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Radar absorbing materials used for target camouflage

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As a result of the developments within signal processing, transmitters and receivers areas radar technology has improved steadily over the past 50 years gaining in the sensor sensitivity, miniaturisation, power consumption, etc which allow to build smaller, more reliable and user friendly radar sensors. The effectiveness of these radar sensors is sufficiently threatening to merit the reduction of radar signature of all battlefield equipment. The paper analyses the potential use of radar absorbing materials to reduce the scattered signal by different metallic parts of military equipment and facilities. The paper is focused on two types of materials whose properties are analysed. The authors emphasise the results they got by simulations using different optimisation programs and measured data. The novelty of the paper is given by the materials used for simulations as well as by the algorithms proposed for reflection coefficient optimisation that gets the parameters of the materials from a database made up of 24 types of materials previously characterised.

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I. Introduction

The radar signature is given by the radar cross section (RCS) that can be viewed as a comparison of the strength of the reflected signal from a target to the reflected signal from a perfectly smooth sphere of cross sectional area of 1 m^2. Radar cross section is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter power per steradian (unit solid angle) in the direction of the radar (from the target) to the power density that is intercepted by the target. The conceptual definition of RCS includes the fact that not all of the radiated energy falls on the target. A target's RCS is most easily visualised as the product of three factors:

-projected cross section;
-reflectivity;
-directivity.

The reflectivity is defined by the percent of intercepted power reradiated (scattered) by the target. Directivity represents the ratio of the power scattered back in the radar's direction to the power that would have been backscattered had the scattering been uniform in all directions. RCS does not equal geometric area. The RCS of a sphere is independent of frequency if operating at sufficiently high frequencies where λ <<range, and λ <<radius (r).

Experimentally, radar return reflected from a target is compared to the radar return reflected from a sphere which has a frontal or projected area of one square meter (diameter of about 44 in). Using the spherical shape aids in field or laboratory measurements since orientation or positioning of the sphere will not affect radar reflection intensity measurements as a flat plate would. If calibrated, other sources (cylinder, flat plate, or corner reflector, etc.) could be used for comparative measurements.

For a flat plate which is frequency dependent, the RCS is equal to $4\pi a^2/\lambda^2$, where a is the area of the plate. A sphere reflects equally in all directions. A flat plate that is perpendicular to the radarline-of-sight reflects directly back at the radar. A tilted plate reflects away from the radar. A corner reflects directly back to the radar somewhat like a flat plate. The sphere is essentially the same in all directions. The flat plate has almost no RCS except when aligned directly toward the radar. The corner reflector has an RCS almost as high as the flat plate but over a wider angle.

Targets such as ships and aircraft often have many effective corners. Corners are sometimes used as calibration targets or as decoys. An aircraft target is very complex. It has a great many reflecting elements and shapes. The RCS of real aircraft must be measured. It varies significantly depending upon the direction of the illuminating radar. Within the normal radar range of 3-18 GHz, the radar return of an aircraft in a given direction will vary by a few dB as frequency and polarisation vary (the RCS may change by a factor of 2-5). It does not vary as much as the flat plate. The RCS is highest at the aircraft beam due to the large physical area observed by the radar and perpendicular aspect. The next highest RCS area is the nose/tail area, largely because of reflections off the engines or propellers. Most self-protection jammers cover a field of view of +/- 60 degrees about the aircraft nose and tail, thus the high RCS on the beam does not have coverage. Beam coverage is frequently not provided due to inadequate power available to cover all aircraft quadrants, and the side of an aircraft is theoretically exposed to a threat 30% of the time over the average of all scenarios.

Typical radar cross sections are as follows: missile 0.5 sq m; tactical Jet 5 to 100 sq m; bomber 10 to 1000 sq m; and ships 3,000 to 1,000,000 sq m.

2. Radar signature reduction techniques

There are four basic techniques for reducing radar cross section: shaping, passive cancellation, active cancellation and radar absorbing material.

