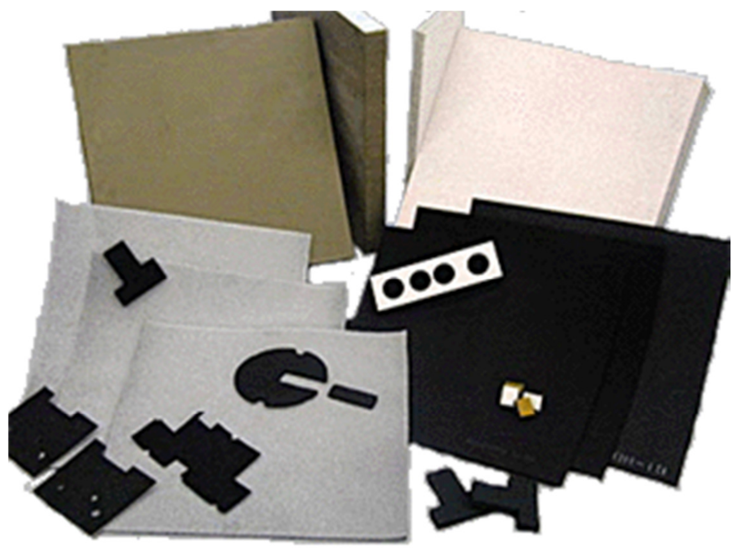
TECH NOTES

THEORY AND APPLICATION OF RF/MICROWAVE ABSORBERS

Absorbers in the RF/microwave realm are materials that attenuate the energy in an electromagnetic wave. Absorbers are used in a wide range of applications to eliminate stray or unwanted radiation that could interfere with a system's operation. Absorbers can be used externally to reduce the reflection from or transmission to particular objects and can also be used internally to reduce oscillations caused by cavity resonance. They can also be used to recreate a free space environment by eliminating reflections in an anechoic chamber.



RF/Microwave absorbers come in a vast range of different types

Absorbers can take many different physical forms including flexible elastomers or foam or rigid epoxy or plastics. They can be made to withstand weather and temperature extremes. Absorbers have become a critical element in some systems to reduce interference between circuit components. This paper will attempt to cover all aspects of absorbers from basic theory through absorber applications and types plus testing methods.

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ABSORBER THEORY

Absorbers generally consist of a filler material inside a material matrix. The filler consists of one or more constituents that do most of the absorbing. The matrix material is chosen for its physical properties (temperature resistance, weatherability, etc.).

Absorbers are characterized by their electric permittivity and magnetic permeability. The permittivity is a measure of the material's effect on the electric field in the electromagnetic wave and the permeability is a measure of the material's effect on the magnetic component of the wave. The permittivity is complex and is generally written as

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

The permittivity arises from the dielectric polarization of the material. The quantity ε' is sometimes called the dielectric constant which is something of a misnomer when applied to absorbers as ε' can vary significantly with frequency. The quantity ε" is a measure of the attenuation of the electric field caused by the material. The electric loss tangent of a material is defined as

$$\tan \delta_e = \frac{\varepsilon''}{\varepsilon'}$$

Knowledge of the permittivity and permeability of materials is essential to modeling absorber performance. If those values are known then material performance is completely determined.

The greater the loss tangent of the material, the greater the attenuation as the wave travels through the material. Analogous to the electric permittivity is the magnetic permeability which is written as

$$\mu^* = \mu' - j\mu''$$

With magnetic loss tangent defined as

$$\tan \delta_m = \frac{\mu''}{\mu'}$$

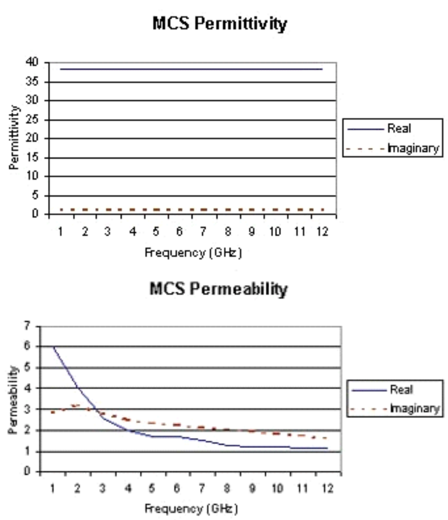
The permeability is a measure of the material's effect on the magnetic field. Both components contribute to wavelength compression inside the material. Additionally, due to the coupled EM wave, loss in either the magnetic or electric field will attenuate the energy in the wave.

In most absorbers, both permittivity and permeability are functions of frequency and can vary significantly over even a small frequency range. If the complex permittivity and permeability are known over a frequency range then the material's effect on the wave is completely known.

The units of permittivity are farads/meter and the permeability units are henrys/meter. The actual values for most materials can be cumbersome in calculation. For this reason they are usually compared to the permittivity and permeability of a vacuum. These values are

$\varepsilon_0 = 8.854x10^{-12}\ farads/mete$ and $\mu_0 = 4\pi x10^{-7}\ henrys/meter$

The values ε* and μ* then become dimensionless. Since ε is dependent on the dielectric polarization which always opposes the electric field, ε for all materials is greater than that of free space and hence is always greater than 1.



Typical parameters for a magnetic microwave absorbent material

Anisotropic Parameters

Most absorber filler materials are spherical in shape leading to isotropic electromagnetic parameters i.e. propagation and attenuation in the material is independent of direction. For nonspherical fillers the parameters may by anisotropic in which case the single values permittivity and permeability must be replaced by a 3x3 tensor

$$\varepsilon = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$

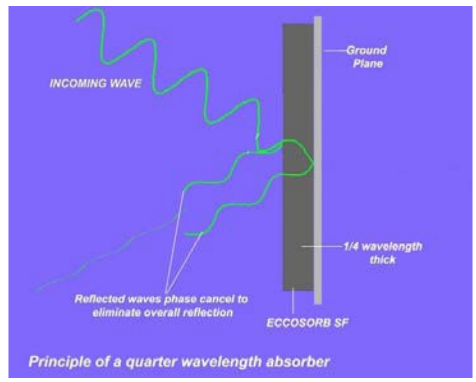
Generally the coordinate system can be rotated to make all but the diagonal components equal to zero.

