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Review of Radar Absorbing Materials

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(U) Radar is a sensitive detection tool and since its development, methods for reducing microwave reflections have been explored. Radar absorbers can be classified as impedance matching or resonant absorbers. Radar absorbing materials are made from resistive and/or magnetic materials. Circuit analog materials give more design freedom through access to capacitive and inductive loss mechanisms. Dynamic absorbers can tune the absorption frequency through control of resistive and capacitive terms. Many conductive and magnetic materials have been trialed for absorption including carbon, metals and conducting polymers. (U) Le radar est un outil de détection sensible. Depuis sa mise au point, des méthodes visant la réduction de la réflexion des ondes ont été analysées. Les absorbants peuvent être classifiés comme des absorbants d'adaptation d'impédances ou des absorbants résonants. Les éléments qui absorbent les ondes radar sont faits de matériaux résistifs et/ou de matériaux magnétiques. La conception de circuits analogiques permet une plus grande marge de manoeuvre, car elle permet d'utiliser des éléments d'affaiblissement de type capacitif et inductif. Le réglage des éléments résistifs et capacitifs permet l'accord sur la fréquence d'absorption. Des essais d'absorption ont été effectués sur de nombreux matériaux conducteurs et magnétiques, y compris du carbone, des métaux et des polymères conducteurs.

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Abstract

Radar is a sensitive detection tool and since its development, methods for reducing microwave reflections have been explored. Radar absorbers can be classified as impedance matching or resonant absorbers. Radar absorbing materials are made from resistive and/or magnetic materials. Circuit analog materials give more design freedom through access to capacitive and inductive loss mechanisms. Dynamic absorbers can tune the absorption frequency through control of resistive and capacitive terms. Many conductive and magnetic materials have been trialed for absorption including carbon, metals and conducting polymers.

Résumé

Le radar est un outil de détection sensible. Depuis sa mise au point, des méthodes visant la réduction de la réflexion des ondes ont été analysées. Les absorbants peuvent être classifiés comme des absorbants d'adaptation d'impédances ou des absorbants résonants. Les éléments qui absorbent les ondes radar sont faits de matériaux résistifs et/ou de matériaux magnétiques. La conception de circuits analogiques permet une plus grande marge de manœuvre, car elle permet d'utiliser des éléments d'affaiblissement de type capacitif et inductif. Le réglage des éléments résistifs et capacitifs permet l'accord sur la fréquence d'absorption. Des essais d'absorption ont été effectués sur de nombreux matériaux conducteurs et magnétiques, y compris du carbone, des métaux et des polymères conducteurs.

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Executive summary

Introduction

Radar cross section has implications to survivability and mission capability. The materials for reduction of radar cross section rely on magnetic and electric materials, while principles from physical optics are used to design absorber structure. Advanced techniques are used for absorber optimisation.

Results

This paper reviews the subject of radar absorbing materials in order to provide a background on theory, absorber types, properties, optimisation and materials used for their design.

Significance

Many of the absorber structures considered here would be useful for military applications. Dallenbach and Jaumann layers would be appropriate for maritime applications. Genetic algorithm optimisation should be used for Jaumann absorber design. If the military is to move to composite materials for ships or super structures then frequency selective surfaces and circuit analog absorbers should be embedded into the composite. Dynamic absorbers should be studied in order to counter frequency agile radars.

Saville, P.. 2005. Review of Radar Absorbing Materials. DRDC Atlantic TM 2005-003, DRDC Atlantic.

Sommaire

Introduction

La section efficace radar a un impact sur la surviabilité et sur la capacité d'exécution de missions. Des matériaux magnétiques et électriques sont utilisés afin de réduire de la section efficace radar. Les principes d'optique physique sont utilisés pour concevoir des structures absorbantes. De plus, des techniques à la fine pointe de la technologie sont utilisées afin d'optimiser les absorbants.

Résultats

Le présent document porte sur l'analyse des matériaux qui absorbent les ondes radar afin de documenter la théorie, les types d'absorbants, les propriétés, l'optimisation et les matériaux de base utilisés dans la conception d'absorbants.

Portée

Plusieurs des structures absorbantes examinées dans le présent rapport seraient utiles pour des applications militaires. Les couches de Dallenbach et de Jaumann conviendraient à des applications maritimes. L'optimisation d'algorithmes génétiques devrait être utilisée pour la conception d'absorbants de type Jaumann. Si on pense, dans le domaine militaire, à utiliser des matériaux composites pour les navires ou les superstructures, alors on devrait intégrer dans ces matériaux des surfaces sélectives en fréquence et des absorbants de type circuit analogique. En outre, des absorbants dynamiques devraient être étudiés afin de « lutter » contre les radars agiles en fréquence.

Saville, P. 2005. Review of Radar Absorbing Materials (Analyse des matériaux absorbant les ondes radar). RDDC Atlantique TM 2005-003, RDDC Atlantique.

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1. Introduction

Exploitation of the electromagnetic spectrum for detection purposes extends from the ultra violet through visible, infrared, microwave and radio frequencies. The theory of physical optics has aided in the advancement of these detection methods. Conversely detection avoidance through camouflage, or signature reduction, exploits the same theory of physical optics to minimise reflections, emissions and hence detection. It is a combination of optics and materials that lead to signature reduction.

The detectability of a target is measured in terms of the radar cross section (RSC). The RCS is a property of the targets size, shape and the material from which it is fabricated and is a ratio of the incident and reflected power. For targets that are small in comparison to the radiation wavelength Rayleigh scattering occurs. Large objects, compared to the wavelength, result in optical scattering including diffraction and specular scattering. For these large objects geometrical optics with diffraction theory (geometrical theory of diffraction) are used to determine the RCS. When the object size is on the order of the wavelength of the radiation, Mie scattering occurs which is characterized by creeping waves.

There are four methods of reducing the radar cross section; shaping, active loading, passive loading and distributed loading. Shaping is the primary method of reducing the backscattered signal. Although shaping is very important, it redirects the radiation through specular reflection hence increasing the probability of detection from bistatic radars. Active and passive loading aims to reduce the scattering from hotspot regions through the application of patches. Active materials detect the incident radiation and emit signals of equal amplitude and opposite phase to cancel the signal, while passive materials are designed to modify the surface impedance so as to cancel the scattered signal. The fourth method, distributed loading involves covering the surface with a radar absorbing material that has imaginary components of permittivity and/or permeability (ie the electric or magnetic fields of the radiation couple with the material properties and energy is consumed).

In this section the field of microwave (radar) absorbing materials (RAM) is reviewed with consideration of the historical development, physical theory, design optimisation and materials behind these devices.

2. A History of RAM Development

The development of Radar absorbing materials has been reviewed in several papers[1-6] and Books.[7-9] Exploitation of radar absorbing materials started in the 1930's shortly after the advent of radar. Absorber design has incorporated materials with different loss mechanisms and has made use of physical optics to optimise absorption over wide bandwidths. Absorbers therefore come with many different shapes and structures, ranging from thick pyramidal structures, to multilayers and single coatings. Microwave absorbing materials have been used in commercial settings, for anechoic chambers and for reducing the reflected signals from buildings and superstructures around radar installations. Current communication technologies at microwave frequencies are driving the development of absorbers and frequency selective surfaces. This section gives a brief review of the historical development of RAM, and referral to subsequent sections will help illustrate the devices, materials and structures being discussed here. Also due to the secret nature of RAM development some details are sketchy or not published.

Research into electromagnetic wave absorbers started in the 1930's,[2,8] with the first patent appearing in 1936 in the Netherlands.[10] This absorber was a quarter-wave resonant type using carbon black as a lossy resistive material and Titanium dioxide for its high permittivity to reduce the thickness.

During World War II, Germany, concerned with radar camouflage for submarines, developed "Wesch" material, a carbonyl iron powder loaded rubber sheet about 0.3 inches thick and a resonant frequency at 3 GHz. The front surface of this material was waffled to produce a larger bandwidth. They also produced the Jaumann Absorber, a multilayer device of alternating resistive sheets and rigid plastic. This device was about 3 inches thick with resistances decreasing exponentially from the front to the back. This device achieved a reduction in the reflectivity of –20 dB over 2-15 GHz. America, during this period, led by Halpern at MIT Radiation Laboratory developed materials known as "HARP" for Halpern Anti Radiation Paint. The airborne version, known as MX-410, had a thickness of 0.025 inches for X-band resonance. The base dielectric had a high permittivity of 150 due to loading with highly oriented disk shaped aluminium flakes suspended in a rubber matrix and carbon black for loss. This material offered a 15-20 dB reduction in reflectivity. Shipborne absorbers were 0.07 inch thick (X-band) iron particle loaded rubber with a permittivity of 20 and enough permeability to produce resonance broadening.[11,12] At the same time the resonant Salisbury Screen was developed with about 25% bandwidth at resonance.[13] Production of Salisbury screens was aided by the US Rubber Company marketing a resistive cloth called Uskon. Another absorber design that arose at this time was a long pyramidal structure with the inside coated with Salisbury Screen and the apex in the direction of propagation. The multiple reflections from the absorber resulted in high attenuation.[14] The importance of ferrites was known. With the exceptions of the Jaumann device and the inverted pyramid, these devices are typically narrow band.

