# 1: Introduction

## 1.1 INTRODUCTION

Engineered planar structures for microwave frequencies find several applications in civil, commercial and defence sectors. Microwave absorbers exploit these planar structures to achieve large bandwidth and high absorption, by using fundamental interaction mechanism between microwave and matter. To begin with, a review of the fundamental aspects of EM waves for designing and realizing high-performance microwave absorbers is presented here.

EM waves are time-varying oscillations of electric and magnetic fields, characterized by wavelength, frequency and energy. The properties of EM waves at the macroscopic level are described by Maxwell's equations. Maxwell equations are a collection of Gauss's law for electric and magnetic fields, Ampére-Maxwell law and Faraday's law. The differential and integral forms of Maxwell equations for time-varying electric and magnetic fields are listed in Table 1- 1.

**Table 1- 1:** Maxwell Equations: Differential and Integral forms

| Equation | Differential form | Integral form | Remarks |
|---|---|---|---|
| *Faraday's law* | $\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$ | $\oint \bar{E}\cdot d\bar{l} = -\frac{d}{dt}\iint \bar{B}\cdot d\bar{s}$ | E=electric field (V/m)<br>D=electric flux density (Coul/m$^2$)<br>H=magnetic field (A/m).<br>B= magnetic flux density (Wb/m$^2$)<br>J=electric current density (A/m$^2$)<br>$\rho$= charge density (Coul/m$^3$) |
| *Ampére-Maxwell law* | $\nabla \times \bar{H} = \frac{\partial \bar{D}}{\partial t} + \bar{J}$ | $\oint \bar{H}\cdot d\bar{l} = \iint \left(\bar{J} + \frac{\partial \bar{D}}{\partial t}\right)\cdot d\bar{s}$ | |
| *Gauss law for electric field* | $\nabla\cdot\bar{D} = \rho$ | $\iint \bar{D}\cdot d\bar{s} = \iiint \rho dv$ | |
| *Gauss law for magnetic field* | $\nabla\cdot\bar{B} = 0$ | $\iint \bar{B}\cdot d\bar{s} = 0$ | |

Faraday's law describes that time-varying magnetic fields induce electric fields. Ampére-Maxwell law is interpreted as the time-varying electric fields produce the magnetic fields. The current density in Ampére-Maxwell law ensures the continuity relation. The Gauss law for electric field describes the total electric flux is equal to charge density which tells the existence of electric charges in isolation. The vanishing divergence of Gauss law for magnetic field does not necessarily imply the magnetic field lines are closed loops. The field is strictly solenoidal, and the field lines have no starting and final points (i.e. no isolated magnetic charge exist), but closed loops is only a particular case of this kind of field lines.

Maxwell equations can be solved to calculate electric and magnetic fields in any material using Helmholtz Theorem [Simon Ramo, 2007]. There are several commercial EM solvers viz. CST (Computer Simulation Technology), FEKO (German Acronym "FEldberechnung für Körper mit beliebiger Oberfläche", which can be translated as "field calculations involving bodies of arbitrary shape".), HFSS (High-frequency Structure Simulator) owing to advancement in computing and data storage facilities. Maxwell equations are solved for appropriate boundary conditions to compute the EM quantities [Pozar, 2005].

EM waves find several applications using a particular frequency band. Classification of EM waves into frequency bands is termed as EM spectrum, as shown in Table 1-2. The EM

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spectrum, in descending order of wavelength, is shown Table 1-2 along with generation techniques.