ABSORBER TYPES

Free Space

Free space absorbers come in two broad types, reflectivity absorbers and insertion loss absorbers. Reflectivity absorbers reduce the reflection level compared to a perfect reflector (metal plate). Insertion loss absorbers reduce the signal travelling from point A to point B

Reflectivity-Narrowband



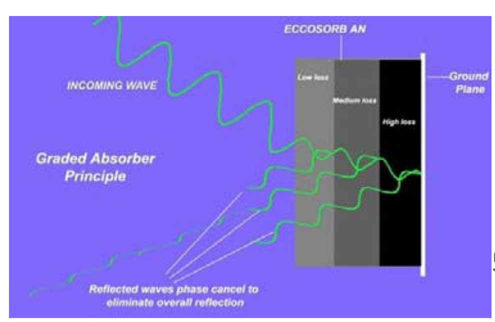
Any single layer homogeneous material will resonate when its thickness is equal to ¼ wavelength. A useful visualization is that the incoming wave will be partially reflected by the front surface of the material while part is transmitted. This transmitted wave then propagates through to the back of the absorber where it undergoes total reflection and propagates back through the front face of the absorber. If the wave reflected off the front face is equal in magnitude and 180o out of phase with the wave reflected off the back face then the waves will cancel and there will be no total reflection. This phenomenon will occur when the transit distance for the wave through the material is 180o. Since the wave transits the material twice, it will occur when the material has a thick- ness of ¼ wavelength. While this is a useful visualization it is not entirely accurate.

There are no separate reflections off the front and back surface. Like virtually everything else in the microwave engineering world, absorber design is an impedance matching problem, in this case matching the impedance of a metal surface (Z=0) to the impedance of free space (Z=377 ohms). If the impedance seen by the wave at the surface of the material is equal to 377 ohms, the wave will be completely absorbed by the material.

One of the earliest absorber types which is inherently narrowband is known as the Salisbury screen. The impedance at a metal surface is equal to zero. At one quarter wavelength in front of the surface the impedance will be infinite and the admittance will be zero. If a resistive sheet with surface resistivity equal to 377 ohms is placed here, the impedance will be equal to 377 ohms.

Since this only works when the substrate material is ¼ wavelength a Salisbury screen is inherently narrowband.

Reflectivity-Broadband

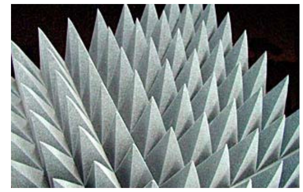


Multilayer

Several absorber types exhibit broadband reflectivity performance. Multiple discrete layers can be stacked which will enable the 377 ohm input impedance condition over a broader range of frequencies. The design of this class of material is similar to de- sign for a quarter wave transformer.

Impedance gradient

A second class of broadband absorbers uses an impedance gradient. The impedance at the front face is very close to 377 ohms but gradually reduces to zero ohms at the back face. Since there is no abrupt transition layer, there is no point which will cause a large reflection. This impedance gradient can take either of two forms. The first is a physical gradient where the material is homogeneous but is formed in a shape such that the wave 'sees' a small portion of the material at the front face and a gradually increasing portion as it travels into the material. The most common shape for this type of material is a pyramid. These are the highest performing absorbers with outstanding reflectivity (better than –50dB) and are usually used in anechoic chambers.



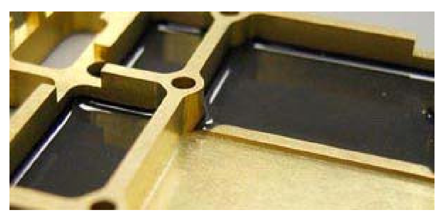
Pyramidal absorber

The second type of impedance gradient absorber uses a parameter gradient. In these absorbers, the material is a flat sheet but the electrical parameters within the sheet will vary continuously with depth into the absorber. This class of absorbers is capable of better than –20 dB reflectivity performance over wide bands.

Jaumann absorber

A Jaumann absorber extends the Salisbury screen concept to multiple layers. Resistive sheets separated by low loss dielectrics enable broadband performance to be achieved. In general, the resistivity of the sheets decreases from front to back in a Jaumann absorber. Since the low loss spacer material is usually a closed cell foam, a Jaumann exhibits inherent water resistance and light weight.

Enclosed Space (Cavity Resonance)



A cavity resonance absorber molded in place inside a circuit board

The physics governing absorber performance in an enclosed space is different than that governing performance in a free space volume. In an enclosed space, there are no propagating waves, only standing waves. In standing waves the E field and H field are 90° out of phase with each other. Material thickness is not as crucial as it is with free space absorbers since material resonance is not the goal. In cavity resonance damping the absorber is a high permittivity/permeability material that will attract the energy and absorb it. Since the tangential magnetic field is at a maximum (MISSING COPY HERE?)

Absorber Forms

Magnetic-Magnetic absorbers utilize a filler with ferromagnetic properties. This gives the absorber a high permeability and high

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magnetic loss. Advantages include the ability to greatly compress the wavelength due to the high permeability enabling quarter wavelength resonant absorbers at a thickness that are a fraction of the free space wavelength. Also, magnetic absorbers are best for cavity resonance damping since the magnetic field is a maximum on the conductive surface where the absorber is placed. Disadvantages of magnetic
absorber include weight and cost.

Magnetic absorbers come in several elastomer forms including silicone, urethane, nitrile and neoprene. The matrix material is generally chosen for its physical properties. Magnetic absorbers are also available in a rigid epoxy form. These absorbers are easy to machine and are generally used in load applications.

Dielectric

Dielectric absorbers have no magnetic properties (i.e. $\mu=1$). The loss mechanism is purely dielectric. The loss can arise from a variety of sources within the dielectric. Dielectric absorbers are usually made in a low cost foam form but can also be used with elastomers. Advantages are low cost and weight. Disadvantages are higher conductivity preventing usage in contact with electronic equipment and their lack of performance in most cavity resonance applications due to their lack of magnetic absorption.


A range of dielectric foam absorbers

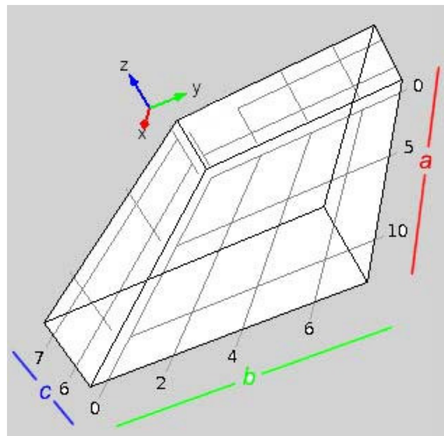
Moldable

Both magnetic and dielectric absorbers are available in moldable forms. This could be a two part liquid which cures at room or elevated temperatures or could be in the form of injection moldable pellets.