The postwar period (1945-1950) was characterized by the development of broadband absorbers using sharp pointed geometric shapes that produce a gradual transition into the absorbing material. These materials found application in anechoic chambers.[15-18] Materials investigated for microwave attenuation include carbon loaded plaster of paris, graphite, iron oxide, powdered iron, powdered aluminium and copper, steel wool, water, powdered "Advance" and "Constantin" and metal wires.[19] Binders included various plastics and ceramics, while supports with a lot of air at the interface included foams, fibres and "excelsior". More functional lossy broadband materials were created with a flat surface by using patterned flat layered resistive sheets that reproduced the pyramidal, or conical structures of above.[12]

The 1950's saw the commercial production of RAM called "Spongex", based on carbon coated animal hair, by the Sponge Products Company, (later to become a division of B.F. Goodrich Company). This material, 2 inches thick, resulted in –20 dB attenuation in the reflectivity over 2.4-10 GHz for normal incidence. 4 and 8 inch versions also produced for lower frequencies. This company was later joined by, Emerson and Cuming Inc and McMillan Industrial Corporation, in the manufacture of absorbers. Research into circuit analog devices was started by Severin and Meyer during this decade.[1,2,20,21] The term circuit analog comes from the use of circuit theory to represent the components/processes occurring in the absorber, and hence to model the reflectivity. This technique was adopted from research programs on acoustical absorbers. Severin and Meyer made experimental absorbers based on resistance loaded loops, slots in resistive foil, resistance loaded dipoles, strips of resistive material with various orientations, strips of magnetic material with various orientations, surface shaping and magnetic loading of resonant materials. This started a new field of research into frequency selective surfaces (FSS).[22]

The 60's and 70's saw continuing work on circuit analog materials,[9] and significant absorber thickness reductions were demonstrated using ferrite underlayers.[23] Pyramidal shaped absorbers were being used for anechoic chambers achieving –60 dB at near normal incidence. Control of the fabrication of Jaumann layers was demonstrated by screen printing,[24] and absorbers were being made from foams, netlike structures, knitted structures, or honeycomb and coated with a paint containing particulate or fibrous carbon, evaporated metal or nickel chromium alloy.[25] Interesting, though not practical one patent describes an absorbers that employing a plasma to absorb the microwaves. The plasma was generated by a radioactive substance requiring about 10 Curies/cm^2![26]

The 1980's. The absorber design process is improved by optimization techniques.[27-29] Bandwidth improvement of Jaumann absorbers was evaluated by using graded layers[6,30] and different resistive profiles to achieve maximum bandwidths. Computers and transmission line models were used to calculate reflectivity from material properties, and for frequency selective surfaces which can be represented as equivalent circuits, the transmission line model are applied.[5] Circuit analog materials are designed[31] and the scattering of these materials is analysed based on the Floquet theorem.[32] Materials continue to use carbon black or graphite, carbonyl iron and ferrites, though now artificial dielectrics are being made by adding inclusions such as rods, wires, disc and spheres.[6] Helical inclusions are found to improve absorption and resulted in research into chiral materials.[33] Mixing theory is used to calculate the desired permittivity and permeability of these new materials. Conducting polymers appear as potential radar absorbing materials.

The 1990's and on to today has seen more optimisation techniques for Jaumann structures including genetic algorithm optimisation.[34-40] Circuit analog and frequency selective surfaces continue to big in the literature.[20,31,32,35,40-49] Conducting polymers and composite materials with these are found along with conducting polymer coated fibres and fabrics for creating devices.[50-84] A new class of absorbers that find their roots in conducting polymers is that of dynamic RAM,[85-89] where the resonant frequency of the absorber is tuneable through variation of resistive and capacitive elements in the absorber.

3. Reflectivity Minimisation

The theory behind the interaction of electromagnetic radiation with matter is discussed in detail in section 3. In this section several points for reflectivity minimization are considered.

In an attempt to minimise the reflection from a surface it is useful to consider the physical equations that represent the reflection process. There are three conditions that result in a minimum reflectivity.

The first equation of interest is that describing the reflection coefficient at an interface.

$$r = \frac{\eta_M - \eta_o}{\eta_M + \eta_o} = \frac{Z_M - Z_o}{Z_M + Z_o} \qquad 1$$

where r is the reflection coefficient and η the admittance of the propagating medium (subscript o for incident medium or air and M for the substrate). The admittance in this equation can be replaced with the intrinsic impedance (Z = 1/η). The reflection coefficient falls to zero when $\eta_M = \eta_o$, or in other words the material in the layer is impedance matched to the incident medium. The intrinsic impedance of free space is effectively given by

$$Z_o = \frac{\mathbf{E}}{\mathbf{H}} = \sqrt{\frac{\mu_o}{\varepsilon_o}} \approx 377 ohms \qquad 2$$

where **E** and **H** are the electric and magnetic field vectors and μo and εo are the permeability and permittivity of free space. Thus a material with an impedance of 377 ohms will not reflect microwaves if the incident medium is free space.

Perfect impedance matching can also be realised if the electric permittivity and the magnetic permeability are equal. This gives the second condition that results in a minimum in the reflection coefficient. In this case equation 2.1 is rewritten as

$$r = \frac{\frac{Z_M}{Z_o} - 1}{\frac{Z_M}{Z_o} + 1} \qquad 3$$

The normalized intrinsic impedance is

$$\frac{Z_M}{Z_o} = \sqrt{\frac{\mu_r^*}{\varepsilon_r^*}} \qquad 4$$

where $\varepsilon_r^* = \frac{\varepsilon' - i\varepsilon''}{\varepsilon_o}$ and $\mu_r^* = \frac{\mu' - i\mu''}{\mu_o}$, the prime and double prime superscripts represent the real and imaginary components of the complex numbers, respectively. If the incident medium is free space and the reflectivity is zero, then it follows that $\mu_r^* = \varepsilon_r^*$. The implication is if both the real and imaginary parts of the permittivity and permeability are equal, then the reflectivity coefficient is zero.

The third consideration is the attenuation of the wave as it propagates into the absorbing medium. The power of the wave decays exponentially with distance, x, by the factor $e^{-\alpha x}$. α is the attenuation constant of the material and can be expressed as

$$\alpha = -\sqrt{\varepsilon_o \mu_o}\,\omega\left(a^2 + b^2\right)^{1/4} \sin\left(\frac{1}{2}\tan^{-1}\left(-\frac{a}{b}\right)\right) \qquad 5$$

where $a = (\varepsilon_r^{'}\mu_r^{'} - \varepsilon_r^{''}\mu_r^{''})$ and

$$b = \left(\varepsilon_r^{'}\mu_r^{''} + \varepsilon_r^{''}\mu_r^{'}\right).$$

To get a large amount of attenuation in a small thickness, α must be large, which implies that $\varepsilon_r^{'}, \varepsilon_r^{''}, \mu_r^{'} and \mu_r^{''}$ must be large. It is noted here that this condition must be tempered with the first condition (equation 2.1), where large values of permittivity and permeability would result in a large reflection coefficient.

4. Types of Radar Absorbing Material

It is useful to consider how the theory in section 2.2 have been put into practice by considering the types of absorbers that have been produced.[1,2,5,6] Absorbers can be classified into impedance matching and resonant absorbers, though it will be shown in the following discussion that many absorbers have features of both of these classifications. These features typically are a graded interface to match impedance or a gradual transition in material properties for impedance matching, and tuned or so called quarter wavelength resonant layers.

4.1 Graded Interfaces – Impedance Matching

As seen in equation 2.1, a propagating wave that impinges upon an interface will experience some reflection that is proportional to the magnitude of the impedance step between incident and transmitting media. From this consideration three classes of impedance matching RAM, pyramidal, tapered and matched, have been developed to reduce the impedance step between the incident and absorbing media. For complete attenuation of the incident wave one or more wavelengths of material are required, making them bulky and adding weight.

4.1.1 Pyramidal Absorbers

Pyramidal absorbers[2,17] are typically thick materials with pyramidal or cone structures extending perpendicular to the surface in a regularly spaced pattern. Pyramidal absorbers were developed so that the interface presents a gradual transition in impedance from air to that of the absorber. The height and periodicity of the pyramids tend to be on the order of one wavelength. For shorter structures, or longer wavelengths, the waves are effectively met by a more abrupt change in the impedance. Pyramidal absorbers thus have a minimum operating frequency above which they provide high attenuation over wide frequency and angle ranges. These absorbers provide the best performance. The disadvantage of pyramidal absorbers is their thickness and tendency to be fragile. They are usually used for anechoic chambers. A more robust flat “pyramidal” absorber has been fabricated using multilayers with a pyramidal type structure being described by resistive sheets.[18]

Pyramidal and wedge shaped absorbers have been designed using a Tschebyshev transformer technique[90] and have been investigated with Finite Element Methods.[91]

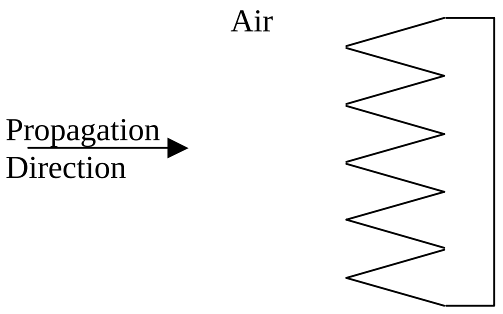

Figure 1. *Pyramidal Absorber*

4.1.2 Tapered Loading Absorbers

This material is typically a slab composed of a low loss material mixed with a lossy material. The lossy component is homogeneously dispersed parallel to the surface, with a gradient perpendicular to the surface and increasing into the material.[12,17] One type of material includes an open celled foam or 3-d plastic net, dipped or sprayed with lossy material from one side, or allowed to drain and dry.[92] It is difficult to reproducibly fabricate a gradient in this manner. A second type is composed of homogeneous layers with increasing loading in the direction of propagation (ie. The gradient is created as a step function) see Figure 2.

The advantage of these materials is that they are thinner than the pyramidal absorbers. The disadvantage is that they have poorer performance and it is best to vary the impedance gradient over one or more wavelengths.

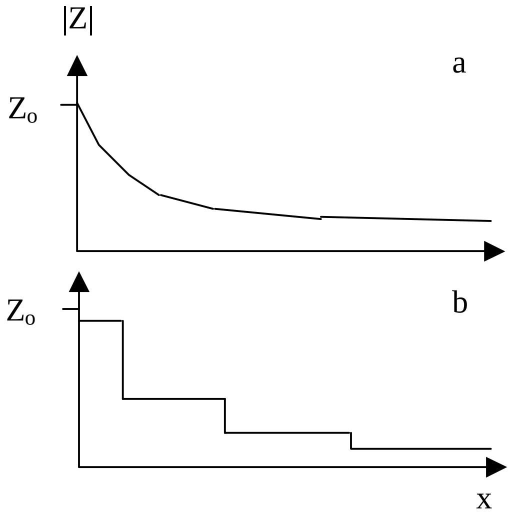

Figure 2. Tapered Loaing Absorber, type a) smooth type b) stepped.