**Table 1-2**: Electromagnetic Spectrum: Types, wavelength range and generation techniques [NCERT, 2016]

| Type | Wavelength range | Production |
|---|---|---|
| Radio | >0.1m | Rapid acceleration and deceleration of electrons |
| Microwave | 0.1m to 1m | Klystron valve of magnetron |
| Infrared | 1mm to 700 nm | Vibration of atoms and molecules |
| Visible light | 700 nm to 400 nm | electrons in atoms emit light when they move from higher energy level to lower energy level |
| Ultra Violet | 400nm to 1nm | Inner shell electrons in atoms moving from higher energy level to lower energy level |
| X-rays | 1nm to $10^{-3}$nm | X-ray tubes or inner shell electrons |
| Gamma rays | <$10^{-3}$nm | Radioactive decay of the nucleus |

## 1.2 CHARACTERISTICS OF MICROWAVES

Microwaves are the EM waves in the frequency range, 300 MHz to 300 GHz ($\lambda \sim$ 1m to 1 mm). Considering the large range number of applications, the microwaves are further designated to different bands. The approximate band designations for microwave frequencies are tabulated in Table 1- 3 [Pozar, 2005].

**Table 1- 3:** Microwave and RF Spectrum [Pozar, 2005]

| Nomenclature | Frequency Range |
|---|---|
| Very Low Frequency | 3kHz to 30kHz |
| Low Frequency | 30kHz to 300kHz |
| Medium Frequency | 300kHz to 3 MHz |
| HF | 3 MHz to 30 MHz |
| VHF | 30 MHz to 300 MHz |
| UHF | 300 MHz to 3 GHz |
| L-Band | 1-2 GHz |
| S-Band | 2-4 GHz |
| C-Band | 4-8 GHz |
| X-Band | 8-12 GHz |
| Ku-Band | 12-18 GHz |
| K-Band | 18-26 GHz |
| Ka-Band | 26-40 GHz |
| U-Band | 40-60 GHz |
| V-Band | 50-75 GHz |
| E-Band | 60-90 GHz |
| W-Band | 75-110 GHz |
| F-Band | 90-140 GHz |

## 1.3 APPLICATIONS OF MICROWAVES

Owing to high frequency and short wavelength, the microwaves show unique qualities in comparison to other EM waves [Gupta, 2011]. The important applications of microwaves are outlined as: -

***Communication Systems*****:** Microwaves are widely used in satellite communications, mobile phones, broadcasting and television systems, WAN, Wi-Fi etc. [Gupta, 2011], [Pozar, 2005] owing to the development of high directivity antenna, large bandwidth and no bending by the ionosphere. Considering these unique features, microwaves are utilized for very fast computing operations with the pulse width of the order of nanoseconds [Gupta, 2011].

Additionally, they are used for radio astronomy to study the EM waves generated from astronomical objects [Pozar, 2005].

***Radar Systems*:** Radars is used for detecting and navigating the objects, particularly aircraft, at ranges where other means of detection and navigation are not possible. Radar system constitutes the majority of microwave equipment. There are different types of radar systems as per their applications viz. early warning radars, missile tracking radars, missile guidance radars, fire control radars, weather detection radars, air traffic control radars and speed control radars for automobiles [Gupta, 2011], [Pozar, 2005].

***Remote sensing*:** The reflected and transmitted EM energy is measured in the form of digital images or spectral signatures for feature extraction and change detection [Jensen, 2013]. Microwaves experience the least attenuation in the atmospheric windows. Microwaves are used for remote sensing applications for change detection and feature extraction [Bhattacharya, 2013].

***Material Characterization*:** At microwave frequency, the rotational transitions take place in molecules. The resonance spectra at microwave frequencies provide useful information regarding the molecular structure and intermolecular energies. Microwave engineering is a powerful tool to study material properties and characterization [A. M. Nicolson, 1970].

***Dielectric heating*:** When a dielectric material is exposed to microwave, dipoles of dielectric material attempt to align with the incident electric field, which is termed as dielectric heating. The dielectric heating effect of the microwaves is used in a microwave oven for cooking purpose for water-rich food. The other applications of microwave heating are in the microwave diathermy machines which used for heating of muscles without heating of tissues and the microwave drying machines for printing, textile and paper industries [Gupta, 2011].

## 1.4 MICROWAVE ABSORBERS

Microwave absorbers are essential to address some of the unwanted effects associated with microwaves viz. cross-talks between the circuit components, Electromagnetic Interference (EMI) [Gupta, 2011], health hazards due to dielectric heating effect [Banik *et al.*, 2003], [Singh *et al.*, 1994] etc.