Shaping-There are different approaches to shaping an aircraft to reduce its RCS:

- using a faceted configuration, with a flat surfaces to minimize normal reflections back to the illuminating radar. There is a region near any sharp edge where the electrical currents are affected by the presence of the edge. If the surface currents are interrupted by a sharp edge, there is no place for them to go except along the edge. The radiation produce by these currents is known as diffraction. The key to the revolutionary US work on faceting in the 1970s, lay in a paper on diffraction published in the Soviet Union in 1962, and translated by the USAF Systems Command Foreign Technology Division in 1971. This has been accepted as being critical to extending the theory then being developed by Lockheed into “industrial strength” method predicting the RCS of simple two-dimensional shapes built up from a series of flat triangular surfaces. This was the only method compatible with the available computing power of the time;

-using a smoothly blended external geometry to achieve a continuously varying curvature (e.g. Northrop B-2).

Passive cancellation - A basic technique for reducing radar cross section by designing the target surface so that the reflected radar signal from a part of the target cancels the reflected radar signal from another part of the target..

Active cancellation - A technique for reducing the radar cross-section of a target, done by emitting radiation that will cancel the reflected radar energy.

Radar absorbing materials (RAM). A good low RCS aircraft design should exploit shaping to the greatest possible extent. However, there are situations where shaping may be inappropriate or fail to meet one’s objective in full. In these cases the aircraft designer turns to RAM in either the design or as a retroit. As its name implies, RAM is intended to reduce the scattered signal by absorbing some part of the incident radiation. Microwave energy is converted into heat energy with hardly any noticeable temperature rise because the energies involved are extremely small. Various kinds of materials can be made to absorb microwave energy by impregnating them with conducting materials such as carbon and iron.

RAM can be more successfully employed to reduce radar signature of other kinds of target like ships, ground military equipment as well as military facilities.

In the main, there are two currently used kinds of absorbers, called dielectric RAM and magnetic RAM. Addition of carbon in an insulating material changes their electrical properties. Hence carbon-based absorbers are called electrical RAM. The most familiar examples absorbers found in anechoic chambers dielectric RAM is usually too bulky and fragile and unusable where space is limited and severe mechanical vibrations exist. Magnetic RAM uses iron products such as carbonyl iron and iron oxides called ferrites. The iron effectively dissipates radar waves and has been used in paint. It is quite effective against the high-frequency radars used in moderns fighters. Unlike dielectric RAM, magnetic RAM is compact, thin and adequate strength to withstand loads and an abrasive environment. However, it is heavy, expensive and its performance deteriorates as operational temperature approach the Curie point (530-800 K) but this does make it suitable for Mach 2 aircraft. The materials have been embedded in a form of rubber tile, as so-called parasitic RAM, which can then be glued in position and they are suitable for inlets ducts.

If used for aircrafts coatings must be able to stay intact and attached to the plane surfaces during flight. Some parts of an aircraft, such as around the jet pipe, experience high temperatures and use may have to be made of ceramic-based RAM.

3. Radar absorbers with tapered conductivity

In order to study this absorbers the fundamental case where the plane wave is incident at an arbitrary angle on the boundary plane between the conducting media and free space is considered. The conductivity is assumed to vary linearly in the direction perpendicular to the interface.

Maxwell’s equations for the electromagnetic field are given by:

$$\begin{cases} rot\overline{\mathrm{E}} = -j \cdot \omega \cdot \mu_0 \cdot \overline{\mathrm{H}} \\ rot\overline{H} = \left(\sigma(z) + j \cdot \omega \cdot \varepsilon_0\right) \cdot \overline{E} \\ div\overline{D} = 0 \\ div\overline{B} = 0 \\ \overline{B} = \mu \cdot \overline{H} \\ \overline{D} = \varepsilon \cdot \overline{E} \end{cases} , \qquad (1)$$

where: - μ_0-is the permeability of free space; ε_0-is the permittivity of free space; σ-is the conductivity; E, H-are the electric and magnetic field intensities and are assumed to vary with time as exp(jωt).