4.1.3 Matching Layer Absorbers

The matching layer absorber attempts to reduce the thickness required for the gradual transition materials. This absorber places a transition absorbing layer between the incident and absorbing media. The transition layer has thickness and impedance values that are between the two impedances to be matched (ie the absorber and incident media). The idea is to have the combined impedance from the first and second layers to equal the impedance of the incident medium, Figure 3. This matching occurs when the thickness of the matching layer is one quarter of a wavelength of the radiation in the layer and

$$Z_2 = \sqrt{Z_1 Z_3} \qquad 6$$

The impedance matching occurs then only at the frequency that equals the optical thickness. This makes the matching layer materials narrow band absorbers. These absorbers are made using an intermediate impedance and quarter wavelength thickness for absorption at microwave frequencies.

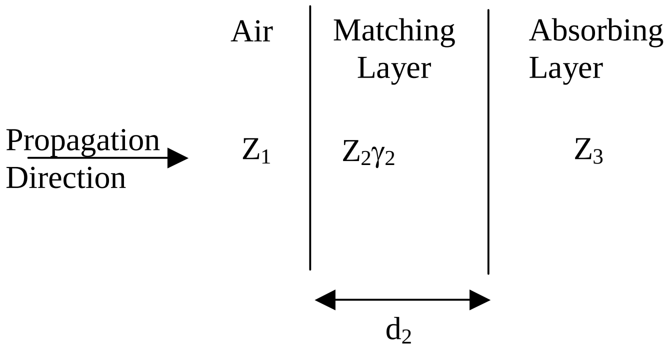

Figure 3. *Matching Layer*

4.2 Resonant Materials

Resonant materials are also called tuned or quarter wavelength absorbers and include Dallenbach layers, Salisbury Screen and Jaumann layers. In this class of materials the impedance is not matched between incident and absorbing media and the material is thin so that not all the power is absorbed. This arrangement results in reflection and transmission at the first interface. The reflected wave undergoes a phase reversal of π. The transmitted wave travels through the absorbing medium and is reflected from a metal backing. This second reflection also results in a phase reversal of π before the wave propagates back to the incident medium. If the optical distance travelled by the transmitted wave is an even multiple of ½ wavelengths then the two reflected waves will be out of phase and destructively interfere. If the magnitude of the two reflected waves is equal then the total reflected intensity is zero.

4.2.1 Dallenbach (Tuned) Layer Absorber

A Dallenbach layer,[93] is a homogeneous absorber layer placed on a conducting plane. The layer's thickness, permittivity and permeability are adjusted so that the reflectivity is minimised for a desired wavelength. The Dallenbach layer relies on destructive interference of the waves reflected from the first and second interfaces. For the reflectivity to result in a minimum, the effective impedance of the layer, Z_L, must equal the incident impedance Z_o.

$$Z_L = Z_2 \tanh \gamma_2 d_2 \qquad 7$$

However, since Z_L is complex and Z_o real there is a requirement that the sum of the phase angles in Z_2 and $\tanh \gamma_2 d_2$ is zero (destructive interference) and the product of their magnitudes is equal to Z_o. In the design of a tuned layer there are five properties to play with, ε', ε", μ', μ" and d.

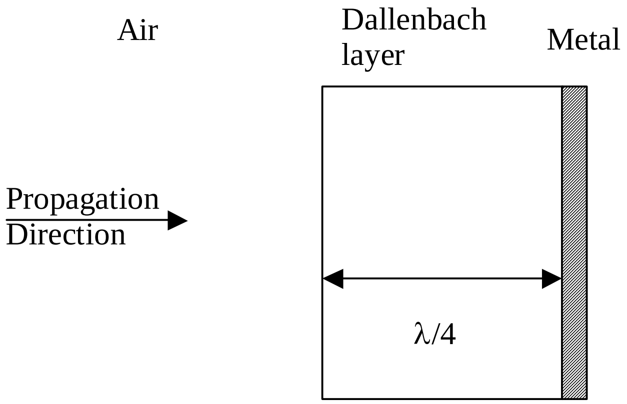

Figure 4. Dallenbach Layer

The reflectivity from Dallenbach layers has been simulated using CAD software called Touchstone and found to agree well with exact methods of calculating the reflectivity.[94]

Optimisation of Dallenbach layers has been investigated[95] and shown that it is not possible to obtain a broadband absorber with only one layer, however several layers stacked together showed increased bandwidth.[96] A modified Powell method has been used to optimise reflectivity as a function of incident angle and frequency.[97]

Dallenbach layers have been patented based on ferrite materials.[96] The use of two or more layers with different absorption bands will increase the absorption bandwidth. Dallenbach layers have also been made with silicone rubber sheets filled with silicon carbide, titanium dioxide and carbon black.[98] The bandwidth of standard ferrite absorbers have been improved through a two layer absorber design, with a ferrite layer at the air/absorber interface and a layer containing ferrite and short metal fibres at the absorber/metal interface. The fibre length is chosen to have a frequency near the required absorption frequency f_o, (ie for 8-13 GHz the fibre length was 1-4 mm for 60 μm diameter wire). The impedance of the wires shifts from being capacitive when the frequency is less than f_o of the fibres, to inductive for $f > f_o$. Impedance is at a minimum at f_o and the induced current is at a maximum. Between f_o and ½ f_o the fibre has a capacitive reactance and for $f < ½ f_o$ the fibre resistance becomes small and the reactance is capacitive only. At f_o the fibre length is nearly ½ λ in the matrix.[99] The ferrite layer acts as an impedance matching layer as well as absorber. Performance is better than –20 dB over 8-12 GHz and up to 45 degrees with an overall thickness of 4.6 mm. Design curves for Dallenbach layers have been considered.[100] Multilayer Dallenbach devices have been designed using a Lagrangian optimization method with constrained variable.[101] This method has also been used for the design of tapered and

¼ wavelength absorbers. A general solution for a single layer absorber is given along with design curves.[102] Ferrite samples have been prepared and characterized for the lower frequency regions (100-200 MHz) with reflectivity profiles.[103]

Although devices can be fabricated with large bandwidths, it is not known whether the maximum bandwidth possible has been achieved. The ultimate thickness to bandwidth ratio of radar absorbers has been calculated for different RAM types.[104] At -10 dB reflectance the thickness of a multilayer dielectric slab cannot be less than $\lambda_{max}/17.2$, where λ_{max} is the maximum wavelength at which the reflectance is –10 dB. For a nonmagnetic Dallenbach layer with this reflectance, the best thickness/$\Delta\lambda$ is 1/3.2 whereas for a narrow-band absorber the ratio is 1/13.9. This indicates that the largest possible bandwidth of a narrow-band dielectric absorber is about 4.4 times larger than that of a nonmagnetic Dallenbach screen of the same thickness.

Design curves for permittivity and permeability values have been calculated.[100,105] The Kramers-Kronig relationship has been investigated to see if it places a limitation on the bandwidth of Dallenbach layers.[95] This study also attempted to use simulation to determine the maximum bandwidths achievable for multilayer (Dallenbach) absorbing structures. The ultimate thickness to bandwidth ratio for a radar absorber has been analytically calculated.[104] Multilayer Dallenbach devices have been designed using a Lagrangian optimization method with constrained variable.[101] A general solution for a single layer absorber is given along with design curves.[102]

4.2.2 Salisbury Screen

The Salisbury Screen (patented 1952)[13] is also a resonant absorber, however, unlike the tuned absorbers it does not rely on the permittivity and permeability of the bulk layer. The Salisbury Screen consists of a resistive sheet placed an odd multiple of ¼ wavelengths in front of a metal (conducting) backing usually separated by an air gap. A material with higher permittivity can replace the air gap. This decreases the required gap thickness at the expense of bandwidth. In terms of transmission line theory, the quarter wavelength transmission line transforms the short circuit at the metal into an open circuit at the resistive sheet. The effective impedance of the structure is the sheet resistance. (If the gap is a half wavelength then the short circuit reappears and perfect reflection occurs). If the sheet resistance is 377 ohms/square (ie the impedance of air), then good impedance matching occurs. An analogue of the electrical screen would be to place a magnetic layer on the metal surface, resulting in a thinner device.[5,27] The -20 dB bandwidth of the Salisbury Screen at the resonant frequency is about 25%.

Salisbury screens have been fabricated and the reflectivity calculated.[71,106-110] Initial structures were made of canvas on plywood frames with a colloidal graphite coating on the canvas.[14] Conducting polymers have been considered in the design of Salisbury screens.[111] The reflectivity has calculated, using the optical matrix method, as a function of conducting polymer thickness, spacer thickness and incident angle.

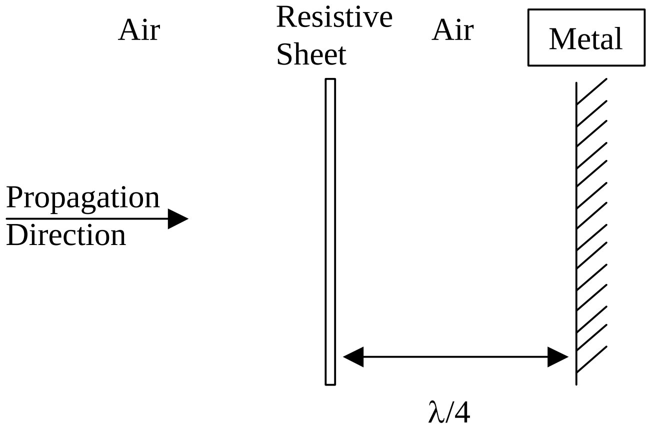

Figure 5. *Salisbury Screen*

Several strategies have been used for the design of the Salisbury screen.[27,112] The thickness of the optimal Salisbury screen can be calculated when the sheet resistance is equal to the impedance of free space (Z_o). The absorber thickness is given by

$$d = \frac{1}{Z_o \sigma} \qquad 19$$

where σ is the conductivity of the sheet. Two approximations are made regarding the resistive layer: The first is that the layer is electrically thin ($1 >> k_o d \sqrt{|\varepsilon^*|}$ where k_o is $2\pi/\lambda_o$ and d is the resistive layer thickness), and the second approximation is that the loss in the layer originates from the conductivity and ε" >> ε'.[112] For practical devices these approximations may not be realistic with the result that the resonant frequency shifts to smaller values as the resistive sheet thickness, or ε' is increased. This was shown using a transmission line model with a RCL circuit representing the Salisbury screen.[112] The thickness of the resistive sheet for optimum absorption has an inverse relationship to the sheet conductivity.[8]

The bandwidth of Salisbury Screens can be maximised given the maximum acceptable reflectivity.[113] The optimum sheet resistance was calculated to be 377 ohms/sq for the lowest reflectivity, while the optimum resistance, R_{sopt}, for a given reflectivity limit is given by

$$R_{sopt} = Z_o \frac{1 - \Gamma_{cutoff}}{1 + \Gamma_{cutoff}} \qquad 20$$

where Γ_{cutoff} is the maximum acceptable reflectivity. Analytically it was also shown that bandwidth decreases with increasing permittivity of the spacing layer.

