PROBLEM OF NON-REFLECTING MATERIALS AT MICROWAVES

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This article reviews the different devices used for evading the detection of important ground installations and aeroplanes by radar. A classification of the objects is given and the different absorbers used for evading their detection are described. The theoretical treatment of the problem has been presented and the present state of the subject is discussed. It is expected that a mixture of some suitable substance can be used as absorbing layers.

The enemy radar can detect the presence of the ground installations, the hangars, aerodromes, ships, etc., and thus uncover no secrecy. The bombers are first detected by the enemy radar and then intercepted by fighters before they are able to reach the target. The anti-radar devices are used for evading the detection of military objects and bombers by the enemy radar.

The anti-radar devices are mainly of two types : (1) jamming type and (2) absorbing type. The jamming type[1] had many difficulties and introduced more complications because of its active nature. The absorbing type works on the principle of reducing the reflections from the object to the receiver, so that there is no indication on the radar receiver. This can be accomplished by reducing the radar cross-section of the objects to be detected. The absorption of microwaves by natural and synthetic material layers has been studied by Germans[2], who used them during the war for radar camouflage. They were used principally to cover the breathing tubes (from the submerged submarines) that extended above the surface of the ocean. The results have been published later only in parts, but the German contribution to this problem is not sufficiently known till to-day[3]. Because of military interest further progress is not correctly known.

The problem might be better understood if the types of objects to be detected by radar are known. A classification of the objects is given below :

Mobile objects

(*i*) *Aircrafts*—Whenever a non-reflecting microwave absorber is used on aircraft bodies it should be seen that its use does not affect the speed or manoeuvrability of the aircraft. This condition rules out all the other methods except that of applying some material in the form of a paint. The aircraft needs to avoid detection by radar of different frequencies, hence the absorbent material used should be effective over a wide band of frequencies. The other alternative is to make the aircraft bodies non-metallic if possible.

(*ii*) *Submarines and surfacecrafts*—Since these objects also may have to avoid detection by radar of different frequencies, the material used should be effective over a wide band of frequencies. In these objects one can afford to use materials in the form of thick layers of paint or thick sheets.

Static objects

(*i*) *Aerodromes, armament and ammunition factories and depots etc.*—These static installations have to be protected against detection by radar carried on enemy reconnaissance planes and so the device used should be a wide band one. These large installations will have also to use camouflage to avoid visual detection ; so the anti-radar materials can be in the form of thick sheets of foam or loosely packed shavings etc. It is neither possible nor necessary to use costly materials in the form of paints on such objects.

(*ii*) *Civilian objects*—Radar is used by civil aviation as an aid to navigation. In many such cases, the objects like buildings surrounding the installation disturb the antenna radiation patterns and sometimes cause confusion and errors in operation. If such objects are covered by non-reflecting materials which are good only for the operating frequency of the particular radar, many difficulties may be removed.

This paper reviews the present state of the problem of non-reflecting materials.

THEORY

If the dielectric medium gives no surface reflection and is also highly attenuating, a non-reflecting absorber at microwave frequencies results. If an electromagnetic wave is incident from a medium with the wave impedance Z_0 upon a boundary surface characterised by the input impedance Z, the reflection coefficient $\bar{r}$ is given by

$$\bar{r} = \left(\frac{Z}{Z_0} - 1\right) \Big/ \left(\frac{Z}{Z_0} + 1\right) \qquad (1)$$

In free space the wave impedance is real and for a plane electromagnetic wave

$$Z_0 = \left(\frac{\mu_0}{\epsilon_0}\right)^{\frac{1}{2}} = 377\ \Omega \big/ \square \qquad (2)$$

in all planes of constant phases, μ_0 and ϵ_0 being the permeability and permittivity of free space.

In general, the characteristic wave impedance of a material is related to its permeability, permittivity, the magnetic and electric loss tangents (μ, ϵ, $\tan \delta\mu$ and $\tan \delta_\epsilon$)

$$Z = \left(\frac{\mu_0}{\epsilon_0}\right)^{\frac{1}{2}} \left[\frac{\mu\,(1 - \tan \delta\mu)}{\epsilon\,(1 - \tan \delta_\varepsilon)}\right]^{\frac{1}{2}} \qquad (3)$$

Therefore zero reflection[4] can be obtained in a wide frequency band, when the input impedance Z of the absorber system is real and independent of frequency i.e. when $Z = Z_0$. This is possible if

$$\mu = \epsilon \text{ and } \tan \delta\mu = \tan \delta_\varepsilon \qquad (4)$$

Such a dielectric layer will normally be backed by a perfect reflector metal sheet and therefore to meet our requirement the dielectric layer should have a high attenuation constant.