The wave equations in inhomogeneous conducting media can be derived from (1) as:

$$\frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} + \beta_0{}^2 \left(1 - j\frac{\sigma(z)}{\omega \cdot \varepsilon_0}\right) \cdot E_x = 0 . \qquad (2)$$

The incident, reflected, and transmitted waves are assumed in the regions z<0 and z>l, respectively:

$$\begin{cases} E_x{}^i(y,z) = E_i \cdot e^{-j\beta_0 \cdot (y \cdot \sin\theta_i + z \cdot \cos\theta_i)} \\ E_x{}^r(y,z) = E_r \cdot e^{-j\beta_0 \cdot (y \cdot \sin\theta_r - z \cdot \cos\theta_r)}, z < 0 , \\ E_x{}^t(y,z) = E_t \cdot e^{-j\beta t \cdot (y \cdot \sin\theta_t + z \cdot \cos\theta_t)}, z > l \end{cases} \qquad (3)$$

where: $\beta_0^{\,2} = \omega^2 \cdot \mu_0 \cdot \varepsilon_0$ and

$$\beta_t^{\,2} = \omega^2 \cdot \mu_0 \cdot \varepsilon_0 \cdot \left(1 - j \cdot \frac{\sigma(z)}{\omega \cdot \varepsilon_0}\right);$$

E_i, E_r, E_t -are the amplitudes of the incident, reflected, and transmitted waves;

θ_i, θ_r, θ_t -are the angles of incidence, reflection and transmission.

By assuming that the y variation is given by $e^{-j \cdot \beta_0 \cdot y \cdot \sin\theta}$, equation 2 becomes:

$$\frac{\partial^2 E_x}{\partial z^2} + \beta_0^{\,2}\left(\cos^2\theta_i - j\frac{\sigma(z)}{\omega \cdot \varepsilon_0}\right) \cdot E_x = 0\,, \tag{4}$$

$$\text{where} \quad \sigma(z) = b \cdot z, 0 \le z \le l\,, \tag{5}$$

and b is the gradient of the conductivity.

By solving 3 E_x and $H_{y.}$ are determined Impedance, at z=0, is:

$$Z = \left.\frac{E_x}{H_y}\right|_{z=0}. \tag{6}$$

The reflection coefficient can be determined:

$$\rho = \frac{Z_i - Z_0}{Z_i + Z_0}. \tag{7}$$

Given the computed value of the reflection coefficient the variation of it as a function of the conductivity gradient, the thickness of the RAM, the frequency and the incidence angle has been analysed. Some of the results are pictured on Figs. 1-4.

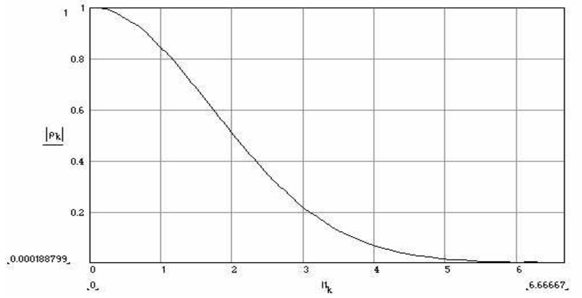

Fig. 1. Variation of reflection coefficient as a function of l/λ, for f=10 GHz, b=1, S/m, θ=0°.

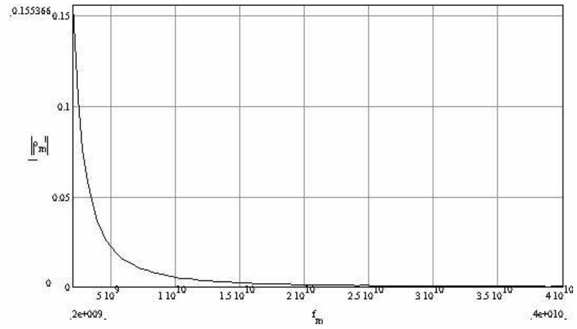

Fig. 2. Variation of reflection coefficient as a function of frequency for l=0.1m, b=5 S/m, θ=0°.

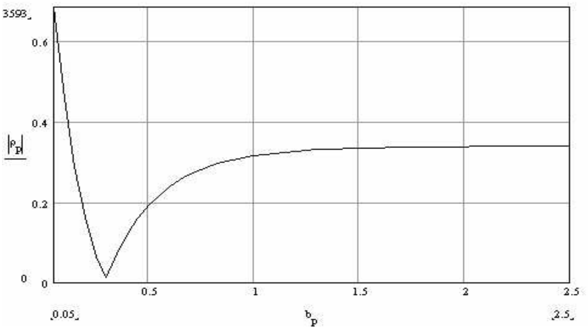

Fig. 3. Variation of reflection coefficient as a function of conductivity gradient (b_p S/m^2), for f = 18 GHz, l=0.1 m, θ=60°.