ABSORBER APPLICATIONS

Cavity Resonance Reduction

Often after a circuit is designed and tested it must be properly shielded and physically protected before it can be put into use. This usually involves covering the entire circuit with a metallic cover. While providing adequate shielding and protection the cover can introduce problems of its own. It can create conductive cavities that will resonate if stimulated at one of its resonant frequencies. This cavity resonance introduces E and H fields across the cavity that can seriously impact the circuit performance. The correct absorber material when introduced to the cavity can damp the resonance, enabling proper operation of the circuit.



In a rectangular cavity the resonant frequencies are given by

$$f_{mnp} = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2}$$

Where m, n, and p are indices indicating the number of half wavelengths across the x, y, and z dimensions of the cavity respectively. The cavity will resonate at frequencies determined by the cavity dimensions. The dominant resonant mode is similar to the TE01 waveguide mode but chosen with the first zero of sin(βz). This mode is designated the TE011 mode. The TE011 mode is the lowest frequency at which the cavity can support a cavity resonance.

Virtually every component of a microwave system uses absorbers. Proper choice of absorber materials is a cost effective way to enhance design.

Below this frequency, a cavity resonance will <u>not</u> exist. For an empty cavity, the cutoff frequency corresponds to where the longest dimension of the cavity is equal to 1/2 free space wavelength.

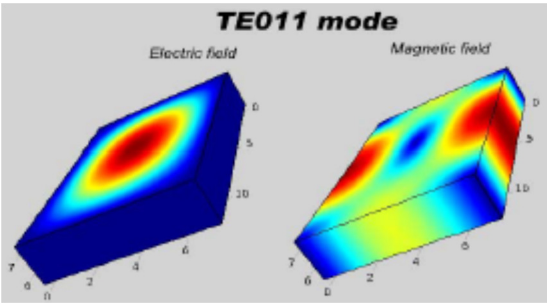
The equations governing the field distribution of the TE011 mode are as follows

$$E_x = E_0 \sin\left(\frac{\pi y}{b}\right)\sin\left(\frac{\pi z}{c}\right)$$

$$H_y = \frac{jbE_0}{\eta\sqrt{b^2+c^2}}\sin\left(\frac{\pi y}{b}\right)\cos\left(\frac{\pi z}{c}\right)$$

$$H_z = -\frac{jcE_0}{\eta\sqrt{b^2+c^2}}\cos\left(\frac{\pi y}{b}\right)\sin\left(\frac{\pi z}{c}\right)$$

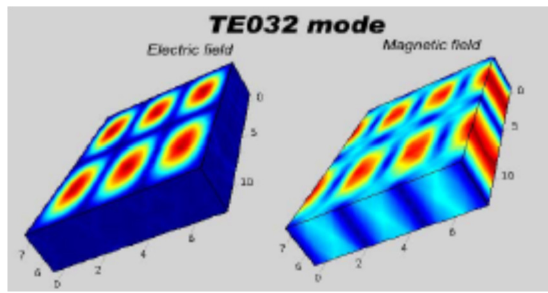
$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$



A range Field distribution of TE011 mode inside an empty cavity

Note the j in front of the equations for the H fields. This indicates that the magnetic field is 90° out of phase with the electric field. This means that when the electric field is at its maximum, the magnetic field is zero and vice versa. Since the impedance at a given point is proportional to the E field divided by the H field, the cavity resonance can cause wild swings in impedance across a cavity.

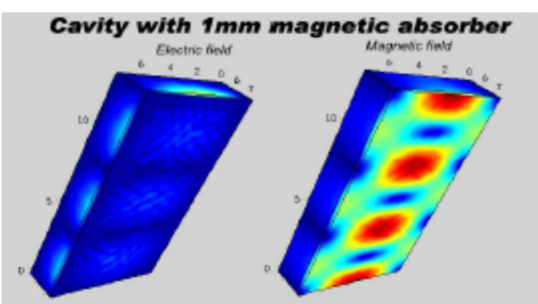
The illustrations at left show the electric and



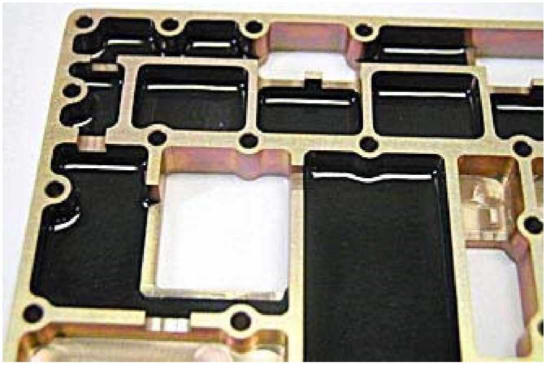
magnetic field norms for two different cavity modes. Note that where the electric field is strong, the magnetic field is weak.

Field distribution of TE032 mode inside an empty cavity dielectric foam absorbers

When an absorber is inserted into the cavity, the high permittivity/permeability of the absorber causes the energy to move into the absorber. The field equations are too complex to solve directly for a partially filled cavity but using Finite Element Method (FEM) software solutions for the fields can be found. Note in the third illustration how virtually all of the magnetic energy resides in the absorber. The higher the permittivity and permeability the more the energy 'wants' to go into the material. Recall from basic electromagnetic theory that the tangential electric field is zero on a conducting wall while the magnetic field is maximum. For this reason, magnetically loaded absorbers are the most effective in damping cavity resonances.



Field distribution in cavity with magnetic absorber at 1mm thickness fr=2.36 GHz



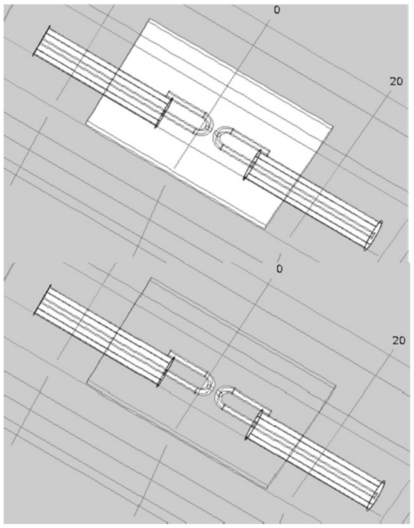
Absorber molded in place in a circuit board cover to damp cavity resonances

Near Field Absorbers

Near field absorbers are a class of absorbers that are placed near or directly upon a radiating element. Since the energy in the near field is predominantly magnetic, near field absorbers have high magnetic permeability and high magnetic loss. Also, since they are often in direct contact with circuit elements, they must have very low conductivity.