From the transmission line theory it is known that the propagation constant is given by the expression

$$\gamma = \left\{ j\omega\mu\,(\sigma + j\omega\epsilon) \right\}^{\frac{1}{2}} \qquad (5)$$

If at microwave frequencies $\omega\epsilon$ is large compared with σ, the expression can be simplified to

$$\gamma = j\omega\,(\epsilon\mu)^{\frac{1}{2}} \left[1 + \frac{\sigma}{j\omega\epsilon}\right]^{\frac{1}{2}} \qquad (6)$$

or

$$\alpha + j\beta = \frac{\sigma}{2}\left(\frac{\mu}{\epsilon}\right)^{\frac{1}{2}} + j\omega\,(\epsilon\mu)^{\frac{1}{2}} \qquad (7)$$

i.e. $$\alpha = \frac{\sigma}{2}\left(\frac{\mu}{\epsilon}\right)^{\frac{1}{2}} \text{ nepers per metre} \tag{8}$$

It is therefore possible to obtain a non-reflecting layer at microwaves if a material having a high conductivity σ and having $\mu = \epsilon$, $\tan \delta_\mu = \tan \delta_\epsilon$ is used. The problem, however, is not so simple. Some earlier theoretical work on the subject is described below for ready reference.

Condition for zero reflection at desired frequency

Dallenbach and Kleinsteuber[5] have obtained the condition to give zero reflection at a desired frequency, when the absorber consists of a layer of thickness 'd' on a metal sheet, the dielectric constant ϵ and loss tangent $\tan \delta_\epsilon$. The voltage reflection coefficient is given by

$$\bar{r} = \frac{[\tanh 2\pi j\ (pd/\lambda)] - p}{[\tanh 2\pi j\ (pd/\lambda)] + p} \tag{9}$$

where $$p = [\epsilon\,(1 - j \tan \delta_\varepsilon)]^{\frac{1}{2}}$$

From the condition of zero reflection (i.e. $\bar{r} = 0$).

$$p = \frac{[\exp 2\pi j\ (pd/\lambda)] - \exp[-2\pi j\ (pd/\lambda)]}{[\exp 2\pi j\ (pd/\lambda)] + \exp[-2\pi j\ (pd/\lambda)]}, \tag{10}$$

it follows as a first approximation that if $2\pi d/\lambda < 1$, the layer thickness must be a quarter of wavelength in the material, i.e.,

$$d = \lambda/4n$$

where the refractive index n is given by

$$n = [\tfrac{1}{2}\,\epsilon\{1 + (1 + \tan^2 \delta_\varepsilon)^{\frac{1}{2}}\}]^{\frac{1}{2}} \tag{11}$$

and the surface resistivity has the value

$$\frac{1}{\sigma . d} = \frac{Z_0}{2} = 188{\cdot}5\Omega \tag{12}$$

where σ is the conductivity of the layer material in mhos/cm. In this case zero reflection arises from the interference of the two waves, which are reflected at the surface of the absorber and at the metal base respectively.

Dependence of reflection coefficient on incident angle

Meyer *et. al.*[6] have described some magnetic absorbers. They have shown that the dependence of the reflection coefficient on the angle of incidence is different for the two polarisations. Under certain conditions they found that the magnitude of reflection coefficient for two polarisations of the electric vector are $\bar{E}^i$ parallel to the plane of incidence

$$\bar{r} = \frac{Z - Z_0 \cos \phi}{Z + Z_0 \cos \phi} \tag{13}$$

and $\bar{E}^i$ perpendicular to the plane of incidence

$$\bar{r} = \frac{Z \cos \phi - Z_0}{Z \cos \phi + Z_0} \tag{14}$$

where ϕ is the angle of incidence and Z_0 is the free space impedance. According to this equation, in the case of vertical polarisation the reflection coefficient decreases with increasing angle of incidence; has a minimum for $Z \cos \phi \approx Z_o$ and increases afterwards. In the case of parallel polarisation the reflection coefficient increases monotonic with the angle of incidence.