Microwave absorbers play an important role in microwave measurements, which are carried out in anechoic chambers. These chambers consist of microwave absorbers to minimize the spurious reflections and the health risk by absorbing the unwanted radiations [Emerson, 1973]. These chambers are used for antenna characterization, impedance calculation, co- and cross-polarization measurement and material characterization[A. M. Nicolson, 1970].

Microwave absorbers are required to minimize the Radar Cross-section of the military targets [E.F. Knott, 2004]. In this context, the radar equations as listed in Table 1- 4, which describe that the reflected power primarily depends on the RCS of the target by keeping the other parameters unchanged. Hence, by minimizing the RCS, the reflected power can be minimized.

**Table 1- 4**: Radar and range equations [E.F. Knott, 2004]

| | | |
|---|---|---|
| Radar equation | $P_r = \frac{P_t G_t G_r \sigma_{RCS} \lambda^2}{(4\pi)^3 R^4}$ | $P_t$=Transmitted power<br>$P_r$= Reflected power<br>$G_t$=Gain of reflected antennas<br>$G_r$=Gain of transmitted antennas<br>$\sigma_{RCS}$=Radar Cross Section<br>λ= Wavelength<br>R=Range |
| Range | $R = \left(\frac{P_t G_t G_r \sigma_{RCS} \lambda^2}{(4\pi)^3 P_r}\right)^{1/4}$ | |

Table 1- 5 shows the range advantage in terms of RCS reduction. For example, R is the range of detection for a given RCS. A 10 dB reduction in RCS results in 0.56R, a new range of detection.

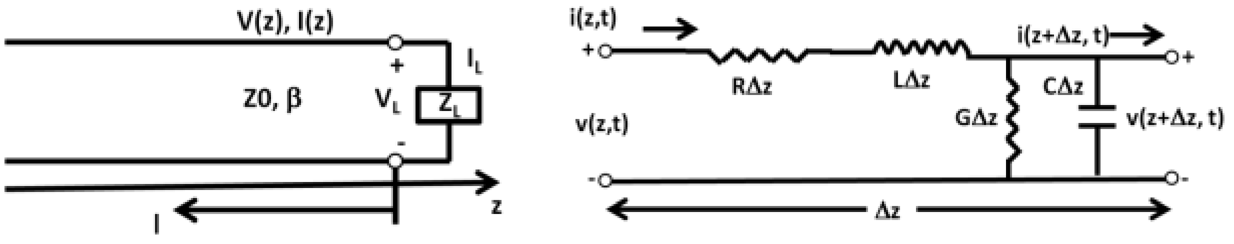
**Table 1- 5:** RCS reduction in dB with percentage absorption and associated range advantage

| **RCS reduction** | **Absorption** | **Range reduction** |
|---|---|---|
| 10 dB | 90 % | 0.56R |
| 15 dB | 97% | 0.42R |
| 20 dB | 99% | 0.32R |
| 25 dB | 99.7 % | 0.24R |
| 30dB | 99.9% | 0.18R |

## 1.5 TRANSMISSION LINE MODEL

At the microwave frequencies, wavelength ranges from 1mm to 1m, which is comparable to the size of circuit components. Consequently, the phase of circuit parameters (voltage, current, power) varies over the length of circuit components. Thus Kirchhoff's circuit laws for current and voltage cannot be applied at microwave frequencies [Gupta, 2011]. At microwave frequencies, transmission line (TL) can be approximated as a distributed circuit [Pozar, 2005]. In distributed circuit approximation, the circuit quantities, viz. resistance, inductance, capacitance and conductance, are represented as per unit length quantities to account for the change in magnitude and phase over the dimension of the circuit components [Gupta, 2011].

The schematic of the two-wire TL is depicted in Figure 1-1(a) along with the distributed circuit approximation in Figure 1-1(b). The TL is represented as the combination of lumped circuit elements of infinitesimal length, $\Delta z \ll \lambda$ [Pozar, 2005].