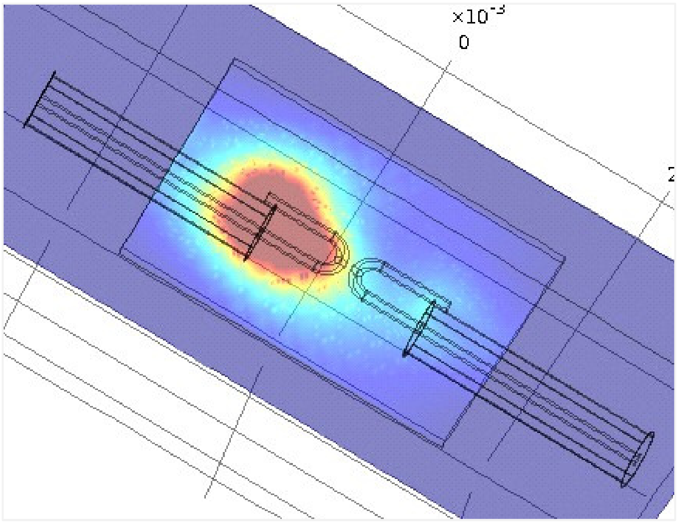
Even the best designed circuit will contain elements that will resonate and radiate at particular frequencies. These radiators could be inductors or capacitors or connecting wires that will behave differently at certain frequencies. In the near field most of the radiated energy is magnetic so radiators are modeled as a loop antenna. Magnetic energy dies off very quickly with distance but can still interfere with nearby circuit components.

Near field modeling consists of exciting a loop antenna and determining the coupling to the test antenna (also a loop). Coupling is compared after placing an absorber material nearly in contact with the loop.



Near field model with coupling loop antennas with and without absorber

FEM model of coupling loop antennas illustrating electromagnetic power loss in absorber material



Loads

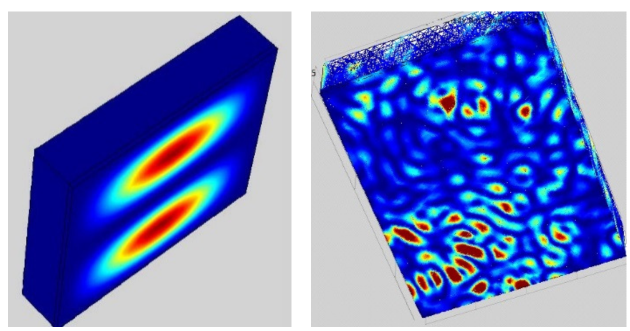
Microwave terminations are waveguide or coax sections that present low reflections to the incoming wave. Terminations are used in many microwave systems such as circulators or couplers to eliminate unwanted signals. A termination must be able to absorb the incident energy, hence the use of absorber load material.

A load must absorb over the entire waveguide band and is therefore shaped to present an impedance taper to the incoming wave. Load materials are generally magnetic absorbers which are easily machined or molded.

Load absorbers

Millimeter Wave Absorbers

Different modes of analysis and absorber types are needed in the RF/microwave band depending upon whether the absorber is used in free space or inside an enclosed cavity. Absorbers for free space reflectivity or insertion loss use a different design philosophy than for cavity resonance reduction. Most applications in the RF/microwave realm are clearly one or the other. The physics will change somewhat as we move into millimeter waves. Even a physically small cavity or enclosure could encompass several wavelengths at millimeter wave frequencies. Where is the line dividing a free space application from a cavity application?



The image on the left is the electric field distribution inside a cavity approximately 2 wavelengths in dimension. Note the clearly delineated resonance peaks indicating cavity resonance. The image on the right is the electric field distribution inside a cavity >10 wavelengths. While there appears to be some resonant behavior there are clearly some propagating elements as well.

Since there is no hard boundary separating free space from cavity resonance, electromagnetic modeling must be used. Modeling of the field distribution inside cavities of different dimensions compared to a wavelength indicate a breakdown of cavity resonance behavior at a cavity size around 5 wavelengths. At millimeter wave frequencies this could be smaller than 1”. This quasi- free space region requires different absorber solutions, requiring different absorber types than those used at lower frequencies.

Reflection Reduction

Any system that transmits energy can experience interference from reflections back to the transmitter. Also, unwanted reflections can interfere with other systems. Often the reflection source cannot be moved as with a building or a ship’s mast. Absorbers can then be used to reduce the reflection level. Typical reflectivity reduction for weather resistant outdoor absorber material is –20dB which will eliminate 99% of the reflection. Care must be taken that the chosen absorber is designed to absorb at the transmit frequency.

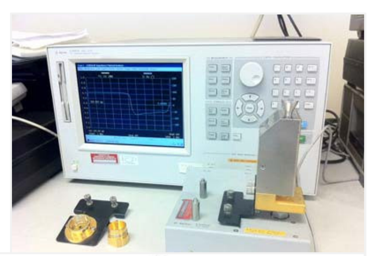
Radar Cross Section Reduction (RCSR)

Absorbers can also be used to reduce the radar cross section of a target object. By reducing the reflection level the object will present a smaller cross section. However, due to the narrowbanded performance of thin radar absorbent material (RAM) and the thickness and weight of broadband RAM, it is difficult to achieve effective radar cross section reduction using absorber alone.

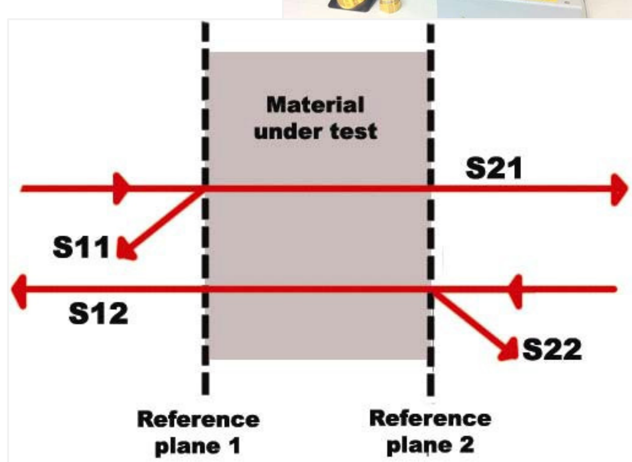
Anechoic Chambers

Anechoic chambers are used to create a free space condition in an enclosed room. Very high performance absorber material is used on the walls, ceiling and floor to eliminate reflections. Reflectivity of absorbers used in anechoic chambers can be –50dB or better. That level of performance is critical to guaranteeing a successful antenna or radar cross section test in a weatherproof secure environment.