Absorbing material in layers

The use of absorbing materials in layers has been suggested by Stubbs and Peyssou[7] and by Meinke[3]. Hosek[8] has considered a system consisting of three layers of different permittivities, loss tangents and thicknesses. The first two layers form a matching medium for the impedance of the free space, while the third layer acts as the absorbing medium for the incident microwave energy. The third layer is terminated with an ideally conducting metal wall. Suski[9,10,11] has considered the problem of absorptive dielectric and the calculation of parameters of non-reflecting layers in detail.

Giger and Tank[12] have shown that in the case of normal incidence the absolute value of the reflection coefficient is

$$r = \left[\frac{\left| \cos \frac{\delta_\mu - \delta_\varepsilon}{2} - \left(\frac{\mu'_r \cos \delta_\varepsilon}{\epsilon'_r \cos \delta_\mu} \right)^{\frac{1}{2}} \right|^2 + \sin^2 \frac{\delta_\mu - \delta_\epsilon}{2}}{\left| \cos \frac{\delta_\mu - \delta_\epsilon}{2} + \left(\frac{\mu'_r \cos \delta_\epsilon}{\epsilon'_r \cos \delta_\mu} \right)^{\frac{1}{2}} \right|^2 + \sin^2 \frac{\delta_\mu - \delta_\varepsilon}{2}} \right]^{\frac{1}{2}} \qquad (15)$$

and the absorption factor in the second medium is

$$\alpha = \frac{(2)^{\frac{1}{2}} \; \pi \, (\epsilon'_r \, \mu'_r)^{\frac{1}{2}}}{\lambda_o} \left[(1 + \tan^2 \delta_\mu) \; (1 + \tan^2 \delta_\epsilon) - 1 + \tan \delta_\mu \tan \delta_\epsilon \right]^{\frac{1}{2}} \qquad (16)$$

where, λ_0 — wavelength in air,

ϵ, μ — permittivity and permeability of the material,

ϵ_r, μ_r — relative permittivity and permeability,

$\epsilon = \epsilon_0 \epsilon_r = \epsilon' - j \epsilon'' = \epsilon' (1 - j \tan \delta_\varepsilon)$

$\mu = \mu_0 \mu_r = \mu' - j \mu'' = \mu' (1 - j \tan \delta_\mu)$

Even in this simple case where it has been treated only at approximate vertical incidence of the waves and where a rear reflecting wall has not been considered, the formulae become very complicated.

At oblique incidence it is necessary to separate two types of polarisations viz. the vertical and horizontal. The attenuation constant in the two cases is given by

$$\alpha_1 = \frac{2 \, |\mu|}{\pi} \; \frac{\cos \phi}{377} \quad \text{for vertical polarisation} \qquad (17)$$

$$\alpha_{11} = \frac{2 \, |\mu|}{377 \, \pi \cos \phi} \quad \text{for horizontal polarisation} \qquad (18)$$

vector $\bar{E}$ being parallel to the face of entrance.

When the dielectric and magnetic losses are equal, the optimum attenuation constant for an angle ϕ is

$$\alpha_{IC} = \frac{2\mu'}{\pi} \cos \phi \quad \text{for vertical polarisation} \qquad (19)$$

$$\alpha_{IIC} = \frac{2\mu'}{\pi \cos \phi} \quad \text{for horizontal polarisation} \qquad (20)$$

The coefficient of reflection for a given angle of incidence is independent of the polarisation of waves and is of the form

$$r = \left| \frac{1 - \cos \phi}{1 + \cos \phi} \right| \tag{21}$$

Voltage and power reflection coefficient

The simple formulae for the voltage reflection coefficient and the power reflection coefficient in terms of ϵ and $\tan \delta_\epsilon$ have been worked out for normal incidence by Mungall and Hart[13].

Voltage reflection coefficient

$$\bar{r} = \frac{1 - (\epsilon)^{\frac{1}{2}}}{1 + (\epsilon)^{\frac{1}{2}}} \tag{22}$$

and the power reflection coefficient is

$$R_0 = | \bar{r} |^2 = \frac{(1 - \epsilon)^2 + 4\epsilon \sin^2 \delta_\epsilon / 2}{[1 + 2(\epsilon)^{\frac{1}{2}} \cos \delta_\epsilon / 2 + \epsilon]^2} \tag{23}$$

where $\epsilon^2 = \epsilon'^2 + \epsilon''^2$.