(a)

(b)

**Figure 1-1:**(a) Transmission line with load (ZL), (b) Schematic of Transmission Line with circuit quantities [*Source*: Pozar, 2005]

As shown in Figure 1-1(b), circuit elements are R: series resistance per unit length (Ω/m), L: inductance per unit length (H/m), C: shunt capacitance per length (F/m), and G: conductance per length S/m.

Kirchhoff's laws can be applied to the distributed circuit representation of transmission line to obtain important equations associated with TL as listed in Table 1- 6 From telegrapher's equation, the circuit quantities are coupled because of the high frequency of microwaves. The algebraic manipulation of the telegraph equation leads to wave equation as listed in Table 1- 6. In microwave circuit analysis, the voltage and current are treated as a wave quantities. The microwave measurements are concerned with voltage and current phasors for the incident, reflected and transmitted waves [Gupta, 2011]. The wave propagation is characterized by complex propagation constant and wave impedance. The reflection coefficient of the reflected wave depends on load impendence and free space impedance as Table 1- 6 and Figure 1-1(a)

**Table 1- 6:**Transmission line: summary of equations [Pozar, 2005]

| | |
|---|---|
| Telegrapher's equation | $\frac{dV(z)}{dt} = -(R + j\omega L)I(z), \frac{dI(z)}{dt} = -(G + j\omega C)V(z)$ |
| Transmission line wave equation | $\frac{d^2V(z)}{dt^2} - \gamma^2 V(z) = 0, \frac{d^2I(z)}{dt^2} - \gamma^2 I(z) = 0$ |
| Complex propagation constant | $\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$<br>$\alpha$=attenuation constant, $\beta$=phase constant |
| Characteristic impedance | $Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$ |
| Reflection Coefficient ($\mathit{\Gamma}$) | $\mathit{\Gamma} = \frac{Z_L - Z_0}{Z_L + Z_0}$<br>$Z_0$=free space impedance, $Z_L$=load impedance |
| Return Loss (RL) | $RL = 20\log(\lvert\mathit{\Gamma}\rvert)$ |
| Transmission line impedance equation | $Z = Z_0 \frac{Z_L + jZ_0 tan\beta l}{Z_0 + jZ_L tan\beta l}$ |
| Impedance for short circuit | $Z = jZ_0 tan\beta l$ |
| Reflection, transmission and absorbance | R+A+T=1 |

For ideal absorbers, there is no reflection and transmission. Since the microwave absorbers are metal-backed [Alici *et al.*, 2010], [Li *et al.*, 2011], there is no transmission. Therefore, while designing meta-backed microwave absorbers, the primary requirement is to minimize the reflection [Gu *et al.*, 2010]. For example, when the load impedance is close to the free space impedance, there is a minimum reflection. This is called impedance matching condition. Load impedance is determined by the dimension of the circuit components, medium parameters and free space impedance [Knott *et al.* 2004]. The metal-backed absorber forms a short circuit TL, and its impedance is tuned by changing the length of TL [Pozar, 2005]. For example, a quarter-wave impedance transformer will transform metal-backed TL (short) into open TL to minimize the reflection [Watts *et al.*, 2012].

## 1.6 MATERIAL PARAMETERS (ε-μ)

Material parameters relate field quantities through constitutive relations: $\bar{D} = \epsilon\bar{E}$ relate electric field strength to displacement field, whereas $\bar{B} = \mu\bar{H}$ relates magnetic field density to the magnetizing field. Where ε and μ are permittivity and permeability respectively. The free space permittivity and permeability are referred as $\varepsilon_o$ and $\mu_o$ with values $8.85\times10^{-12}$

F/m and 4π×10$^{-7}$ H/m respectively. The phase velocity of the EM wave is given by $v = \frac{1}{\sqrt{\varepsilon\mu}}$, which is 3×10$^{8}$ m/sec for free space. The wave impedance is expressed as $\eta = \sqrt{\frac{\mu}{\varepsilon}}$, which is 120π Ω or 377 Ω for free space. The energy carried by EM waves is described by the Poynting vector, $\bar{S} = \bar{E} \times \bar{H}^*$.