PARAMETER TEST METHODS



Accurate measurement of electromagnetic parameters is critical to modeling the performance of microwave absorbers. The electric permittivity $\varepsilon^*=\varepsilon'-j\varepsilon''$ and magnetic permeability $\mu^*=\mu'-j\mu''$ are, in general functions of the frequency so swept frequency methods are desired.



At low frequencies (<1 GHz) parameters can be measured using an impedance analyzer with custom test fixtures. The permittivity test fixture measures the capacitance of two parallel test heads both with and without the material under test. The permittivity is then derived from the capacitance. The permeability is determined from the change in inductance of a cylindrical cavity by insertion of a donut shaped MUT. Very good results can be found down to 1 MHz.

At higher frequencies measuring the capacitance or inductance no longer yields satisfactory results and field theory must be used. Parameter measurement testing at these frequencies entail sending a wave into the material and measuring the material response. Since 4 results are needed (real and imaginary ε, μ), 4 measurements need to be taken on a sample which are usually the magnitude and phase of S11 (reflection) and S21 (transmission) through the sample. If it is known that the material has no magnetic components (μ=1) then the electric permittivity can be determined with 2 measurements, S11 magnitude and phase or S21 magnitude and phase.

Insertion loss/phase test fixture for broadband parameter measurement of non-magnetic material

While free space measurements of reflection/transmission amplitude and phase have yielded good results the best results are seen in closed systems using coaxial lines or waveguides. In these cases the calibration of the network analyzer is critical. Full 2 port calibration or TRL calibration is needed for accurate phase measurements, particularly of reflection. Sample fit inside the coax or waveguide is very important as a poorly fit sample will not yield good results. As frequencies extend into millimeter waves, calibration and sample fit become even more critical due to the short wavelength.

Waveguide and coaxial test fixtures

For non-magnetic material, free space techniques can yield excellent results all the way up through millimeter waves. It is much more straightforward to measure transmission phase plus good measurements can be made in free space eliminating the sample fit problem.

ABSORBER TEST METHODS

Attenuation

Attenuation is a measure of how much a wave propagating through a material is attenuated. It is not a direct measurement but is calculated from the material's complex permittivity and permeability. The definition is that if all space is filled with the material, a wave will attenuate at this rate per unit distance. Attenuation is usually expressed in dB/cm. Attenuation values do not relate directly to any particular measurement and the reader should be cautioned about using the numbers to predict reflectivity. It is used to compare the relative absorption of different materials. In any real world situation, the material impedance must also be taken into account. Attenuation in dB/cm is given by

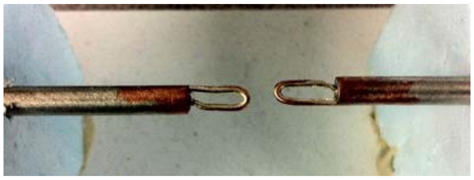
$$Attenuation\left(\frac{dB}{cm}\right) = \frac{2\pi(8.686)}{\lambda_0}\sqrt{\frac{\mu'\varepsilon'}{2}\left(\sqrt{(1+\tan^2\delta_d)(1+\tan^2\delta_m)}-(1-\tan\delta_d\tan\delta_m)\right)}$$

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad \mu^* = \mu' - j\mu'' \qquad \tan\delta_e = \frac{\varepsilon''}{\varepsilon'} \qquad \tan\delta_m = \frac{\mu''}{\mu'}$$

Near Field Test

Near field interference takes several forms so there is no single test that suffice to fully characterize the performance of near field absorbers. The IEC has designated four tests to measure noise suppression of near field absorbers.


Microstrip Line test fixture


Coupled loops for inter and intra decoupling test

- **Intradecoupling ratio** – This test is designed to measure the effective- ness of the absorber in reducing the coupling between elements on the same side of the absorber sheet. Two loop antennas are deployed as illustrated on the right. The coupling between the antennas is measured and the absorber is placed above the loops and the coupling compared to the case with not absorber
- **Interdecoupling ratio** – This test measures the absorber effectiveness when the source and receiver are on opposite sides of the absorber. The setup is the same as for intradecoupling ratio but in this case the absorber sheet is placed between the antenna loops
- **Transmission Attenuation Power Ratio** – This test measures the effectiveness of the absorber in suppressing current noise along a printed circuit board. A microstrip line is used and transmission and reflection characteristics measured. The material is then place on top of the conductor and transmission and reflection remeasured.
- **Radiation suppression ratio** – This rest requires an anechoic chamber. The microstrip line is used as the source and the radiated emissions at a fixed distance away is measured.

NRL Arch

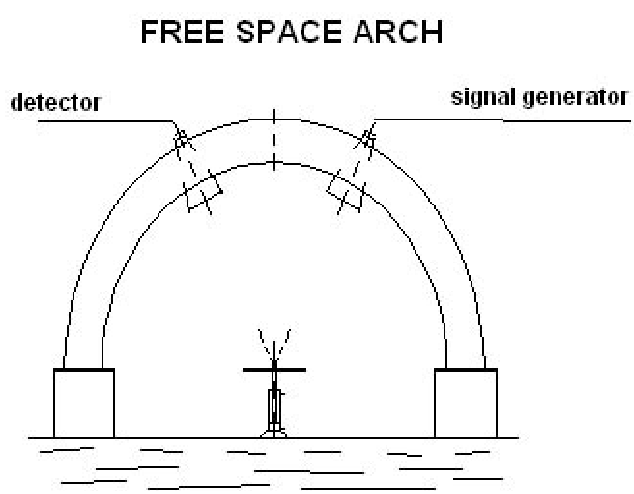
The NRL Arch is the industry standard for testing the reflectivity of materials. Originally designed at the Naval Research Laboratory, the NRL Arch allows for quick, repeatable non-destructive testing of microwave absorbent materials over a wide frequency range.

Reflectivity is defined as the reduction in reflected power caused by the introduction of an absorbent material. This reduction in power is compared to a 'perfect' reflection which is approximated very well by the reflection off a flat metallic plate.

As seen in the diagram below, an NRL arch consists of a transmit and receive antenna which are oriented towards a metal plate. To measure normal incidence reflectivity the antennas are located as close to each other as physically possible. Absorbent material is often used to minimize antenna cross talk. The antennas can be located anywhere on the arch to allow measurements of performance at off normal angles of incidence with the practical limitation of the ability to separate the signal from the material under test from the direct antenna to antenna cross talk.