However the exact equations for the reflection coefficients in the two standard directions have been given by Wait *et al*[14]. They are

$$\bar{r}_{\parallel} = \frac{U - X}{U + X} \tag{24}$$

$$\bar{r}_1 = \frac{V - X}{V + X} \tag{25}$$

where

$$U = \frac{\epsilon' (1 - j \tan \delta_\epsilon) \cos \phi}{[\epsilon' (1 - j \tan \delta_\epsilon) - \sin^2 \phi]^{\frac{1}{2}}}$$

$$V = \frac{[\epsilon' (1 - j \tan \delta_\epsilon) - \sin^2 \phi]^{\frac{1}{2}}}{\cos \phi}$$

$$X = \tanh \left[j\alpha \epsilon'^{-\frac{1}{2}} \{ \epsilon' (1 - j \tan \delta_\epsilon) - \sin^2 \phi \}^{\frac{1}{2}} \right]$$

$$\alpha = 2\pi h \frac{(\epsilon')^{\frac{1}{2}}}{\lambda}$$

and ϕ is the angle of incidence.

$\bar{r}_{\parallel}$ and $\bar{r}_1$ (their real and imaginary parts) have been calculated for different range of parameters ϵ', $\tan \delta_\epsilon$ and ϕ. For example one set of these parameters is

$\epsilon' = 2, 3, 5, 8, 15, 25, 40$
$\tan \delta_\epsilon = 0{\cdot}03, 0{\cdot}1, 0{\cdot}3, 1{\cdot}0$
$\alpha = 0$ to $3{\cdot}0$ in steps of $0{\cdot}2$
$\phi = 0°, 45°$.

The computation has been done in the University of Toronto by means of a computer. The results have not been published but they can be seen in the report 'Microwave Reflection Coefficients[15]. As seen by these theoretical curves it is obvious that the reflection coefficients $\bar{r}_{\parallel}$ and $\bar{r}_1$ do not become zero.

The formulae given above have been further simplified by the same author for the case where the loss tangents are small compared to 1 i.e. less than 0·03.

Wait[16, 17] has derived a solution for reflection from a plane boundary between a homogeneous medium and one in which the permittivity varies exponentially with distance from the boundary.

A treatment of oblique incidence reflection from the plane interface of a dissipative medium is given by Wait & Froese[18].

Unbehauen & Hoffman[19] have calculated the reflection coefficient as a function of λ for an electromagnetic wave incident perpendicularly on a thin absorption layer. They have given numerical and graphical methods for the evaluation of layer parameters which make the reflection coefficients as small as possible over a wide range of λ.

Single layer microwave absorbing material

The theory of the design of a single layer microwave absorbing material has been given by Waidelich[20] who considers the structure consisting of a homogeneous lossy dielectric material backed by a good conductor. A similar treatment was given by Dallenbach & Kleinsteuber[5], who assumed that the electric dissipation factor was greater than zero while the magnetic dissipation factor $\tan \delta\mu$ was zero.

Waidelich has considered the case where either or both the loss tangents are greater than zero.

The intrinsic impedance of the dielectric is

$$\left(\frac{\mu}{\epsilon}\right)^{\frac{1}{2}} = \left(\frac{\mu_0\,\mu'}{\epsilon_0\,\epsilon'} \cdot \frac{(1 - j\tan\delta\mu)}{(1 - j\tan\delta\epsilon)}\right)^{\frac{1}{2}}$$

$$= \left(\frac{\mu_0}{\epsilon_0}\right)^{\frac{1}{2}} \cdot \eta\,\underline{\lfloor\theta} \qquad (26)$$

The propagation constant for the entire thickness of l the dielectric material is

$$\gamma = \alpha + j\beta \qquad (27)$$

The loss tangents $\tan\delta\mu$ and $\tan\delta\epsilon$ can be written in terms of α, β, and θ as

$$\tan\delta\mu = \frac{1 - \beta/\alpha \tan\theta}{\beta/\alpha + \tan\theta} \qquad (28)$$

$$\tan\delta\epsilon = \frac{1 + \beta/\alpha \tan\theta}{\beta/\alpha - \tan\theta} \qquad (29)$$