4.2.3 Jaumann

Jaumann layers (1943)[1] are a method of increasing the bandwidth of the Salisbury screen, the simplest form of a Jaumann device. The first device consisting two equally spaced resistive sheets in front of the conducting plane was mathematically shown to produce two minima in the reflectivity, thus increasing the bandwidth. Multilayer Jaumann devices consisting of low loss dielectric sheets separating poorly conductive sheets (with conductivity increase towards metal plane) were described and the reflectivity calculated(1948).[1]

Resistive layers have been formulated using powdered carbon (25 weight %) in a phenol-formaldehyde, cellulose or polyvinyl acetate binder with polyethylene foams as spacers.[24] Silk screening the resistive layers has been shown to produce better control of thickness and resistance. A six-layer device was capable of about 30 dB decrease in the reflectivity from 7-15 GHz.

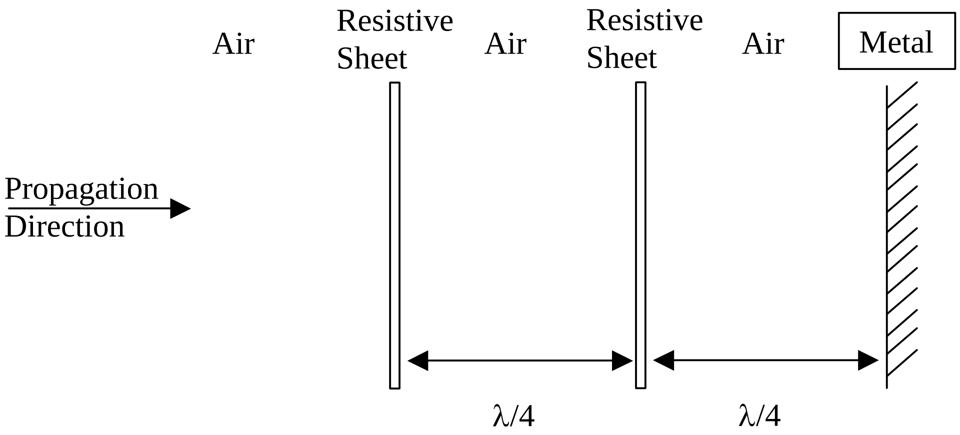

Figure 6. Jaumann Layers

The first calculations demonstrating that conducting polymers could be used as Jaumann absorbers occurred in 1991,[114,115] and the first measurements of Jaumann absorbers incorporating conducting polymers occurred in 1992.[107,116] Resistive polypyrrole films were grown electrochemically or by chemical methods using paper or fabrics as a support.[106,108,110,116] Touchstone software has been used to model the reflectivity from conducting polymer materials, using Transmission line modelling. Simple RC networks have been used to fit the measured reflectivity.[107-110]

Optimisation of Jaumann absorbers is complex due to the number of parameters involved, which increase as the number of layers increase. Empirical procedures and numerical optimization techniques[28] have been used for designing Jaumann absorbers.

Two analytical techniques have been used to optimise Jaumann absorbers up to a stack of three resistive sheets. These techniques are called the Maximally Flat or binomial design and the Tschebyscheff polynomial, or equal-ripple design after the shape of the reflectivity curve.

4.2.3.1 Maximally Flat Design

The objective of maximally flat design, or binomial expansion, is to have the flattest possible bandpass in the frequency region of interest. This is achieved by stacking up several Salisbury screens.[27] An approximate expression for such a quarter wave stack is

$$\Gamma = \Gamma_0 + \Gamma_1 e^{-2j\theta} + \Gamma_2 e^{-4j\theta} + \cdots + \Gamma_n e^{-2nj\theta} = \sum_{n=0}^{N} \Gamma_n e^{-2nj\theta} \qquad 21$$

where Γ_n is the reflection coefficient from an interface and

$$\theta = \beta_n d_n = \frac{2\pi}{\lambda_n}\frac{\lambda_{n_o}}{4} = \frac{\pi f}{2 f_o}$$

The summation on the right hand side of equation 3 can be expanded in a Taylor series in frequency so that the form is $\Gamma = A + Bf + \cdots$. It is desirable to have the reflectivity at the center frequency of the band equal to zero, and $\frac{dR}{df} = 0$ for the flat bandpass. The material properties are then solved for that set the coefficient A and B to 0. This technique has been extended to 3 resistive sheets and explored for magnetic and electric materials.[27] The bandwidth was found to increase over that of the Salisbury screen and with the bandwidth increasing as the admittance of the spacer decreases. The bandwidth of an absorber, with an outer magnetic and inner electric screen, increases with admittance. For this case the reflectivity does not necessarily reach a maximum (R=1). With two magnetic screens, one on the surface of the conductor and one a distance in front of the conductor plane, the reflectivity is independent of the separation of the second magnetic layer if the normalized complex magnetic impedance is 1/Y. This is due to the first screen absorbing all the radiation. However, there is a frequency dependence that requires the second screen for compensation and the bandwidth was calculated to increase. A three-screen Jaumann device was shown to have a larger bandwidth than the two-screen device. The three-screen device was also shown to reduce the reflectivity for incidence angles up to 60 degrees.

4.2.3.2 Tschebyscheff (Equal-Ripple) Design

In this design strategy the interference fringes from the quarter wavelength spaced resistive sheets are forced to approximate an equal amplitude ripple, with one ripple for each resistive layer. This is achieved by replacing the summation in equation 3 with a Tschebyscheff polynomial.[117]

$$\Gamma = e^{-jN\theta}\,\frac{T_N \sec\theta_m \cos\theta}{T_N \sec\theta_m} \qquad 22$$

where

$$T_N \sec\theta_m = p_m^{-1} \qquad 23$$

p_m is the ripple magnitude in dB, N is the number of ripples and layers,

$\theta = \dfrac{\pi}{2(1+F)}$ and $F = \dfrac{f - f_o}{f_o}$.

This method yields a wider bandwidth than the corresponding maximally flat solution. Tshebyscheff polynomials are also used to optimize the bandwidth of a Jaumann device.[117] This study showed that choosing the optimal spacer had a big influence on the bandwidth of the absorber. The Tshebyscheff technique has also been applied to the design of tapered absorbers.[90]

4.2.3.3 Gradient Methods

The analytical approach of using binomial, maximally flat design and polynomial, Tshebysheff design was only found to be suitable up to a stack of 3 and 5 resistive sheets, respectively. For larger stacks up to 20 resistive sheets a Newton-Raphson method is used to solve for maximally flat and equi-ripple designs.[28,29] The optimum maximum relative dielectric constant of the spacer tends to 1.0 as the number of layers increases.

The optimal control method has been used to optimise absorber design and has been compared to solutions from simulated annealing for the purpose of overcoming local optimum traps.[118] In simulated annealing the coating is subdivided into a large number of thin layers with fixed thicknesses. Each layer is assigned a material chosen from a predefined set of available materials. The optimal solution is found through iterative random perturbations of the material. Choices for each layer and evaluations are based on the metropolis criterion. This optimization technique usually leads to thinner, less reflective material than the optimal control approach.

A number of objective functions were formulated for optimizing the absorber properties. For instance the objective function for reflectivity performance of an absorber, *OF*, could be the mean reflectivity evaluated across the frequency band

$$OF = \frac{1}{n}\sum_{i=1}^{n} R(f_i) \qquad 24$$

where R is the reflectivity as a function of the frequency, f_i, and n is the number of frequency points across the band. A variation on this objective function is to optimise the reflectivity in comparison to a target reflectivity, R_c,

$$OF = \frac{1}{n}\sum_{i=1}^{n}\left|R(f_i) - R_c(f_i)\right| \qquad 25$$

A final objective function, includes weights for different regions of the frequency spectrum

$$OF = \sum_{i=1}^{n} p_i\left|R(f_i) - R_c(f_i)\right| \qquad 26$$

where $\sum p_i = 1$ and $p_i > 0$. This function permits the reduction in reflectivity for different frequencies.

If more than one objective function is to be optimised for then a weighting factor, α, is used to combine the weighting factors into a single expression,

$$OF = \alpha OF_1 + (1-\alpha)OF_2 \qquad 27$$

Modified Powell Algorithm (does not rely on explicit gradient information)

All these methods rely on local characteristics and so converge to local optima.

4.2.3.4 Optimisation of Jaumann Layers: Genetic Algorithm

The above optimization methods have produced significant increases in bandwidth and reduction in reflectivity. These methods, however, do not produce the optimal absorbing material, based on a number of factors such as minimum thickness or weight, or whether the solution is a local or global minimum. For these reasons, the Genetic Algorithm (GA) has been investigated as an optimization technique for RAM. Use of the GA is explored in this section and the GA method is reviewed in Section4.