All materials, natural and artificial, can be classified according to the four quadrants as presented in Figure 1- 2. Most of the naturally occurring materials take place in the first quadrant (Double Positive (DPS) viz. ε>0 & μ>0). There are only a few materials viz. metals and doped semiconductor below plasma frequency, which lies in the second quadrant (Epsilon Negative (ENG) viz. ε<0 &μ>0). Similarly, few magnetic materials viz. ferrites at GHz frequency region lies in the fourth quadrant (Mu Negative (MNG) viz. ε>0 & μ<0). Further, there is no naturally occurring material lies in the third quadrant which classifies as Double negative (DNG) with ε<0 & μ<0. It is possible to tailor the effective constitutive parameters by designing suitable structural patterns of naturally occurring materials, also called metamaterials.

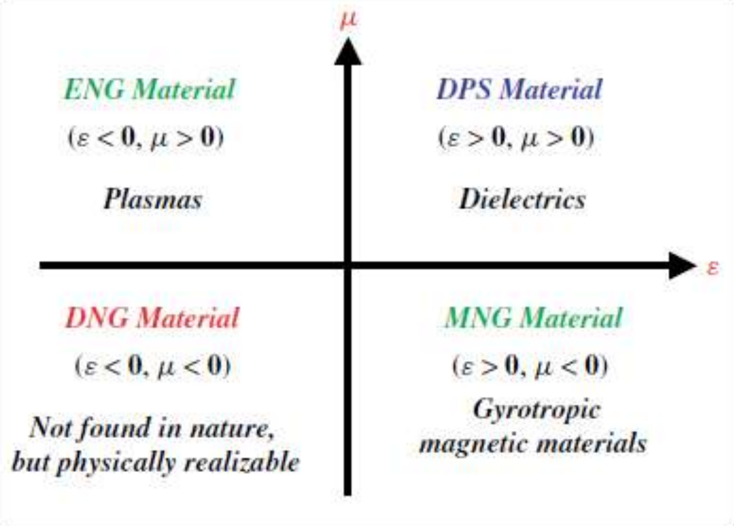


**Figure 1- 2:** Material classifications based on constitutive parameters (*Source*: Engheta and Ziolkowski, 2006)

## 1.7 ENGINEERED PLANAR STRUCTURES (EPS)

Material constitutive parameters play an essential role in designing and realizing perfect absorbers. Russian physicist Victor Veselago presented the theoretical aspects of material with simultaneously negative ε and μ [Veselago, 1968]. It took almost 40 years to design and physically realize the materials with negative permittivity, permeability and refractive index [Pendry *et al.*, 1996], [Pendry *et al.*, 1998], [Pendry *et al.*, 1999] [Smith et al., 2000]. Later, these materials were termed as Metamaterials, i.e. materials with unusual properties viz. high values of ε and μ, negative ε, negative μ and both (μ, ε) negative. Figure 1-3 shows the Physical realization of negative ε through engineered thin conducting wires [Engheta and Ziolkowski, 2006].

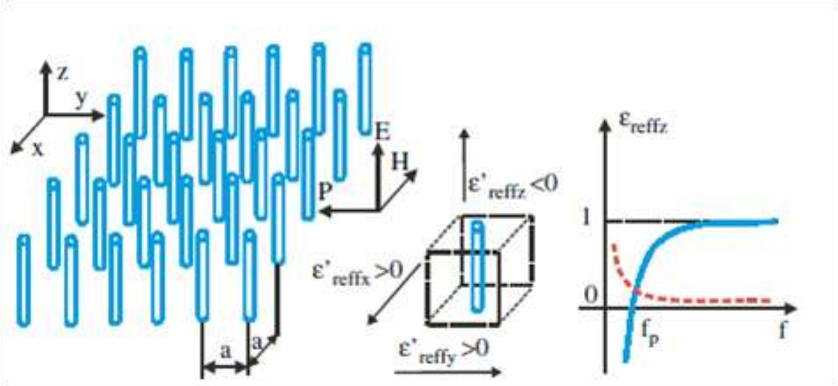


**Figure 1-3:** Physical realization of negative ε: thin conducting wires (*Source*: Engheta and Ziolkowski, 2006)

Figure 1-4 shows the Physical realization of negative μ through engineered Split Ring Resonator (SRR) [Engheta and Ziolkowski, 2006]