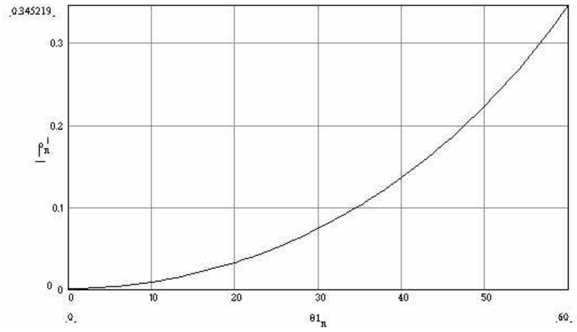

Fig. 4. Variation of reflection coefficient as a function of incident angle for l = 0.1m, b =5 S/m^2, f=18 GHz.

4. Multylaered absorbers

Be a metal -backed multilayer absorber having n homogeneous layers, with the thickness of the ith layer being l_i and its complex permeability and permittivity μ_I, ε_i respectively, i=0,1,2,3,...n. A transverse electromagnetic (TEM) wave propagating along the z-direction with its electric field (E_x) parallel to the x-axis and magnetic field parallel to the y-axis, is incident normally on the absorbers and gives rise to a series of waves travelling in both the positive and negative z-directions within the layers.

The electric and magnetic components satisfy the Helmholtz equation

$$\frac{\partial^2}{\partial z^2} E_x - \gamma^2 \cdot E_x = 0\,; \tag{8}$$

$$\frac{\partial^2}{\partial z^2} H_y - \gamma^2 \cdot H_y = 0\,; \tag{9}$$

$$\text{where - } \gamma = j \cdot \omega \cdot \sqrt{\mu_i \cdot \varepsilon_i}\,. \tag{10}$$

Both μ_I, and ε_I are, in general, complex and frequency-dependent

The time variation $e^{j \cdot \omega \cdot t}$, is suppressed in the following. Electric fields in different regions can be written as:

$$\begin{cases} E_{x0} = E_{d0} \cdot e^{-\gamma_0 \cdot z} + E_{r0} \cdot e^{+\gamma_0 \cdot z}, E_{d0} = 1 \\ E_{xi} = E_{di} \cdot e^{-\gamma_i \cdot z} + E_{ri} \cdot e^{+\gamma_i \cdot z}, i = 1,2,\cdots,n \end{cases}; \quad (11)$$

where E_{di} and E_{ri} are the amplitudes of the incident and reflected waves respectively in the ith layer. E_{d0} is the amplitude of the resultant reflection of the electric field in free space due to an incident wave of unit amplitude. The corresponding magnetic fields can be obtained by using Maxwell's equation:

$$\overline{\nabla} \times \overline{E} = -j \cdot \omega \cdot \mu \cdot \overline{H}, \quad (12)$$

thus:

$$\begin{cases} H_{y0} = \dfrac{\gamma_0}{j \cdot \omega \cdot \mu_0} \cdot \left(E_{d0} \cdot e^{-\gamma_0 \cdot z} + E_{r0} \cdot e^{+\gamma_0 \cdot z}\right), E_{d0} = 1 \\ H_{yi} = \dfrac{\gamma_i}{j \cdot \omega \cdot \mu_i} \cdot \left(E_{di} \cdot e^{-\gamma_i \cdot z} + E_{ri} \cdot e^{+\gamma_i \cdot z}\right), i = 1,2,\cdots,n \end{cases} \quad (13)$$

The coefficients E_{di} and E_{ri}, i=0, 1, 2,…,n, can be obtained by involving the boundary conditions at the interfaces between adjacent layers and at the conducting surface at $z=L_n$. Using these conditions :

$$E_{r0} = \frac{1 - D_1 - \nu_1 \cdot (1 + D_1)}{1 - D_1 + \nu_1 \cdot (1 + D_1)}, \quad (14)$$

where:

$$\nu_i = \sqrt{\frac{\dfrac{\varepsilon_{ri}}{\mu_{ri}}}{\dfrac{\varepsilon_{r(i-1)}}{\mu_{r(i-1)}}}}, \text{ i=0, 1, 2,…,n.} \quad (15)$$