A review of the use of genetic algorithms in engineering electromagnetics provides a good description of the genetic algorithm with some examples including the design of microwave absorbers.[119] Genetic Algorithms were first used in 1993 for the optimization of Jaumann absorbers[120-122] and built on the approaches used for the optimal control method.[118] A set of available materials, their frequency dependent optical properties (permittivity and permeability), and the layer thicknesses were used to define a population of absorbers. A genetic algorithm was used to optimise the absorber design against objective functions including reflectivity, thickness and weight. Both TE and TM polarisations of the reflection coefficient were calculated as well, in order to optimise the absorber as a function of incident angle as well. The reflectivity was calculated using a recursion relationship and the permittivity, permeability of the materials. Pareto fronts for the thickness vs reflectivity were presented.[123] Several Pareto Genetic Algorithms were compared with the non-dominated sorting genetic algorithm, NSGA, producing the best results.[123]

The genetic algorithm has also been used to optimise Jaumann absorbers based on transmission line theory.[88,124-127] Absorber bandwidth was shown to increase rapidly as a function of the number of resistive layers before asymptotically approaching the maximum bandwidth as the layer number approached infinity.[128] The optimum sheet resistance profile, assumed to have an exponential form,[30] was shown to have a sigmoid form with the resistance of the outer layers asymptotically approaching a maximum sheet resistance.[88,124,127] In these studies the bandwidth was studied as a function of both polarisations so that the absorbers could be optimized for incident angle as well. The bandwidth was defined as

$$BW = 2\frac{\left(f_u - f_l\right)}{\left(f_u + f_l\right)} \tag{28}$$

and the objective function for the combined polarisations as

$$OF = \frac{BW_{II} BW_{\perp}}{\left(\left|BW_{II} - BW_{\perp}\right| + 1\right)} \tag{29}$$

The optimised bandwidth for both polarisations was found to be less than that for normal incidence or one polarisation. At oblique incidences up to about 30 degrees the optimum bandwidth was found to remain fairly constant (near the value at normal incidence) before decreasing.[88] It was found that a two-stage strategy was useful in optimising absorber design. In the first stage an objective function based on the sum of the reflectivity below –20 dB was used to ensure that the –20 dB bandwidth was non-zero. Then in stage two, objective function sought to maximize the bandwidth and ensure that the reflectivity was still below –20 dB.[88] Absorbers with a protective skin were also optimised[88] and it was found that with proper choice of the outer layer material the absorber acted as if it had another resistive sheet and therefore had a wider bandwidth. With more than two resistive sheets, shinned absorbers could not be optimised below the –20 dB reflectivity limit, though the bandwidth could be improved for higher reflectivity targets.

The design of active (dynamic) radar absorbers has been investigated by using the genetic algorithm to optimise the absorption over different frequency bands by varying the sheet resistance, the spacer thickness or the spacer permittivity.[88]

Resistive sheets with capacitive properties have been used for making absorbers.[110] The optimal design of resistive-capacitive material based microwave absorbers has been studied using the genetic algorithm and transmission line theory.[36,129] The use of adaptive mutation has been explored to get out of local minima and to protect designs that are near the global minimum.[37] The genetic algorithm was also applied to the design of magnetic Dallenbach layers.[130]

A unique absorber design has been proposed and optimised using a genetic algorithm, where patches of material are organised to form a sheet.[131] These patches are either of the same material with different thicknesses or different materials with the same or different thicknesses.

A variant of the genetic algorithm, the microgenetic algorithm has been used for optimising frequency selective surfaces and circuit analog absorbers.[34,132,133] The microgenetic algorithm uses a small randomly generated population for optimisation in the usual manner for a genetic algorithm. Convergence occurs in a few generations and the fittest individual is added to those from previous generations. A new population is then randomly selected. Narrow band Salisbury Screens with circuit analog patterns replacing the resistive sheet have also been considered.[134-136]

4.2.3.5 Optimisation of Jaumann Layers: Other methods (Finite Element, FDTD and Taguchi Methods)

Scattering from cylindrical absorbers has been modelled using finite element method, FEM, and for single layer Jaumann (Salisbury Screen) the numerical method gives results similar to the analytic result.[137]

Preliminary FDTD calculations of the RCS of tapered Salisbury Screens and Jaumann layers have shown that the performance of these devices is not limited by resonant behaviour.[138]

The Taguchi method of optimization was used as a means of exploring less parameter space to explore the sensitivity and interaction of parameters in the design of planar and curved Jaumann Absorbers.[139]

4.3 Circuit Analog RAM

Improvement can be made on the bandwidth and attenuation of the resonant absorbers (Jaumann layers and Salisbury screen) by employing materials that take advantage of other loss mechanisms. The Salisbury screen and Jaumann layers were initially designed using purely resistive sheets. Replacement of the resistive sheets with materials also containing capacitance and inductance gives added scope for making broadband absorbers. Resistive-capacitive materials have been made in the form of conducting polymer coated fibers,[140] and resistive-inductive materials have been made with helical metal coils imbedded in a dielectric layer.[141] However, the field of circuit analog absorbers generally refers to materials where the resistive sheet has been replaced with lossy materials deposited in geometric patterns on a thin lossless sheet.[1] The thickness of the lossy material determines the effective resistance and the shape, geometry and spacing of the patterns control the effective inductance and capacitance. These materials show improved reflectivity and bandwidth performance and tend to be thinner absorbers.

A simplistic view of how a circuit analog material work is shown in Figure 7. The resistive loss comes from the conductivity of the material used for the patterns. The spacing between the elements of the patterns gives rise to a capacitance and the length of the element gives rise to an inductance.[22]

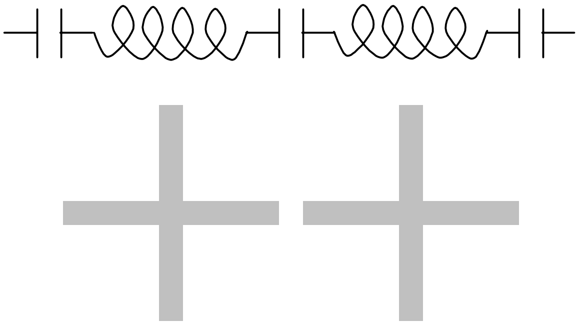

Figure 7. *Circuit Analog Sheet of crosses. The spacing between the elements gives rise to a capacitance, and the length, to an inductance. The resistive component is a result of the lossy material.*

The circuit analog equivalent of a Salisbury screen can be treated with transmission line theory (Section 6). The circuit analog sheet is modelled as a series circuit containing elements of resistance, capacitance and inductance, Figure 8. By varying the spacing between elements and element size the input impedance of the device can be tuned to that of free space.[1] The bandwidth of a simple Salisbury Screen made from dipoles was measured to be 44% at –10dB Reflectivity. Lower reflectivity was obtained using a dielectric spacer compared to air.[22]

$$Z_s = R_s + j\omega L_s + \frac{1}{j\omega C_s}$$

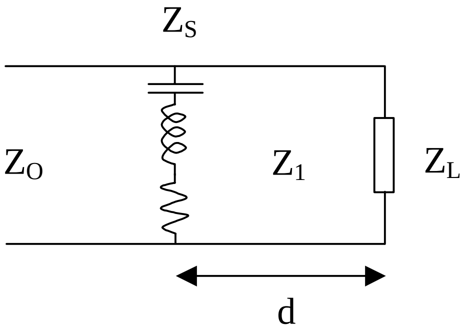

Figure 8. *Transmission line circuit for a Salisbury Screen with a Circuit Analog sheet. Z_L is the load impedance. For an absorber on a perfect electrical conductor the load impedance is a short circuit and thus equal to zero. Z_1 is the impedance of the spacer. There will be a finite thickness for the sheet and circuit analog material.*

The first artificial lossy materials were based on magnetic absorbers as these can be placed against the metal surface, resulting in thinner absorbers than the electrical analogs, which are spaced ¼ wavelength from the metal surface. These artificial magnetic materials were formed from an array of loop antennas distributed on the surface of a metal plate. This arrangement produces an impedance that can be tuned to match free space by varying the surface density of the loops and by varying the resistance of the resonator which absorbs the energy from the antenna. The resistive load was in the form of a few mg of iron powder.[1,20,21] This was an anisotropic material that resulted in different reflection coefficients depending on the magnetic field polarization; only absorbing when the magnetic field vector has a component it the direction of the magnetic dipoles represented by the loop antennas. A second device was based on the pyramidal absorber material with resistive cards placed perpendicular to the metal plate and parallel to the E field direction.[1,21] The resistive cards acted as a waveguide below the cutoff frequency if spaced at less than ½ wavelength and the surface resistivity was low. For such an arrangement, the incident wave does not penetrate into the absorber and is reflected. Thus spacings larger than ½ wavelength are needed. Results show maximum attenuation when the spacer separation is a little larger than half the wavelength. The reflectivity's dependence on incident angle depends on the resistive card spacing. For specular reflection the reflectivity is a smoothly increasing function with angle. The periodic structure causes diffraction, so that there are maxima in the reflectivity at specular and off-specular angles. Diffraction can be avoided by having pyramids of different lengths. These absorbers are very thick.

A frequency selective surface, FSS, is similar to a circuit analog absorber, however the patterned elements are made from metallic materials. FSS are typically used as bandpass filters for radomes. A FSS acts differently from a circuit analog absorber. Consider a FSS of metallic dipoles or slots with a dielectric spacer of ¼ wavelength or more. The dipoles act as short circuits and slots act as open circuits. The resonant frequency of a slotted layer varies around $\frac{f_o}{\sqrt{\varepsilon_r}}$, while for dipoles f_o is independent of dielectric slab thickness. Stacking frequency selective surfaces improves transmission or reflection bandwidth. Placing dielectric slabs on either side of a FSS also increases bandwidth, insensitivity to angle of incidence and falloff.[22] Three dielectrics and two screens produces good results. With the outer dielectric layers made of the same material (ε_r),a constant bandwidth over a wide angle of incidence and polarization is realised. The middle slab determines the flatness of the top of the bandpass.

Due to the complexity of patterns there are no simple means to model and optimise circuit analog and frequency selective surfaces. Transmission line models for broadband microwave absorbers have been used to analytically solve for the reflectivity.[142] The transmission through periodically perforated conducting screens has been treated using Babinet's principle.[143] Resistive and metallic strips were modelled using the spectral-Galerkin method.[144] These strips represent a grating in free space. The repeat spacing of the strips (periodicity), results in a minimum reflectivity for normal incidence, when equal to the wavelength. Transmission line models for strip gratings have been made and applied to circuit analog Salisbury screens made by replacing the screen with a resistive grating and the base conductor by a conductive grating. This device is polarisation sensitive, absorbing TE and transmitting TM polarised waves.[145] A method for determining the scattering from a device made from periodic arrays of resistive dipoles and crossed dipoles has been developed.[32] This study was built on the spectral domain (spectral-Galerkin) methods of Mitra[144,146,147] for frequency selective surfaces, which was extended to include resistive surfaces. Perfectly conducting patterns arrayed on the surface with a periodicity larger than the wavelength, show an influence from a ground plane (ie Salisbury Screen Configuration). If the periodicity is smaller than the wavelength, the ground plane is screened and has little influence.