The bandwidth B is obtained by assuming that η and θ of equation (26) are independent of frequency and that α and β of equation (27) are directly proportional to the frequency. If R be the power reflection coefficient, the bandwidth is

$$B = \frac{2R^{\frac{1}{2}}\cos(\delta\epsilon - \theta)\sinh 2\alpha}{\beta\cos\theta} \qquad (30)$$

For $\theta = 0$ and large values of α, the bandwidth is given by

$$\frac{B}{R^{\frac{1}{2}}} \approx \frac{e^{2\alpha}}{\alpha} \qquad (31)$$

This shows that the bandwidth can be made very wide provided that a material can be made with electric and magnetic dissipation factors large and approximately equal. Such a material would very likely have a large relative permittivity ϵ' and a large relative permeability μ' and would have a small thickness.

This is about the design requirements of a microwave absorber consisting of a dielectric layer backed by a good conductor. The author Waidelich[21] extended his work by investigating regions of finite but unequal electric and magnetic dissipation factors.

When the frequency is very high, α and β are large. Then the power reflection coefficient R is given by

$$R^{\frac{1}{2}} = \left| \frac{(\mu'/\epsilon')^{\frac{1}{2}} - 1}{(\mu'/\epsilon')^{\frac{1}{2}} + 1} \right| \qquad (32)$$

If μ'/ϵ' is chosen very close to unity, $R^{\frac{1}{2}}$ will approach zero for a sufficiently high frequency and will remain zero for all frequencies higher than this limit.

The effect of increasing $\delta\epsilon$ and $\delta\mu$ is to lower the frequency at which an impedance matching is obtained. While reflections may often be eliminated at some frequency when $\delta\epsilon \neq \delta\mu$, the results indicate that it is desirable to make $\delta\mu$ and $\delta\epsilon$ equal and large in order to reduce reflections over a large frequency range.

PAST WORK AND PRESENT KNOWHOW

It has been mentioned previously that most of the work on the subject remains unpublished. From the material available it has been found that three types of absorbers have been used: (*a*) Resonance absorbers; (*b*) Large bandwidth absorbers; (*c*) Absorbers made of the different combinations of circuits.

The theories of these have already been given. A brief description of some important ones is given below:

Resonance absorbers

(*i*) One simple absorber consisted of a resistance card[4], whose surface resistivity was equal to 377 ohms and which was placed a quarter of wavelength from a reflecting metal plate. A voltage reflection coefficient better than 0·05 was obtained over a bandwidth of ±5 %.

(*ii*) A more practicable absorber consists of a layer of thickness d, on a metal plate (Dallenbach[5]). Here the zero reflection is obtained by interference, the amplitudes being adjusted by choice of tan δ_ϵ and the phase by ϵ and d.

Improved bandwidth can be obtained by multiple layers or by framing the material into a series of pyramids or cones. Suitable materials have been described by Meyer *et.al.* [22,23] with typical voltage reflection coefficients less than 0·02 over a frequency range of 2–50 Gc/sec.

(*iii*) A magnetically operated absorber may be arranged immediately before a metal sheet, and loss of bandwidth due to path difference is then avoided. For example, magnetic dipoles in the form of loops can be arranged to couple to absorbing resonators. In the resonance absorber described by Meyer, Severin & Umlauft[6], coaxial lines loaded with iron powder were used at a frequency of 10 Gc/sec. Minimum reflection was obtained when the number of resonators per unit area and their resistance were adjusted to optimum values. Voltage reflection coefficients were typically less than 0·1 for angles of incidence upto 30° and over a frequency range of ±1%.

This bandwidth may be improved by combining two specially dimensioned resonant circuits. A short circuited line $\lambda/4$ long, represents a parallel resonant circuit, so that to make a metal plate non-reflecting, suitable elements of series character have to be mounted at a distance of $\lambda/4$ in front of the metal base plate. Such elements include electric dipoles having the same resonant frequency. The total depth of absorbing medium may be reduced further by embedding the resonant circuits in a dielectric material. The performance of a typical dipole absorber has been given by Severin. With an upper limit of $0 \cdot 1$ for the voltage reflection coefficient, the effective bandwidth extended from $\lambda = 2 \cdot 6$ cm to $4 \cdot 1$ cm with an absorber system having a total depth of 5 mm.

