet resistance. As the fabrication of tapered resistive strip is difficult, it is desired to validate the practicability of realizing tapered resistive strip by patterning. So a patterned resistive strip with the proposed sheet resistance distribution is used in the experiment. It is realized by geometric variations based on Frequency Selective Surfaces (FSS) concepts, and discussed in Ref. [16, 19, 20]. Fig. 3 shows the relation between the reflectivity Γ and the ratio d/D of the periodic unit cell. In the experiment, sheet resistance of the constant resistive strip is $75\,\Omega/\square$. Fitting the curve in Fig. 3, the relation can be express in equation as

$$\begin{aligned}\Gamma_{Air} &= 1.7516\left(\frac{d}{D}\right)^5 - 3.3171\left(\frac{d}{D}\right)^4 + 2.406\left(\frac{d}{D}\right)^3 \\ &\quad -0.1863\left(\frac{d}{D}\right)^2 + 0.0596\frac{d}{D} - 0.7167 \qquad (8a)\\ \Gamma_{Metal} &= -0.0837\left(\frac{d}{D}\right)^5 + 0.3653\left(\frac{d}{D}\right)^4 - 0.313\left(\frac{d}{D}\right)^3 \\ &\quad -0.2183\left(\frac{d}{D}\right)^2 - 0.0351\frac{d}{D} - 0.7146 \qquad (8b)\end{aligned}$$

According to the transmission line theory, the relation between sheet resistance and reflection coefficient Γ can be expressed as [21]

$$\Gamma = \frac{-\eta_0}{2R_e + \eta_0} \qquad (9)$$

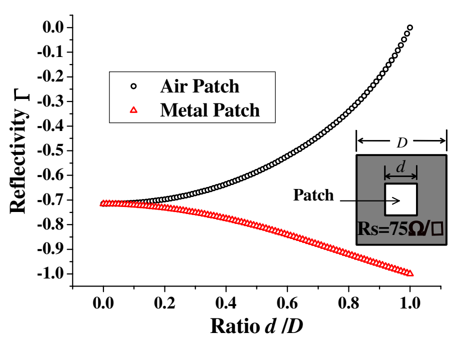

Figure 3. Relation between reflectivity Γ and ratio d/D of the patterns.

where η_0 is free space impedance, and R_e is the equivalent sheet resistance of the patterned resistive strip. Γ is Γ_{Air} or Γ_{Metal} in Eq. (8) with the corresponding ratio d/D. Combining Eqs. (8) and (9), the relation between R_e and ratio d/D can be determined. The equivalent sheet resistance can be well controlled by changing the size of the center square, whose property is *Air* or *Metal*. Thus the geometry of the patterned resistive strip can be determined by setting the size of the periodic unit cell.

Take the fabrication accuracy into account, the unit cell of square with the edge $D = 10$ mm is considered. Thus 10 transition steps between air and metal should be made as depicted in Fig. 4(b). The constant resistive strip used for experiment is a thin layer of graphite which realized by screen printing. The substrate on which the graphite is printed is a 0.2 mm thick layer of paper processing the relative permittivity constant about $2.3 - 0.1j$. It should be mentioned that the electric thickness of the substrate is very small (0.004λ), which λ is the free space wavelength at 6 GHz, the influence of the substrate can be neglected. The ratio d/D and picture of the fabricated patterned resistive strip used for experiment are also shown in Fig. 4. It turns out that the first three transition steps at the air side are far beyond our fabricated limit, thus the alternative 7-transition-steps resistive strip is used for testing.

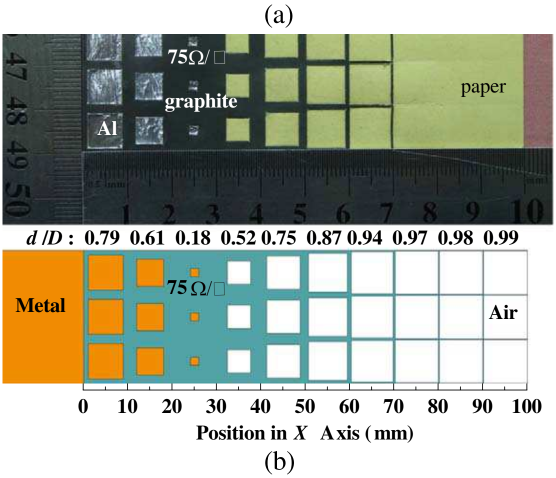

Figure 4. Geometry and d/D ratio of the tapered resistive strip. (a) Picture of the fabricated patterned resistive strip. (b) Sketch of the patterned resistive strip.