D_1 can be obtained through the following equations:

$$L = \sum_{m=1}^{i} L_m, \text{ I=1,2,...,n} \quad (16)$$

$$D_n = e^{-2 \cdot \gamma_n \cdot L_n}. \quad (17)$$

$$\frac{e^{-2 \cdot \gamma_{i-1} \cdot L_{i-1}} - D_{i-1}}{e^{-2 \cdot \gamma_{i-1} \cdot L_{i-1}} + D_{i-1}} = \frac{e^{-2 \cdot \gamma_i \cdot L_{i-1}} - D_i}{\nu_i \cdot \left(e^{-2 \cdot \gamma_i \cdot L_{i-1}} + D_i\right)}. \quad (18)$$

$$C_i = \frac{e^{-2 \cdot \gamma_i \cdot L_{i-1}} - D_i}{\nu_i \cdot \left(e^{-2 \cdot \gamma_i \cdot L_{i-1}} + D_i\right)} \quad (19)$$

$$D_{i-1} = \frac{1 - C_i}{1 + C_i} \cdot e^{-2 \cdot \gamma_{i-1} \cdot L_{i-1}}, \quad (20)$$

D_1 is thus obtained by following the successively computing D_n and C_n, then D_{n-1} and P_{n-1} and so on in a descending order until D_1 is reached. The coefficient E_{r0} is in general a complex function of frequency.

The properties of the materials in different absorber layers and their thickness are to be chosen to create maximum absorption of the incident power over a desired bandwidth and under the constraint that the total thickness L of the n-layers slab should not exceed a state limit.

4.1 Computed results

Based on some preliminary calculation the needed parameters of materials are established and then the materials have been manufactured and characterised. There are 24 materials, 16 lossy dielectrics carbon impregnated numbered from 500 to 516 and 8 lossy magnetic materials numbered from 601 to 608. The complex permittivity and permeability have been recorded into a database, from where they are read by the C++ optimisation program. The program computes following some optimisation strategy all the solutions that provide a reflection coefficient less than a certain imposed value. All the solutions together with their correspondent reflection coefficient are recorded into a file solution from which they might be displayed through a graphical interface, the order of the layers, the type of the material as well as the thickness are written onto pictures.

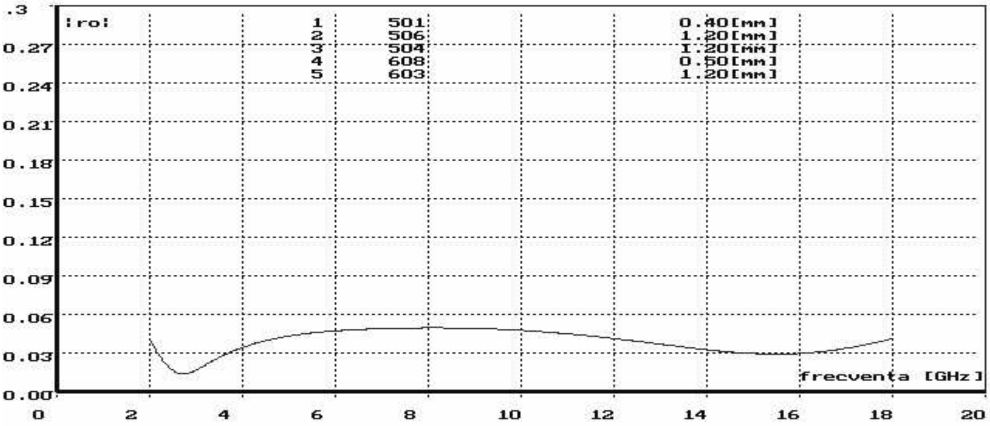

Fig. 9. Variation of reflection coefficient for a structure with five layers achieved from lossy dielectric and magnetic materials.