In the magnetically operating absorber, the prototype of an element reacting to the magnetic field is the magnetic dipole in the form of a loop antenna. Therefore a regular distribution of extremely small loop antennas on the metal sheet itself has been considered, which gives an absorber device of small thickness.

Because of the considerable difficulties in manufacture in the range of centimeter waves, the field of practical application of this type of resonance absorber will be in the range of decimeter and meter waves.

Large bandwidth absorbers

The other non-reflecting microwave absorber is characterised by a relatively large effective bandwidth, and as a consequence of this property by a large layer thickness. In contrast to the resonance systems most of the energy of the incident wave will be absorbed before reaching the reflecting surface and multiple reflections in the layer itself are avoided. The characteristic impedance of the absorber should be equal to that of free space. An efficient absorber should have large and equal values of the dielectric and magnetic loss angles δ_ϵ and δ_μ as well as ϵ and μ; moreover these material constants should be independent of frequency. The realisation of an absorber utilising these principles has not been possible uptill now.

We describe three steps taken in this direction.

(*i*) In actual construction of a wide band absorber for microwaves, reflection is avoided by tapering a homogeneous absorption material, or by arranging different layers parallel to the base plate in such a manner that the loss tangent increases towards the base plate.

For practical applications, spacings and corresponding surface resistivities for maximum attenuation are chosen in such a way that the absorber thickness necessary for getting the required total absorption is not too large.

(*ii*) Improved performance was obtained by using two conducting layers with two equal air gaps in front of a metal sheet. The voltage reflection coefficient curve contained two zeros and its value was kept below $0 \cdot 1$ within the range of one octave. This construction was extended so that the absorber consisted of alternate layers of a loosless dielectric and thin sheets of poorly conducting material. The surface resistivity decreased towards the metal base by a constant factor from one sheet to the next and the voltage reflection coefficient calculated by transmission line theory[24] was below $0 \cdot 1$ in a range of nearly three octaves. The manufacturing difficulties arising from the exact observance of specific values of surface resistivity are avoided by using a uniform absorbing material in such a geometric shape that the absorption coefficient increases towards the base plate. In one example, the absorber was built up with resistance cards arranged parallel to the base plate[4, 25]. To avoid the polarisation dependence, two such systems were arranged perpendicular to each other. Spacings greater than half a wavelength were used and the medium corresponded to a highly attenuated waveguide.

The conducting sheets were tapered to match the absorbing parallel plate medium to the characteristic impedance of free space, and the teeth were given different lengths to avoid reflections at sloping angles of incidence owing to the periodic nature of the absorber, The medium was made weather-proof by embedding the sheets in foamed dielectric.

(*iii*) Instead of indented foils, other forms of tapering can be used such as wedges, pyramids or cones[26—28].

Absorbers made of different combinations of circuits

The third type of absorber is one in which the effective bandwidth is increased by combining different circuits.

In low frequency techniques, it is possible to construct a two terminal network with an input impedance, which is real and independent of frequency by combining two specially dimensioned resonant circuits[29]. By regular distribution of such elements on a surface, an absorber system with defined properties, determined by the single absorber elements and their distribution can be obtained for microwaves also.

It is known that a short circuited quarter wave line represents a parallel resonant circuit. In order to make a metal plate non-reflecting, suitable elements of series circuit character have to be mounted at a distance of $\lambda/4$ in front of the metal plate. Among such elements are electric dipoles having the same resonant frequency as the parallel resonant circuits. The necessary damping of the dipoles can be obtained by manufacturing them of resistive material. Very small reflection coefficients independent of the polarisations can be obtained by adding a second grating, the elements of which are turned by 90° with respect to those of the first one. The main applications of these absorbers will be radar camouflage when the transmission frequencies are known.

These absorbers have been described by Severin[4], Harvey[30] and Schmitt[31] in the review articles on microwave absorbers. Besides these, multicircuit resonant absorbers, multilayer absorbers and dipole absorbers have been described by Schmitt & Futtermenger[32], Schmitt[33], and Kurtze & Neumann[34] respectively.