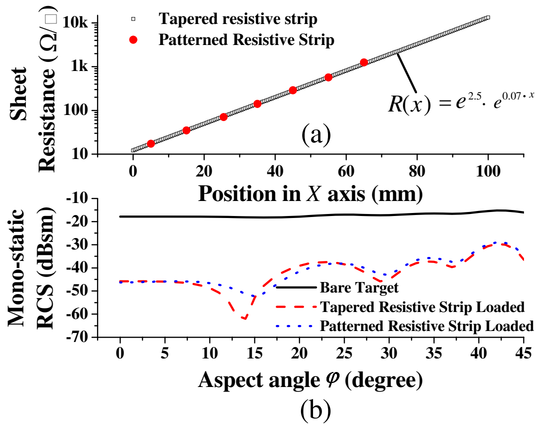

Figure 5. Comparison of sheet resistance distribution and simulated mono-static RCS spectrums of the two kinds of tapered resistive strips. (a) Sheet resistance distribution of the two kinds of resistive strip. (b) Simulated mono-static RCS of the target loaded by the two kinds of resistive strip.

Figure 5(a) demonstrates the sheet resistance distribution of the chosen tapered resistive strip and equivalent sheet resistance of each transition step on the realized tapered resistive strip. The equivalent sheet resistance of the transition steps being realized tally with that of the tapered resistive strip. With these two resistive strip loaded on the scatterer, Fig. 5(b) presents the effects of edge scattering suppression. The simulation results of the two kinds of tapered resistive strips possess similar shape. The RCS spectrum of the scatterer loaded by the realized patterned resistive strip highly coincides with the one loaded by ideal tapered resistive strip.

Figure 6 shows the simulation and test results of scatterer loaded by the chosen patterned resistive strip at the frequency of 6 GHz. For both the results of the bare target and target loaded patterned resistive strip, the simulation results are in agreement with the test ones. Simulation results show similar shape with the test ones but with a little low echo strength. This indicates that sheet resistance variation can be realized by patterning the constant resistive strip. Taking the test result of the bare target as basis, the geometric mean of tested reduction in the range $\varphi = 0°$ to $\varphi = 45°$ is 20.14 dB, which is close to the 23 dB in Fig. 2. While based on simulation result of the bare target, this value is 18.16 dB. This is comprehensible because the test result of the bare target is a bit higher than the simulation one.

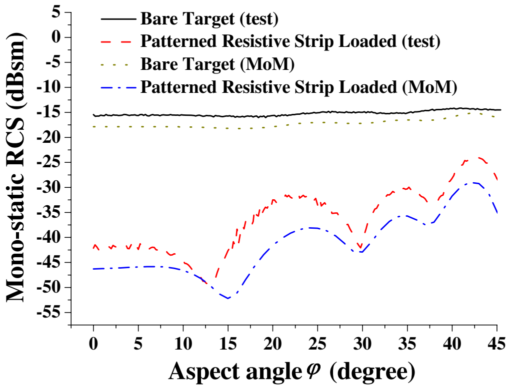

Figure 6. Comparison of simulation results and test results.

It should be mentioned that changing the sheet resistance by patterning has some limitation. The matching method is based on the geometry variation. The electrical size of the pattern on the resistive strip increases as the operating frequency. In higher frequency, the patterned resistive strip could not be treated as uniform medium and result in complex sheet resistance. And in this case, the angular property of the patterned resistive strip deviates from that of the corresponding ideal tapered resistive strip of uniform medium. Smaller size of unit cell is optional, but this also results in higher difficulty in fabrication.

5. CONCLUSION

The effect of patterned resistive strip loading on edge diffraction suppression is verified by mono-static RCS testing. The simulation and test results of the patterned resistive strip loaded wedge are in agreement with each other. Patterning a constant resistive strip to create a gradient in sheet resistance is feasible. It is a simple way to realize tapered sheet resistance distribution in the engineering perspective. The electrical size of the unit cell of the pattern should be small enough so that the structure could be regarded as uniform medium. By using a proper tapered resistive strip loading, edge scattering can be effectively controlled in a large angular range. For the geometric mean of RCS in the angular range of 45°, 20 dB reduction is achieved. The wide band property of the patterned tapered resistive strip can be a further work.