One of the first patents on FSS for microwave absorption describes a multilayer grid device, where resistive grids are spaced with increasing mesh in the direction of propagation.[148] Another early patent reports the use of multilayered arrays of disks or squares.[49] Two patents have been issued for Jaumann type circuit analog absorber designs.[31,48] These designs are reported to reflect less than –15 dB over a bandwidth of 2-18 GHz. FSS's are printed using silk screening and result in conductors ca 0.18 inches thick on Mylar sheets 0.03 inches thick. Resistances of the conductive elements ranged from 0.04 to 1.5 ohms/square. It also has been reported[22] that the use of vapour deposited resistive sheets, optical masking and etching produced much better control over reproducibility. Another patent discusses a novel polymeric material blended with conducting materials such as carbon, metal powder, ferrites or conducting polymers.[149] The conductivity of this material was controlled and holes punched in the material with a certain period. Several of these layers were arranged into a metal terminated device and the reflectivity measured. The effect of conducting disks has been considered.[150] An array of conducting disks will increase the effective thickness of an absorber by introducing a capacitive admittance. The resonant thickness of the layer decreases as the disk diameter increases to the periodicity of the disks. Thinner absorbers are achievable with the same bandwidth. The capacitance of an array of disks is frequency dependant and harmonics are eliminated. Two layer Jaumann devices made with disks were also shown to reduce the absorber thickness. The effective permittivity of dielectric honeycombs has been studied. Mention is also made of dipole crosses and perforated materials.[151]

FDTD methods have been used to model the reflectivity from a FSS.[152] A checkerboard design of lossy dielectric and magnetic material was studied and indicated the possibility of achieving absorbers with better than –25 dB over a bandwidth of 5 to 40 GHz. Composite frequency selective surfaces laminated with radar absorbing material (a chopped carbon fibre layer) have been made and their reflectivity measured.[153] The measured results were compared against theoretical predictions made using micro genetic algorithms.[34] Fractal like FSS have been studied and optimised using genetic algorithms.[154]

4.4 Magnetic RAM

Magnetic absorber have been based on carbonyl iron and hexaferrites. These materials have absorb in the MHz and GHz ranges. The resonance frequency is related to particle size. Optical properties of M-Type Hexaferrites have been measured and reflection losses calculated.[155,156] These materials can be tuned to absorb at higher frequencies (5-20 GHz) based on particle size and sintering temperature. Optical parameters for a single layer of carbonyl iron loaded in polychloroprene rubber have been measured and then used to calculate the reflectance of this material. The results compared favourably with reflectivity measurements.[157] Dallenbach layers have been patented based on ferrite materials.[96] At least two layers with different absorption bands are used to increase the absorption bandwidth. They have also been patented based on silicone rubber sheets filled with silicon carbide, titanium dioxide and carbon black.[98] The bandwidth of standard ferrite absorbers have been improved through a two layer absorber design, with a ferrite layer at the air/absorber interface and a layer containing ferrite and short metal fibres at the absorber/metal interface. The fibre length is chosen to have a frequency near the required absorption frequency f_o, (ie for 8-13 GHz the fibre length was 1-4 mm for 60 μm diameter wire). The impedance of the wires shifts from being capacitive when the frequency is less than f_o of the fibres, to inductive for $f > f_o$. Impedance is at a minimum at f_o and the induced current is at a maximum. Between f_o and ½ f_o the fibre has a capacitive reactance and for $f <$ ½ f_o the fibre resistance becomes small and the reactance is capacitive only. At f_o the fibre length is nearly ½ λ in the matrix.[99] The ferrite layer acts as an impedance matching layer as well as absorber. Performance is better than –20 dB over 8-12 GHz and up to 45 degrees with an overall thickness of 4.6 mm.

4.5 Adaptive RAM (Dynamically adaptive RAM)

The potential to make adaptive absorbers has been explored. Mechanical devices that change the spacer thickness using a lossless dielectric fluid filled cell behind the resistive sheet have been explored, (see GB patent 9302394.3 1993). More practical methods have looked at tuning the absorption by changing the sheet impedance.[85-89,158-164] [22] This methodology is akin to circuit analog materials where the capacitance and resistance of the impedance sheet can be tuned.

5. Recursion Relationship for Calculating the Reflectivity

The following is a simple procedure for calculating the reflectivity from a multilayer material. Each layer is defined by three parameters: the thickness, complex permittivity and permeability, Figure 9. A recursion formula is used to calculate the reflectivity at the air/absorber interface. In this strategy the layers are numbered 1 to n starting at the first layer next to the perfect electrical conductor, PEC, and the interfaces are numbered 0 to n starting at the PEC/first layer interface (Figure 9). The recursion formula, expressed below, starts by calculating the reflectivity from interface i = 1, 2, 3,….n, where at interface n the reflectivity coefficient from the whole absorber, is obtained.

$$\Gamma_i = \frac{\tilde{\Gamma}_i + \Gamma_{i-1} e^{-2jk_{i-1}t_{i-1}}}{1 + \tilde{\Gamma}_i \Gamma_{i-1} e^{-2jk_{i-1}t_{i-1}}} \text{ for i >0} \qquad 8$$

where k_i is the component of the wave vector normal to the interface,

$$k_i = 2\pi f \sqrt{\mu_i \varepsilon_i - \sin^2 \theta_i} \qquad 9$$

$\tilde{\Gamma}_i$ is the reflection coefficient from interface i, and is dependent on the polarisation such that

$$\tilde{\Gamma}_i^{TE} = \frac{\mu_{i-1}k_i - \mu_i k_{i-1}}{\mu_{i-1}k_i + \mu_i k_{i-1}} \text{ for i > 0} \qquad 10$$

$$\tilde{\Gamma}_i^{TM} = \frac{\varepsilon_i k_{i-1} - \varepsilon_{i-1}k_i}{\varepsilon_i k_{i-1} + \varepsilon_{i-1}k_i} \text{ for i > 0} \qquad 11$$

For the PEC/first layer interface,

$$\tilde{\Gamma}_i^{TE/TM} = -1 \text{ for i = 0.} \qquad 12$$

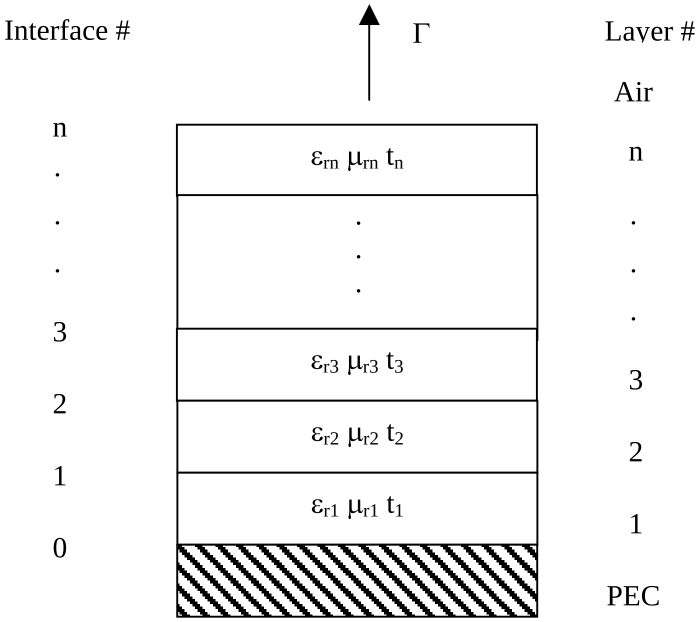

Figure 9. *Reflectivity from Jaumann absorber layers*

6. Transmission Line Theory

Transmission Line theory, has been used to model and optimise absorbers and essentially follows the logic of the previous section. A multisection transmission line is shown in Figure 10. The layer electrical lengths, L, are given by

$$L_i = \frac{n_i l_i}{\lambda_o} = \frac{l_i}{\lambda_i}, \quad \text{for } i = 1,2,\ldots,\text{M}. \qquad 13$$

where λ_i is the wavelength of section *i*.

The phase thickness of a section, δ , is then

$$\delta_i = \beta_i l_i = 2\pi L_i \frac{f}{f_o} = 2\pi L_i \frac{\lambda_o}{\lambda}, \quad \text{for } i = 1, 2, \ldots\text{M}. \qquad 14$$

The wave impedances, $\overline{Z}_i$, are continuous across the interfaces and are related by the recursion relationship

$$\overline{Z}_i = Z_i \frac{\overline{Z}_{i+1} + jZ_i \tan\delta_i}{Z_i + j\overline{Z}_{i+1} \tan\delta_i}, \quad \text{for } i = \text{M}, \ldots.,1. \qquad 15$$

The recursion is started with $\overline{Z}_{M+1} = Z_L$. The reflection coefficients from the left of each interface are then

$$\Gamma_i = \frac{\overline{Z}_i - Z_{i-1}}{\overline{Z}_i + Z_{i-1}} \qquad 16$$

and the values of Γ_i are obtained by the recursion relationship

$$\Gamma_i = \frac{\rho_i + \Gamma_{i+1} e^{-2j\delta_i}}{1 + \rho_i \Gamma_{i+1} e^{-2j\delta_i}}, \quad \text{for } i = \text{M}, \ldots..,1. \qquad 17$$

The recursion is started at $\Gamma_{M+1} = \Gamma_L = \frac{Z_L - Z_M}{Z_L + Z_M}$, and ρ_i is the reflectivity coefficient at the interface, calculated from

$$\rho_i = \frac{Z_i - Z_{i-1}}{Z_i + Z_{i-1}}, \quad \text{for i = 1, 2, \ldots.,M+1, and } Z_{M+1} = Z_L . \qquad 18$$

When the load at the end of the transmission line is a short circuit, $Z_L = 0$.