In general a network analyzer is used for measurements on an NRL Arch to provide both the stimulus and the measurement. A calibration is performed by measuring the resultant power reflecting off the metal plate over a broad frequency range. This is established as the 'perfect' reflection or 0 dB level. The material under test is then placed on the plate and the reflected signal measured in dB. Time domain gating may be used to eliminate antenna cross talk and reduce the error introduced by room reflections.

The size of the material under test and the antenna to plate distance are determined by the desired frequency range of test. A standard setup tests from 2-18 GHz using a material size of 12"x12" or 24"x24" and an antenna to plate distance of 30"-36". Lower frequency (longer wavelength) testing would require a larger sample size and longer antenna-plate distance. Higher frequencies could use a smaller arch and sample size.



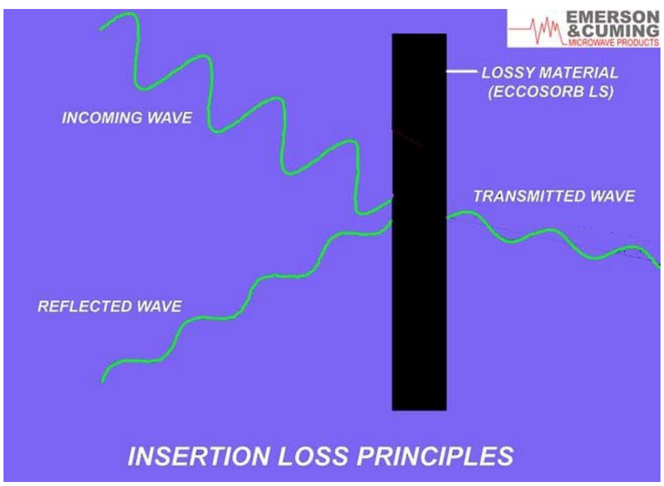
An NRL Arch for millimeter wave measurements

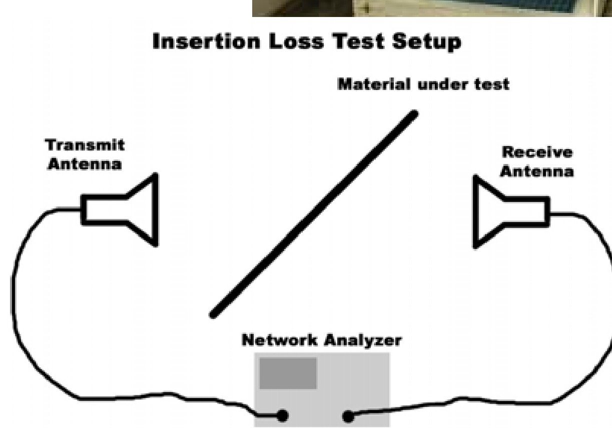
Insertion Loss

Insertion loss is a measure of how much microwave energy traveling from Point A to Point B is reduced by the introduction (or insertion) of a microwave absorbent material in the path. An insertion loss measurement does not differentiate between all the factors which will affect the reduction in power including reflection from the material and loss as the wave transits through the material.

A well designed setup for testing insertion loss would include two antennas oriented so that their maximum directivity is towards each other. They will be separated sufficiently to satisfy far field requirements though the greater the separation, the larger the sample size must be to minimize errors caused by energy leaking around the edges of the sample under test.

In practice insertion loss measurement is straightforward. A signal is transmitted through one antenna and the response measured at the second antenna. This establishes the reference or 0 dB level and is usually measured as a function of frequency. The material under test is then placed between the antennas and a measurement is performed. The insertion loss is expressed in dB as a function of frequency.





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ABSORBER THEORY

Reflection and transmission of waves at a material boundary

Absorbers are used to eliminate unwanted electromagnetic energy. In free space they do so by presenting an impedance to an incoming wave equal to the impedance of free space (377 Ω). At a material interface, the incident, reflected and refracted waves must obey the boundary condition that the sum of E and H fields of the waves must be continuous. Requiring continuity of the amplitudes leads to Fresnel's equations. Continuity of phase leads to Snell's Law. Reflection from a dielectric interface depends on the polarization. There are two polarization states defined. Parallel polarization occurs when the electric field vector is parallel to the plane of incidence. The plane of incidence is defined by the vector normal to the material and the propagation direction of the incident wave. Perpendicular polarization occurs when the electric field vector is perpendicular to the plane of incidence.

$$r_{par} = \frac{\sqrt{\mu^*\varepsilon^* - \sin^2\theta} - \mu^*\varepsilon^*\cos\theta}{\sqrt{\mu^*\varepsilon^* - \sin^2\theta} + \mu^*\varepsilon^*\cos\theta} \quad \text{and} \quad r_{perp} = \frac{\cos\theta - \sqrt{\mu^*\varepsilon^* - \sin^2\theta}}{\cos\theta + \sqrt{\mu^*\varepsilon^* - \sin^2\theta}}$$

The phase delay experienced by the wave in propagating a distance d is given by

$$\phi = \frac{2\pi d}{\lambda}\sqrt{\mu^*\varepsilon^* - \sin^2\theta}$$

Where λ is the free space wavelength. Note that for a non-magnetic material these equations are simplified by $\mu^*=1$

The interface reflection coefficients are only half the story though. Eventually the wave will reach the other side of the absorber and reflect. The total reflection is then derived from the sum of the reflected waves.

The voltage reflection coefficient for a thickness d of a material is

$$R = \frac{-r^*(1-e^{-j2\phi})}{1-r^2e^{-j2\phi}}$$

where r is the appropriate interface reflection coefficient.
Reflection coefficients are usually expressed in dB

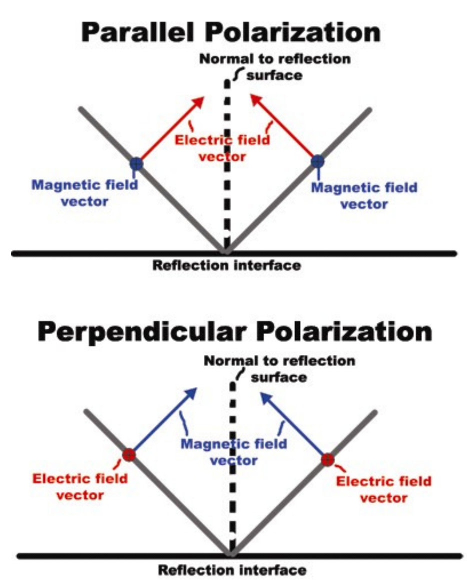
$$REFLECTION(dB) = 10\log\left(\frac{1}{|R|^2}\right)$$