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REFERENCES

1. Gomez-Sousa, H., J. A. Martínez-Lorenzo, and O. Rubiños-López, "Three-dimensional wedge diffraction correction deduced by the stationary phase method on the modified equivalent current approximation (MECA)," *Progress In Electromagnetics Research M*, Vol. 23, 207–227, 2012.
2. Zhu, N. Y. and M. A. Lyalinov, "Diffraction by a wedge or by a cone with impedance-type boundary conditions and second-order functional difference equations," *Progress In Electromagnetics Research B*, Vol. 6, 239–256, 2008.
3. Chen, H. T., G.-Q. Zhu, and S.-Y. He, "Using genetic algorithm to reduce the radar cross section of three-dimensional anisotropic impedance object," *Progress In Electromagnetics Research B*, Vol. 9, 231–248, 2008.
4. Pesque, J. J., D. P. Bouche, and R. Mittra, "Optimization of multilayer antireflection coating using an optimal control method," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 40, No. 9, Sep. 1992.
5. Terracher, F. and G. Berginc, "A broadband dielectric microwave absorber with periodic metallizations," *Journal of Electromagnetic Waves and Applications*, Vol. 13, No. 12, 1725–1741, 1999.
6. Chen, H.-Y., L.-J. Deng, and P.-H. Zhou, "Suppression of surface wave from finite conducting surfaces with impedance loading at margins," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 14–15, 1977–1989, 2010.
7. Kempel, L. C. and J. L. Volakis, "TM scattering by a metallic half plane with a resistive sheet extension," *IEEE Transactions on Antennas and Propagation*, Vol. 41, No. 7, 910–917, Jul. 1993.
8. Rothwell, E. J., M. J. Havrilla, and S. Dorey, "An improved physical optics formulation for scattering by a thin resistive strip," *Electromagnetics*, Vol. 30, No. 5, 403–418, Jun. 28, 2010.
9. Hatamzadeh-Varmazyar, S., M. Naser-Moghadasi, E. Babolian, and Z. Masouri, "Numerical approach to survey the problem of electromagnetic scattering from resistive strips based on using a set of orthogonal basis functions," *Progress In Electromagnetics Research*, Vol. 81, 393–412, 2008.

10. Umul, Y. Z. and U. Yalcin, "Diffraction theory of waves by resistive surfaces," *Progress In Electromagnetics Research B*, Vol. 23, 1–13, 2010.
11. Senior, T. B. A., "Backscattering from resistive strips," *IEEE Transactions on Antennas and Propagation*, Vol. 27, No. 6, 808–813, Nov. 1979.
12. Senior, T. B. A., "Scattering by resistive strips," *Radio Science*, Vol. 14 No. 5, 911–924, Sep. 1979.
13. Senior, T. B. A. and V. V. Liepa, "Backscattering from tapered resistive strips," *IEEE Transactions on Antennas and Propagation*, Vol. 32, No. 7, 747–751, Jul. 1984.
14. Rojas, R. G. and M. Otero, "EM diffraction by a resistive strip attached to an impedance wedge," *Journal of Electromagnetic Waves and Applications*, Vol. 7, No. 3, 373–402, Jan. 1, 1993.
15. Otero, M. F. and R. G. Rojas, "Resistive treatment to reduce edge diffraction from large wedge-shaped objects and planar antennas," *Radio Science*, Vol. 32, No. 5, 1745–1759, Sep. 1997.
16. Sjoberg, D. and M. Gustafsson, "Realization of a matching region between a radome and a ground plane," *Progress In Electromagnetics Research Letters*, Vol. 17, 1–10, 2010.
17. Kuester, E. and D. Chang, "Scattering of a surface wave from a curvature discontinuity on a convex impedance surface," *IEEE Transactions on Antennas and Propagation*, Vol. 25, No. 6, 796–801, Nov. 1977.
18. Sadasiva, M. R., D. R. Wilton and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Transactions on Antennas and Propagation*, Vol. 30, No. 3, May 1982.
19. Chen, H. Y., L. J. Deng, P. H. Zhou, and J. L. Xie, "Tapered impedance loading for suppression of edge scattering," *Microwave, Antennas and Propagation, IET*, Vol. 5, No. 14, 1744–1749, Nov. 22, 2011.
20. Chen, H. Y., "Study on Scattering Mechanisms and RCS Reduction of Electromagnetic Discontinuities," Ph.D. dissertation, School of Microelectronics and Solid-State Electronics, University of Electronic Science and Technology of China, ChengDu, China, 2011.
21. Sjoberg, D., "Analysis of wave propagation in stratified structures using circuit analogs, with application to electromagnetic absorbers," *Eur. J. Phys.*, Vol. 29, 721–734, 2008.