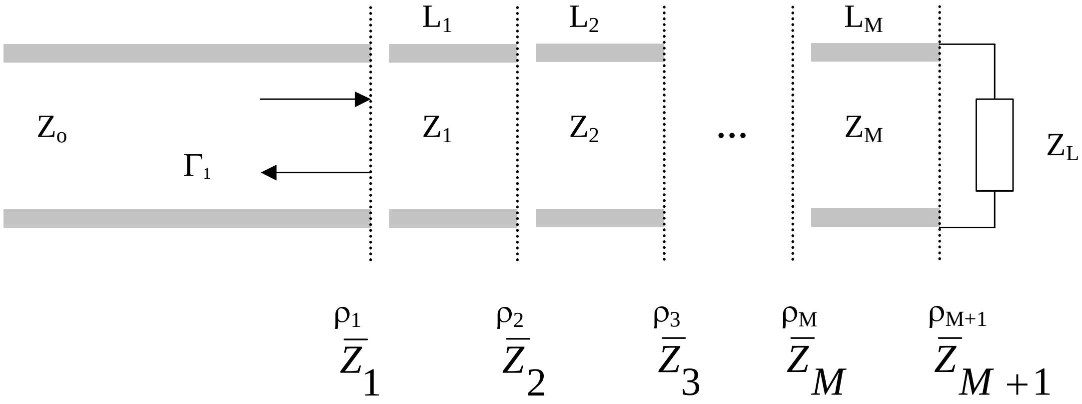

Figure 10. *Multisection transmission line.*

7. Absorbing Materials

7.1 Carbon

Absorbers for anechoic chambers were originally made, by coating mats of curled animal hair with carbon black impregnated neoprene. The front surface has then been moulded into geometric forms (ie pyramids) or the amount of lossy material was increased as a function of depth into the mat by dipping.[1,17] Carbon black and fibrous carbon has been incorporated into Dallenbach layers.[10,14,25,98]

Percolation networks of randomly distributed graphite-type microsphere inclusions have been theoretically studied as a function of permittivity and frequency for RAM applications.[165] Multiple-scattering effects were noted to increase the effective absorptivity through scattering losses.

7.2 Metal and Metal Particles

Broad band absorbers have been made from solid aluminum metallic particles or dielectric filled metallic shells in the shape of spheroids (oblate or prolate) dispersed in a matrix.[166] Iron oxide, powdered iron, powdered aluminum and copper, steel wool, water, powdered "Advance" and "Constantin", evaporated metal or nickel chromium alloy and metal wires.[19,25] ,

7.3 Conducting Polymers

In a polymer such as polypyrrole, partial oxidation of the polymer (doping) causes it to become conducting through the formation of polarons and bipolarons; the charge carriers along the chains. The conductivity of a conducting polymer is modelled by phonon assisted hopping between the randomly distributed localized states (that result from the partial oxidation).[167]

One of the inherent problems with conducting polymers is that they are typically intractable. Some of them can be compressed into shapes, such as polyaniline, PANI. Formation of composites with thermoplastic materials is another method. Polypyrrole, PPy, has been polymerised on the surface of PVA, PVC and within it to form composites. Emulsion polymerisation has also been used. PANI is soluble in solvents such as DMF, or the solubility of monomers has been increased by chemical modification though usually at the expense of conductivity. Textile materials have been used as substrates for a number of materials and have been coated with conducting polymers by soaking them with oxidant and then exposing them to monomer.[52] This procedure was also reversed soaking in the monomer and then adding oxidant.[72] The first investigation of PANI and PPy deposition onto fabric by an *in situ* polymerization technique was reported in 1989.[59]

7.4 Polypyrrole

Polypyrrole by itself does not have great physical properties and so most of the useful materials are composites of polypyrrole and other materials such as latex, fibres or polymer blends. Polypyrrole finds great use due to its relative stability in air.

7.4.1 Polypyrrole-Polymer Composites

The frequency response of polypyrrole-PMMA composites has been studied in the range of 10 kHz to 8 GHz.[168] The imaginary component of the permittivity, and hence the conductivity, were observed to be frequency dependent. At low frequencies, below 10^5 Hz, the conductivity displays percolative behaviour and does not depend on the frequency. Subtraction of the direct current conductivity reveals a relaxation at frequencies up to 10^9 Hz. This work shows the dependence of the imaginary component of the permittivity on the ac and dc conductivity. At frequencies above 1 GHz, the conductivity is dominated by the ac conductivity resulting from the hopping mechanism of charge transport in the conducting polymer. It was shown that the ac conductivity in the composites is an intrinsic property of the conducting polymer independent of the polypyrrole concentration.

One of the few references that presents permittivity, conductivity and reflectivity data for polypyrrole, shows that processing has a great effect on the final product.[169] Polypyrrole/PVC composite was compressed and melt injected into sheets. The compressed material was macroscopically conductive with $\varepsilon'' \propto K\omega^{-s} = \dfrac{\sigma(\omega)}{\omega\varepsilon_o}$, where K is a constant and the conductivity is frequency dependent. The melt-injected material was macroscopically insulating with Maxwell-Wagner type relaxation. The relaxation frequency is given by $f_r = \dfrac{\sigma_2}{2\pi\varepsilon_o\left(2\varepsilon_1^{'} + \varepsilon_2^{'}\right)}$, where the subscript 1 denotes the properties of the matrix and 2 the conducting phase. The compressed material is difficult to make into a tuned absorber , while the melt injected material readily forms a resonant Dallenbach layer.[169] This material shows a very narrow absorption with more than –40 dB reflectivity.

Dallenbach layers have also been made from polypyrrole doped with *p*-toluene sulphonic acid sodium salt, or 5-sulfosalicyclic acid dehydrate.[81,170] The chemically prepared powder was dispersed in a commercial paint, or milled with natural rubber and moulded into flat sheets and both were applied to an aluminum backing panel. These materials show resonance absorption if the content of the conductive powder is not below the percolation threshold. The percolation threshold for these materials was 2-4% due to the high aspect ratio of the PPy. Mixing was noted to destroy the fibrous nature, resulting in thresholds up to 16%. The rubber composites, and inclusion of conducting fibres that did not produce a macroscopically conductive material, still had a reasonable high value of ε'' and were therefore useful in making Dallenbach layers. A hybrid dielectric/magnetic material was also made using carbonyl iron, however, extra bandwidth was not realised for this material. [81,170] Powder processing was noted to have an influence on the final material properties.

Materials with conductive gradients have been made.[170] Phenolic foam, with a pore size on the order of 1 μm, was soaked in aqueous ferric chloride and then exposed to pyrrole vapour from one side. The gradient was obtained by controlling the exposure time. Uniformly coated foam was prepared by immersing the oxidant doped foam in an aqueous pyrrole solution and flowing the pyrrole solution through the foam. The permittivity of the foam was measured and showed very low values of ε_r' in the range of 1-2 and good values of ε_r'' in the range of 0.5-10. Two problems are associated with vapour polymerization, a thick coating on one surface of the foam and poorly conducting polymer doped with chloride from the ferric chloride. The wet method produced a material with better properties and a gradient could be induced into the material. It was noted that a 15 mm thick foam prepared in this manner [170] performed better than other published gradient absorbers.[171,172]

7.4.2 Polypyrrole-Fabric Composites

Several materials have been formed by polymerising pyrrole in the presence of a fabric or fibres. Pyrrole has been oxidatively polymerised with ferric chloride in the presence of paper (cellulose)[52,173] to form a PPy coated paper composite. Through manipulation of the chemistry and deposition time, the electrical conductivity of the composite could be carefully controlled. Absorbers were fabricated from these materials and measured.[107] The same techniques have been applied to cotton and polyester fabrics.[108] Modelling the phase and amplitude of reflected microwaves from the composite has allowed values of the resistance and capacitance of the fabric sheets to be determined as a function of fabric type and PPy loading.[106-110] The resistance decreases with loading while capacitance increases to maximum at about 2 to 3 mg cm^{-2}. At low loadings the PPy coating is smooth (hence decrease in R and increase in C). At higher loadings the coating becomes more particulate results in short circuits between fibres (hence a decrease in C).[106] Another feature of the PPy-fabrics occurs when asymmetrical weaves are used. This results in different properties based on the polarisation of the microwaves to the weave.[106] The use of polypyrrole coated fabrics (including glass fibres) enables the formation of structural RAM. The properties of the fabric-coated materials were modelled and made as Salisbury Screens and Jaumann layers.[106,108,110]

PPy-fabrics have been marketed by Milliken & Company under the trademark Contex®. These have been used as nets for microwave attenuation (trademark Intrigue®)[67] and as Salisbury screens and Jaumann absorbers.[109] Other applications have been realised by patterning the polypyrrole by changing its conductivity.[50,75] This has been used for “edge-card” materials in low observable aircraft.[60]

The stability of PPy coated PET and PVA fibres for use as microwave and millimeterwave obscurants have been studied for environmental concerns.[174]

7.4.3 Conducting Polymer Latex

Conducting polymer latex falls into two categories, pure latex and core-shell latex where a conducting polymer shell is coated onto an existing non-conducting latex core. Another area that falls into this general subject heading is that of conducting polymer nanocomposites which have been reviewed.[175]

Methylcellulose has been used to stabilise chemically formed polypyrrole, resulting in small particles dispersed in a methylcellulose matrix.[176] Similarly, PPy-Polystyrene sulfonate particles have been made by oxidizing pyrrole in presence of Fe^{3+}.[177] The size of particles is controlled by the Fe:py ratio. Pure conducting polypyrrole lattices have been formed by the polymerization of the mononer in the presence of a steric stabilizer such as poly(vinylpyrrolidone), PVP, or poly (vinyl alcohol-co-acetate, PVA,[178,179] poly (2-vinyl pyridine-co-butyl methacrylate,[180] and a comprehensive study of a number of stabilizers.[181] Poly(ethylene oxide), PEO, polyacrylic acid and various block copolymers based on PEO, failed to provide steric stabilization. PANI latex has also been made and forms needle shaped particles.[182,183] Polypyrrole and polyaniline lattices and composite beads (PPy-PMMA) have been synthesized and cast into conducting films by mixing with a dispersion of a 1:1 copolymer of polymethylmethacrylaye-polybutylacrylate.[184] The PPy lattices were spherical and PANI lattices needle-like, giving percolation thresholds of about 20 and 5 wt% respectively. The surface energy of conducting polymers (PPy and PANI) is high, capable of strong interactions either via London dispersion or Lewis acid-base forces.[185] For PPy, the surface energy decreases within a few days, which is not seen for PANI. PMMA adsorbs to the PPy particles, forming a uniform coating when 1,4-dioxane is used as the solvent and a patchy coating when chloroform is used.