The voltage transmission coefficient is given by

$$T = \frac{(1-r^2)e^{-j\phi}}{1-r^2e^{-j2\phi}}$$

Transmission coefficient in dB is given by

$$TRANSMISSION(dB) = 10\log\left(\frac{1}{|T|^2}\right)$$



In most cases with absorbers the material is backed by metal. The total reflection coefficient (now called the reflectivity) becomes

$$R_{MB} = \frac{r - e^{-j2\phi}}{1 - re^{-j2\phi}}$$

And the reflectivity in dB is given by

$$REFLECTIVITY(dB) = 10\log\left(\frac{1}{R_{MB}{}^{2}}\right)$$

An alternative method of prediction is to treat the problem as a transmission line containing an absorber with a thickness d . The input impedance at the front of the absorber is then

$$Z_{in} = Z_c \frac{Z_L + Z_c \tanh(j\beta d + \alpha d)}{Z_c + Z_L \tanh(j\beta d + \alpha d)}$$

Where

Z_L = the load impedance seen at the back of the absorber

Z_C = characteristic impedance of absorber material = $\sqrt{\frac{\mu *}{\varepsilon *}}$

α and β are the attenuation and propagation coefficients respectively and are derived from

$$\gamma = j\omega\sqrt{\varepsilon^{*}\mu^{*}} = \alpha + j\beta$$

Where

$$\omega = 2\pi * \upsilon = 2\pi * frequency$$

For a single layer metal backed absorber the equation is simplified because ZL=0 giving

$$Z_{in} = Z_c \tanh(j\beta d + \alpha d)$$

The reflection coefficient is then found by comparing to the impedance of free space (377 Ω)

$$R = \frac{Z_{in} - 377}{Z_{in} + 377}$$

And

$$REFLECTION(dB) = 10\log\left(\frac{1}{|R|^{2}}\right)$$

The input impedance method is easier computationally than the reflection-transmission method but it cannot predict performance at off normal angles. The input impedance method can model multiple layer absorbers by replacing the load impedance ZL by the input impedance of the preceding layer. The reflection-transmission method cannot. A third method must be used to predict off-normal performance of multiple layer absorbers.

The problem of modeling multiple layer absorbers at off normal incidence angles is solved by using the wave amplitude transmission matrix method. The voltages on either side of a junction are related by

$$\begin{bmatrix} V_1^+ \\ V_1^- \end{bmatrix} = \begin{bmatrix} \dfrac{1}{S_{12}} & \dfrac{-S_{22}}{S_{12}} \\ \dfrac{S_{11}}{S_{12}} & \dfrac{(S_{12}{}^2 - S_{11}S_{22})}{S12} \end{bmatrix} \begin{bmatrix} V_2^+ \\ V_2^- \end{bmatrix}$$

Where S_{11} and S_{22} are the reflection coefficients of each layer looking towards side 1 and side 2 of the absorber respectively and S_{12} and S_{21} are the transmission coefficients of each layer from side 2 towards side 1 and side 1 towards side 2 respectively. For a homogeneous layer the equation is simplified since $S_{11}=S_{22}$ and $S_{12}=S_{21}$. This simplifies the matrix to

$$\begin{bmatrix} \dfrac{1}{R} & \dfrac{-R}{T} \\ \dfrac{R}{T} & \dfrac{(T^2 - R^2)}{T} \end{bmatrix}$$

Where R and T are calculated using the reflection-transmission equations. To model multiple layers the matrices for each layer are multiplied. The result is a 2x2 matrix from which the multilayer reflection and transmission coefficients can be derived.

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

$$R = \frac{1}{a_{11}} \qquad T = \frac{1}{a_{11}a_{21}}$$

The metal backed reflection coefficient is given by

$$R_{MB} = \frac{a_{21} + a_{22}}{a_{11} + a_{12}}$$

Wave Propagation in Absorbers

For waves in a material two of Maxwell's equations can be written as

$$\nabla \times H = \varepsilon^* \frac{\partial E}{\partial t} \text{ (Ampere's Law)} \qquad \nabla \times E = -\mu^* \frac{\partial H}{\partial t} \text{ (Faraday's Law)}$$

Differentiating each equation by t and substituting yields

$$\frac{\partial^2 E}{\partial x^2} = \varepsilon^* \mu^* \frac{\partial^2 E}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 H}{\partial x^2} = \varepsilon^* \mu^* \frac{\partial^2 H}{\partial t^2}$$

If it is assumed that E and H are functions of x and t only the solution is a plane wave

$$E = E_0 e^{j\omega t - \gamma x} \quad \text{and} \quad H = H_0 e^{j\omega t - \gamma x}$$

where $\gamma = j\omega\sqrt{\varepsilon^* \mu^*} = \alpha + j\beta$

and $\omega = 2\pi * \upsilon = 2\pi * frequency$

Expanding gives

$$E = E_0 e^{-\alpha x} e^{j2\pi(\upsilon t - \frac{\beta x}{2\pi})}$$

A nonzero α leads directly to an exponential attenuation of the wave. The complex exponential leads to a time period of

$$T = \frac{1}{\upsilon}$$

and a space period (wavelength) $\lambda = \frac{2\pi}{\beta}$

For all materials with β>1 the wavelength will be compressed inside the dielectric compared to free space by a factor of β. For a low loss material, a very good approximation to β is

$$\beta = \omega\sqrt{\varepsilon^* \mu^*}$$

GLOSSARY

Anechoic – An environment with no reflections. Generally used with anechoic chamber as in a room with no reflections off the walls

Angle of incidence – The angle measured from a perpendicular axis to the plane of a surface which energy arrives at. "Normal incidence" refers to the perpendicular direction of propagation to the surface. "Grazing Incidence" refers to energy arriving from the direction almost parallel to the surface (high incident angle"). Important in the performance of specular absorbers.

Antenna – A device which increases the efficiency of transmission or reception of radio or radar signals into or from a medium. For instance, transmitting and receiving antennas are the same device.

Attenuation – Loss of energy (i.e. conversion to heat) as radiation passes through a lossy (absorptive) medium (expressed in dB). Function of the properties of the medium. In contrast to insertion loss or reflectivity.

Capacitance – The ability of a capacitor to store electric energy

Cavity Resonance – An enclosed space will resonate at certain frequencies which could interfere with the performance of a circuit inside. Resonant frequency depends on the dimensions of the cavity and can be reduced by using absorbers

Coaxial line – A pipe (so called outer conductor) with a concentric wire (inner conductor) that is used to carry microwave energy with little loss of power

Decibel (dB) – A logarithmic ratio (base 10) between two quantities denoted as ""dB."" In terms of energy reflection: dB = 10 x LOG (power reflected/power reflected by metal plate) e.g. dB = 10 x LOG(1/2) = -3 (50% reflected power)

Dielectric – A medium through which electric attraction or repulsion may be sustained - an insulator.