The absorbers described in (*a*) and (*b*) have the disadvantage that the whole system becomes very bulky and has a large thickness, which does not allow their use on moving objects. The practical use of the resonance absorbers is, on the other hand, reduced by their small bandwidth. Type (*b*) have been used in radar camouflaging of disturbing superstructures in air fields and decoupling the transmitting and receiving antennas of a microwave relay station. They have also been used for the construction of a free space room for electromagnetic waves. Such rooms are called Anechoic Chambers and are used for indoor investigations of wave propagation phenomenon, as the radiation patterns of directional antennas, the backscattering from obstacles etc.

A list of the materials which have either been proposed or have been used as non-reflecting materials is given below :

LIST OF MATERIALS

1. Non-reflecting Materials	Wavelength (cm.)	Reflection Coeff. (per cent)
(*i*) Glasswool upon metal covered with corrugated cardboard[35]	3·2	15 to 20
(*ii*) Hair covered with corrugated cardboard[35]	0·9	45 to 50
(*iii*) Wood shavings[35]	3·2	10 to 15
(*iv*) Metal shavings loosely heaped[35]	3·2	4 to 6
(*v*) Metal shavings mixed with hair between corrugated cardboard[35]	3·2	5 to 8

2. Ferromagnetic materials[12]

Constants	Fe-Pulverstoff1			Fe-Pulverstoff2			Fe-pulverstoff 3	
$\lambda_0$cm	30	10	3	30	10	3	10	3
ε'_r	25	25	25	15	12	9	12·2	12·7
$\tan\delta\varepsilon$	0·02	0·04	0·1	0·009	0·01	0·013	0·059	0·072
μ'_r	6	4	1·3	3	2·2	1·5	2·12	1·37
$\tan\delta\mu$	0·25	0·5	1·5	0·1	0·15	0·4	0·34	0·68
r	0·34	0·42	0·57	0·38	0·40	0·42	0·40	0·49

3. Resin with a fine powder of carbonyl iron[36].

4. Ferrite material (type Ferramic *E*)[37,38].

5. Conductors embedded in a plastic or elastomeric former is used for gasketting and for reducing the reflection coefficient of vehicles.

6. Layers of mixed dielectric and paraffin and magnetic materials such as iron dust in paraffins are used. Its three-layer-absorber system gives 5% at $\lambda = 3$ cm.

7. Absorbers with highly refractive lossy characteristics reduce the back scattered cross-section.

8. Absorber composed of suitably designed multilayers having step-wise increasing lossy characteristics are suitable for the electromagnetic wave absorption.

It seems possible to use ferrites[39,40] as absorbers at microwave frequencies. Ferrites are mostly combinations of Fe_2O_4 and a divalent metal. They show only very small eddy current losses. It is possible to use ferromagnetic materials of high resistivity and their alloys as absorption substances. Their fine powder is usually embedded in an insulating material such as amorphous silicic acid, paraffin and certain expanded materials in order to lower the conductivity and ϵ. A number of ferrite materials are marketed today under different trade names e.g., Ferroxcube, Ferroxplana, Ferramics, etc. Sintered powders of some of these in a suitable binder may be useful.

CONCLUSION

It is clear that the ideal solution to the problem of non-reflecting materials at microwaves for use on aircraft has yet to be found. The material has to satisfy very stringent requirements. It must possess in the microwave region equal and very high value of μ and ϵ and also large and equal tan $\delta\mu$ and tan $\delta\epsilon$. These constants have to be independent of frequency also. A number of other problems have to be faced particularly because the material has to be used on aircraft bodies. The substance has to be used in such a way that the speed and manoeuvrability of the aircraft are not impaired. The next problem is that of the adherence of the dielectric paint to the metal surface (aluminium alloy). Most of the materials which might be suitable absorbers do not adhere well to the metal surface directly. The problem becomes more difficult in view of the high speed of the aircraft and the wide range of temperature and humidity it encounters during its operation. It has been found that the greenish yellow zinc chromate primer sprayed on a sand blasted clean metal surface forms a good base on which the dielectric layer can be deposited. The paint layers have to be protected by the application of a suitable lacquer. During flight, the aircraft very often passes through regions where the body gets electrically charged; the charges do not collect at certain spots due to the high conductivity of the body. This condition should be satisfied even after the absorbing material has been applied, otherwise dangerous charge collection may take place on the body during flight.

It is expected that a mixture of certain compounds can be profitably used as absorbing layers. They may be put on the aircraft surface upto a thickness of one millimeter without getting chipped off during flight for a sufficiently long period.

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