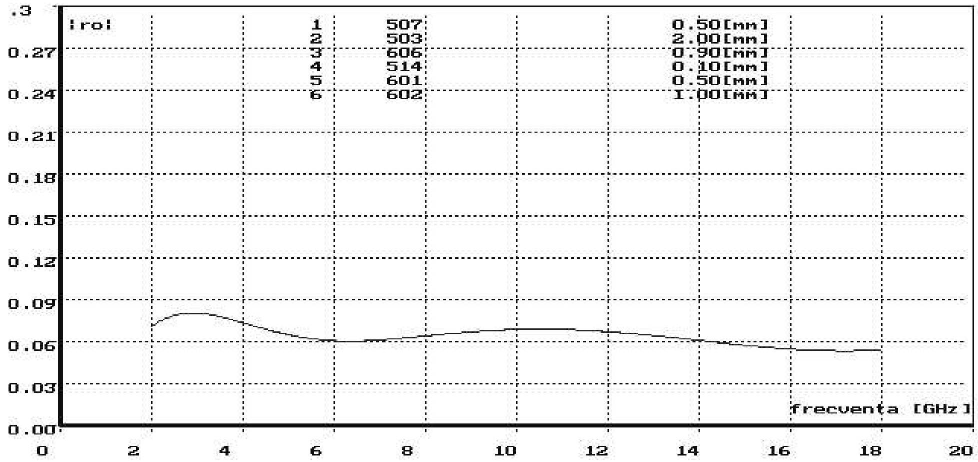

Fig. 10. Variation of reflection coefficient for a structure with six layers achieved from lossy dielectric and magnetic materials.

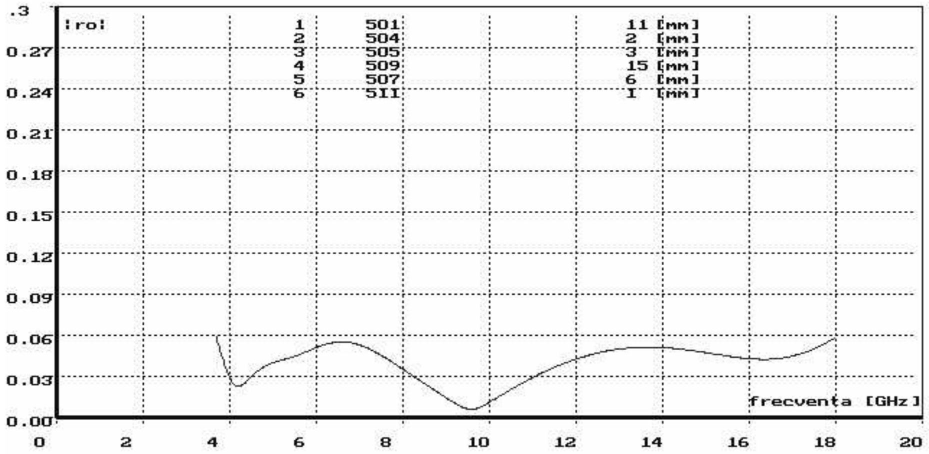

Fig. 11. Variation of reflection coefficient for a structure with five layers achieved from lossy dielectric materials.

The properties of the materials in different absorber layers and their thickness are to be chosen to create maximum absorption of the incident power over a desired bandwidth and under the constraint that the total thickness L of the n-layers slab should not exceed a state limit.

5. Conclusions

1. The camouflage of aerial, marine and ground targets are of great interest today when the radar technology has reached a very high level. Among other types of target camouflage means the use of RAM is more and more feasibly at least for ground targets.

2. The paper analyses the performances that can be obtained with tapered conductivity RAM and multilayered lossy dielectric and magnetic RAM when they cover a metallic surface.

3. A RAM must assure an attenuation of electromagnetic waves and a good match at the air/material interface and these involve that the material must satisfy two contradictory conditions.

4. The object is to match the impedance of the air at the front surface, and slowly taper this impedance to a very low value, approaching a short circuit, at the back surface. By this means reflections of incident energy are minimised while the increasing loss gradually attenuate the energy through conversion to heat.

5. Most military applications require thin absorbent coating.

6. A thin absorber can be theoretically designed to give any reflectivity but it is very difficult to manufacture.

7. Multilayer RAMs have the best performances but they are complicated to manufacture.

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