Dielectric Constant – The power loss in a dielectric due to heating as a wave passes through it. It can be expressed as "dielectric loss tangent" (power factor) or "loss factor". Low loss makes a good dielectric (ECCOSTOCK dielectric materials). High loss is an absorber (ECCOSORB), poor dielectric.

Electromagnetic field – A vector field of Electromagnetic energy. The Magnetic (H) and Electric (E) fields generated by any system of electric charges. A low current, high voltage, source will generate mainly an ELECTRIC FIELD. A high current, low voltage, source will generate mainly a MAGNETIC FIELD

Far Field – The region where Antenna patterns and RCS patterns need to be measured with adequate transmission distance (in terms of wavelength) or they will not be typical of the patterns expected in typical use over long distances. Measurements made over short distances (near field) contain errors because the fields are curved rather than planar.

FEM – Finite Element Method-a type of electromagnetic modeling software

Free space – Refers to the medium of air (or vacuum) in which radio waves may travel. This is in contrast to waves traveling on transmission lines such as coax or waveguide, or through a medium, such as an Free Space Absorber (Specular Absorber)

Frequency – The number of cycles per second of an electromagnetic wave. Units: Hertz (Hz) 1-cycle. KiloHertz (1000 cycles), Meg- aHertz (10^6 cycles), GigaHertz (10^9 cycles)

H field – the magnetic field

Impedance – The ratio of electric to magnetic field (E/H)

Inductance – The ability of an inductor to store magnetic energy

Insertion Loss – The reduction in energy emitted from point A to reach point B caused by the introduction (insertion) of an absorber material between the 2 points

Interface reflection coefficient – Reflection coefficient calculated from a single material interface

Isotropic/anisotropic – Isotropic materials have uniform electromagnetic properties independent of the electric and magnetic field direction. Anisotropic materials have electromagnetic properties dependent on the field direction

j=the square root of –1. Often used in exponential to exploit the fact that $e^{j\theta} = \cos\theta + j\sin\theta$

Layer reflection coefficient – Reflection coefficient of a single layer of material

Loads/Terminations – Lossy slug of material which is used to terminate energy propagation in a waveguide or coxial line with mini- mum impedance discontinuity

Loss tangent – The loss tangent is a parameter of a dielectric material that quantifies its inherent dissipation of electromagnetic energy. The term refers to the angle in a complex plane between the resistive (lossy) component of an electromagnetic field and its reactive (lossless) component

Lossy – The ability of a material to attenuate or absorb energy. Based on either the dielectric or magnetic properties of the material.

Maxwell's equations – A set of partial differential equations first published by James Clerk Maxwell in 1862 which form the foundation of classical electromagnetics

Microwave – Common usage of electromagnetic waves that refers to the frequency range of 700 MHz to 40 GHz in the electromagnetic spectrum.

Millimeter wave – A portion of the electromagnetic spectrum with varying definitions but generally covering the frequency band from 18-100 GHz (wavelengths~3-17 mm)

Near field – The near field is defined as the region very close to a radiating element (commonly < 1 wavelength) where the relation- ship between the electric and magnetic fields are complex with strong inductive and capacitive effects from the antenna elements

Network analyzer – Device used for measuring the reflection and transmission frequency response of microwave networks

NRL Arch – Is the standard system for measurement of reflection properties of absorber at high frequencies. It involves bouncing microwaves from a metal plate and determining reflection properties by alternately covering and uncovering the metal plate with the absorber piece under test. The difference in signal level between these two conditions indicates the absorption capability of that absorber.

Parameters – The permittivity and permeability of a material as a function of frequency

Permeability – measure of material's effect on the magnetic field. Related to inductance. Generally written as $\mu^* = \mu' - j\mu''$

Permittivity – measure of material's effect on the electric field. Related to capacitance. Generally written as $\varepsilon^* = \varepsilon' - j\varepsilon''$

Plane Wave – Propagating electromagnetic waves that are equal in magnetic and electric energy. In the far field, all waves propagate as plane waves

Polarization – The orientation of the electric field of the radiation. Radiation transmitted from a dipole antenna has its electric field parallel to the antenna. The wave travels in a direction perpendicular to the antenna. The electric field of the radiation being transferred is perpendicular to the widest dimension of the rectangle.

Radar Cross Section – Refers to the level of signal reflected from the radar target. The term RCS pattern refers to the manner in which a specific target at a specific frequency varies in reflective signal level as the target is rotated.

Reflection Coefficient – The ratio of reflected to incident energy

Reflectivity – The portion of incident energy which is reflected from a surface. A flat metal surface reflects all incident radiation. Measured in dB which is a logarithmic measure of the portion of energy reflected as compared to that reflected from a flat metal plate of the same area. A metal plate has a reflectivity of 0 dB down. A material which reflects half of the incident energy is 3 dB down or has a reflectivity of -3 dB. A material which reflects one tenth of the incident energy has a reflectivity of -10 dB. For flat sheet absorbers, 20 dB down is generally the best possible and desired performance

RF – Radio Frequency **–** frequency of radio waves, commonly 3 kHz-300 GHz

Salisbury Screen – Maybe the first ever anti-reflective concept RAM (radar absorbent material). The most easy to understand salisbury screen design consists of a ground plane which is the metallic surface that needs to be concealled, a lossless dielectric of a given thickness (a quarter of the wavelength that will be absorbed) and a thin lossy screen

Sidelobes – side lobes are the lobes of the far field radiation pattern of an antenna that are not the main beam

Standing Wave – If a wave continuously impinges on a surface (CW or continuous wave) a situation often occurs where the voltage at any given point between the transmitter and receiver is constant. This phenomenon is used to determine dielectric and magnetic properties of materials at radar frequencies.

Surface Currents – Traveling and creeping waves which contribute to RCS of an object. Also can contribute to RFI in a micro- wave module.

VSWR – Voltage Standing Wave Ratio **–** The ratio of maximum to minimum of voltage over a single cycle of field variation. Refers to the fact that, with reflections present, fields are periodic, i.e. they vary as a sine wave in intensity. The greater the level of reflection, the greater the so called VSWR (the greater the ratio of maximum to minimum over a single cycle of field variation).

Waveguide – Is a rectangular metal tube used to carry microwave energy with little loss of power. The electric field of the radiation being transferred is perpendicular to the widest dimension of the rectangle. A wave guide is useful over a narrow frequency range.

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