Conducting polymer-coated latex particles (core-shell) have been reviewed.[186] Conducting polymers based on pyrrole, aniline and EDOT, polymerized with ferric chloride, APS and ferric tosylate. Core lattices discussed are PS and PU[187,188]. Potential applications are found in anti-corrosion and anti-static coatings. High performance electrochromatography and novel marker particles for immunodiagnostic assays.[189] PS/PANI core/shell lattices have been made in the presence of PVP,[185,190] and SDS (sodium dodecyl sulfate).[191] PPy deposits onto submicron poly (ethylene glycol) stabilized PS latex as nanoparticles, bridging the PS particles and causing flocculation.[192] Other PANI/PS-co-PSS lattices have been made.[193]

Nanocomposites of conducting polymers (PPy and PANI) and iron oxide magnetic particles have properties different from pure magnetic particles.[194] Electrophoretic mobilities of glass beads coated with PPy in the presence of a nonionic surfactant Rhodasurf TB970, have been measured.[195] 20 nm Silica colloidal particles have been coated with PPy,[190] and PANI[196,197]. Both of these produced agglomerates of silca and conducting polymer giving a raspberry like structure. Carboxylic acid derivatized polypyrrole-silica composites showed improved colloidal stability.[198]

A reverse core-shell PPy/polyacrolein latex has been synthesized and studied by atomic force microscopy, AFM.[199] The surface of the PPy particle was not completely covered by the polyacrolein.

7.5 Polyaniline

Polyaniline, PANI, is another inexpensive, simple to make, readily available conducting polymer that has suitable properties for the fabrication of an absorber. Polyaniline is slightly soluble and there are many derivatives of its monomer. Thus there is a large potential for tuning absorber properties with this material.

7.5.1 Polyaniline Fibres

Polyaniline has been used to coat glass fibre textiles[58,59] and PET textiles.[59]

7.6 Other Conducting Polymers

One of the first calculations showing that conducting polymers could be used for Salisbury Screens and Jaumann layers used the permittivities at 9.89 GHz of poly-p-phenylene-benzobis-thiazole and polyacetylene.[114,115]

Bithiophene has been electropolymerised into a latex matrix deposited onto a conducting plate. It was also noted that the latex could contain magnetic particles and other polymers such as pyrrole would be effective.[200]

7.7 Tubules and Filaments

Polypyrrole tubules have been synthesized chemically and electrochemically by growth within a pore or by using surfactant mediation. Pore templated growth of PPy tubes has been accomplished by polymerisation within the pores of porous alumina[201] and polycarbonate[202-205] membranes. Selective dissolution of the membrane results in PPy tubules. A two probe method for measuring the tubule resistance (conductivity) is given with conductivity decreasing for thicker tubes. The centres of the tubules tend to be filled with less well-ordered polymer.

A number of surfactant systems have been used to template the growth of polypyrrole tubules. A reverse microemulsion system using sodium bis(2-ethylhexyl) sulfosuccinate (AOT) was found to form nanotubes about 95 nm wide and up to 5 μm long.[206] Naphthalene-2-sulphonic acid also acts as template for polypyrrole growth (chemical or electrochemical) with a range of morphologies dependent on the surfactant concentration.[207,208] Diacetylenic phospholipid tubules template polypyrrole growth, however, it tends to be at the seems or edges of the lipid tubules, rather than coating the walls.[209] Polymer fibrils have also been detected in electrochemical deposits with *p*-Toluene sulfonic acid as the dopant.[210]

Radar absorbing materials can be formed by loading an insulating polymer matrix with conducting filaments or tubules. The length of the filaments should be less than ½ λ of the median frequency to be absorbed. For these materials, ε' reaches a maximum as the loading increases and starts to fall off at the percolation threshold, where the composite becomes macroscopically conducting. ε'' increases with loading around the percolation threshold and continues to increase to a saturation value at high loading. This is due to the dependence of ε'' on the conductivity. For spherical particles the percolation threshold is about 33 volume percent according to an effective-mean field theory[211]. For elongated particles, tubules or filaments, the percent conductive material required for percolation is considerably reduced. Some of these materials have been made from lipid derived tubules that were coated by electroless deposition of copper or nickel.[212,213] Other tubule formation has been noted for polyaniline and polypyrrole where surfactant drives tubule formation[214] and through templating reactions in ion etched polycarbonate microchannels.[205]

7.8 Chiral Materials

A reasonable amount of work has been conducted on chiral inclusions in a matrix as a radar absorbing material. Dallenbach layers have been formulated with metal inclusions such as right of left handed metal wire helices.[33,141,215] A helix is said to be chiral (ie it is not superimposable with it's mirror image). Materials made with these chiral inclusions have been shown to be effective microwave absorbers and have been patented.[33] The propagation constant for these materials is modified from isotropic materials due to the optical activity and circular dichroism of the material. A term is added for the chirality admittance similar to the permeability and permittivity,[33] which gives another method of fine tuning the reflectivity. Chiral materials have the effect of rotating linearly polarized electromagnetic radiation to the right or left as it passes through the media and this has been noted for microwaves.[141,215] The chirality of the material has been thought to lead to enhanced loss and greater design capability due to the chirality parameter β. This parameter is complex similar to the permittivity, ε*, and permeability, μ*, and results in a variation of the Maxwell equations (Drude-Born-Fedorov equations)

$$\mathbf{D} = \varepsilon\mathbf{E} + \beta\varepsilon\nabla\times\mathbf{E} \quad \text{and} \quad \mathbf{B} = \mu\mathbf{H} + \beta\mu\nabla\times\mathbf{H} \qquad 30$$

The left and right fields propagate with different complex propagation constants which are express as

$$k_L = \frac{k}{1-k\beta} \quad \text{and} \quad k_R = \frac{k}{1+k\beta} \qquad 31$$

k is the commonly excepted propagation constant, which for $\mu_r = 1$, is

$$k = \omega\sqrt{\varepsilon\mu}$$

Spherical objects coated with absorber material including chiral inclusions have been studied theoretically with the conclusion that the radar cross section is lower than without the chiral material.[216,217]

Theoretical[218] and experimental[141] studies of chiral materials concluded that chiral inclusions are not necessary in the formulation of RAM. The chiral and racemic mixtures both showed rotation and ellipticity, possibly from improper mixing of the racemic mixture. The decrease in reflectivity was slightly greater for the chiral medium, on the order of a few dB at the resonance point. Chiral materials will not produce thinner RAM than achiral materials.[218] It was noted that the absorption properties of the chiral inclusion comes partly from the interaction of the electric field with the metal helices, producing a magnetic field through induction and hence a complex permeability. These materials could be classified as circuit analog.

More recently it is acknowledged that chiral inclusions are not necessary, however, helical inclusions can be useful in the design of microwave absorbers. Modelling and measurement of real absorbers are presented.[219]

7.9 Shielding

Many of the materials discussed above can be used for shielding. For instance PET and PE fabrics coated with PPy or metal show utility as electromagnetic interference (EMI) shielding, giving between 20 and 80 dB depending on thickness and conductivity.[68]

8. Conclusion

Many of the absorber structures considered here would be useful for military applications. Coatings in the form of Dallenbach layers, although not broadband, would be useful for reducing the RCS from intricate shapes. Jaumann layers would be appropriate for broadband lightweight absorbers and a genetic algorithm should be used for design optimisation. If the military is to move to composite materials for ships or super structures then frequency selective surfaces and circuit analog absorbers should be embedded into the composite. Dynamic absorbers should be studied in order to counter frequency agile radars. Combined electric-magnetic materials offer the best potential for thin broadband absorption. Magnetic materials are limited to carbonyl iron and ferrites, raising a question of corrosion resistance. Conducting polymers are attractive electrical materials due to the potential for controlling their permittivity and permeability through synthetic means.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
PPy	Polypyrrole
PANI	Polyaniline
RAM	Radar Absorbing Material
RCS	Radar Cross Section
FSS	Frequency Selective Surface
FDTD	Frequency Domain Time Domain
GA	Genetic Algorithm

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14. ABSTRACT

(U) Radar is a sensitive detection tool and since its development, methods for reducing microwave reflections have been explored. Radar absorbers can be classified as impedance matching or resonant absorbers. Radar absorbing materials are made from resistive and/or magnetic materials. Circuit analog materials give more design freedom through access to capacitive and inductive loss mechanisms. Dynamic absorbers can tune the absorption frequency through control of resistive and capacitive terms. Many conductive and magnetic materials have been trialed for absorption including carbon, metals and conducting polymers.

(U) Le radar est un outil de détection sensible. Depuis sa mise au point, des méthodes visant la réduction de la réflexion des ondes ont été analysées. Les absorbants peuvent être classifiés comme des absorbants d'adaptation d'impédances ou des absorbants résonants. Les éléments qui absorbent les ondes radar sont faits de matériaux résistifs et/ou de matériaux magnétiques. La conception de circuits analogiques permet une plus grande marge de manœuvre, car elle permet d'utiliser des éléments d'affaiblissement de type capacitif et inductif. Le réglage des éléments résistifs et capacitifs permet l'accord sur la fréquence d'absorption. Des essais d'absorption ont été effectués sur de nombreux matériaux conducteurs et magnétiques, y compris du carbone, des métaux et des polymères conducteurs.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Absorber; Adaptive; Circuit Analog; Conducting Polymer; Dallenbach; Dynamic; Frequency Selective Surface; Jaumann; Layered; Magnetic; Pyramidal; Radar Absorbing Material; RAM; Review; Salisbury Screen; Tapered; Matching; Microwave; Tschebyscheff; Maximally Flat; Equal Ripple; Genetic Algorithm; Polypyrrole; Polyaniline