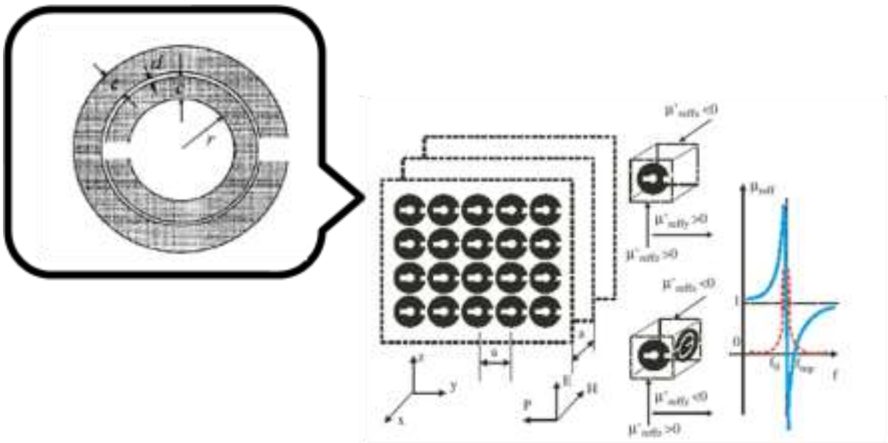


**Figure 1-4:** Physical realization of negative μ: Split Ring Resonator (SRR) (*Source*: Engheta and Ziolkowski, 2006)

The metamaterials are periodic subwavelength engineered planar structures. They are physically metal-backed as metallic engineered planar structures printed on the dielectric substrate. Owing to unusual properties of metamaterials, they find a wide range of applications in superlens, detectors, antennas and cloaking devices [Fang *et al.*, 2005], [Pendry, 2000] [Tao *et al.*, 2011], [Shrekenhamer *et al.*, 2012], [Li and Pendry, 2008] [Shin *et al.*, 2012].

## 1.8 THESIS STRUCTURE

This thesis is organized as follows. The first chapter highlights the significance and applications of microwaves. The basic theory is revisited and engineered planar structures are described. They can be used for tuning the material parameters to design microwave absorbers. The objective of the thesis is to design, simulate and fabricate the bandwidth-enhanced microwave absorbers using engineered planar structures. The accomplished work is discussed in seven chapters.

Chapter 2 highlights the literature review and the motivation for the thesis work. The literature review covers the different classes of reported state of the art microwave absorbers along with their limitations. The methodologies for bandwidth enhancement based on engineered planar structures are covered.

Chapter 3 presents the bandwidth enhancement techniques by using engineered wire-based absorbers in terms of Multiband (Single/Dual/Triple) and overlapping of multiband reflections minima. The chapter also introduced the use of dielectric cap layer to enhance the bandwidth of wire-based absorber.

Chapter 4 presents the technique for bandwidth enhancement of material based absorbers using square patches. Based on design parameters, the absorbers are synthesized and characterized. These designed showed single band with a large bandwidth of the order of 8 GHz.

Chapter 5 describes the bandwidth enhancement of Salisbury Screen microwave absorbers using engineered planar square patch and wire elements. The parametric analysis and field quantities are numerically evaluated to present the physical insight of the absorbers.

Chapter 6 deals the design methodology for bandwidth enhancement of Triple-layer Microwave Absorbers using the metallic engineered planar square patch. The absorber is physically realized and characterized for varying aspect angles for practical applications.

Chapter 7 summarizes the thesis work. The chapter describes the future work along with the challenges regarding the realization of the absorbers based on engineered planar structures.

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