國立臺灣大學物理學研究所
碩士論文
Graduate Institute of Physics
College of Science
National Taiwan University
Master Thesis

高頻微波吸波器材之研究

Study of High-frequency Microwave Absorbers

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中華民國 102 年 6 月
June, 2013

誌謝

在這短短兩年中，能接受嚴謹的科學訓練、學習到如何作學術研究、以及清楚簡潔的表達研究結果，這都要感謝我的指導教授−朱國瑞教授，朱老師的用心指導與啟發，讓我在微波領域能深入的學習與了解；老師也常常提醒我作研究要「處處用心思，細節全掌握」，對研究結果要做到「驗證、理解、判斷」等作研究的好習慣，使我有充實的碩士研究生涯；而這篇論文的完成，也為此畫下了一個完美的句號。

同時也要感謝實驗室成員在這兩年的幫助，首先感謝姜惟元學長和吳光磊學長在 Wave absorber 實驗和學習 HFSS 模擬軟體的幫忙及指導，讓我可以順利的完成這篇論文；感謝張培哲學長和李冠德學長在研究與課業上的討論，特別是 UCDavis gyrotron cavity 的計算研究，讓我獲益良多；也謝謝張舜喬學長及周劭祁同學，在 Open cavity 與 ECM 這兩個練習上的討論，以及其他同學與學弟們，很高興能夠與你們一起學習。

最後，我要感謝我的父母，有你們的支持與鼓勵，讓我更有信心與毅力完成學業，在此僅將本論文獻給你們，謝謝!

中文摘要

因應高頻微波或毫米波實驗的需要，這篇論文提出了吸收高頻電磁波的方法。材料的物理性質與入射波的頻率皆會影響反射係數(reflection coefficient)與肌膚深度(skin depth)，因此可以從這兩個參數中找出適合吸收高頻電磁波的吸波材料。以往的吸波材料多半是介電質材料，雖然介電質吸收電磁波的效果很好，但是提高頻率會使的所需要的吸波材料厚度增加，如此的高頻吸波裝置會不易製造及使用。然而，在這篇論文中，我們改以導電性損耗材料(conductive lossy material)作為吸波材料，對應高頻微波其肌膚深度小於 1 ㎜，因此只需要塗上一薄層，就可以有效地吸收高頻率的電磁波。

為了驗證這個現象我們做了微波吸波器的模擬與量測實驗；將微波吸波器放置於 Ka-band 的波導管中去計算電磁波的反射損失(return loss)，使用的頻率是 26.5 到 40 GHz，由此了解電導性損耗材料吸波器的吸波效果，並且將透過網路分析儀量測到的結果與之比較。

關鍵字:電容率、導電性損耗材料、肌膚深度、吸波材料、微波吸波器

Abstract

Wave absorbers are widely used to attenuate and absorb the unwanted reflected waves creating a no-reflecting environment in anechoic chamber. The researches on wave absorbers for frequency below 20 GHz are extensively presented in many papers. For higher frequency, this thesis reports an applicable way to absorb the high-frequency electromagnetic waves by conductivity lossy materials and a simulation study of microwave absorbers settled in Ka-band waveguide, the recommended frequency of which is between 26.5 and 40 GHz.

In the beginning of this thesis, we present the theoretical calculation on reflection coefficients and skin depth characterized by complex permittivity of materials and the frequency of applied waves. These parameters have great help for finding the proper absorbing material for high-frequency microwave absorbers. The electromagnetic wave interactions with dielectric and electrical conductive materials are also discussed. In the second part, two types of wave absorber, wedge-shaped and pyramidal absorbers are addressed to compare their competence in absorbing electromagnetic waves. Simulation and measurement results presented in chapter 4 and 5 indicate that the shape has a great impact on the reflection and absorption performance of a wave absorber, and that, more significantly, microwave absorbers with conductivity lossy materials can effectively absorb the power in high-frequency EM waves.

Key words: complex permittivity, conductivity lossy material, skin depth, wave absorbing material, microwave absorber

Contents

List of Figures

Chapter 1

Introduction

Electromagnetic wave (or electromagnetic radiation) is a type of energy carried by the electric and magnetic field and exists everywhere in the world. It can propagate with or without medium and travels at the speed of light in the vacuum. In 1865, electromagnetic wave first is postulated by James Maxwell with the renowned electromagnetic wave equations and then substantiated by Heinrich Hertz's discovery of radio waves. From then on motivated by numerous application needs for electromagnetism, massive resources and money have been investigated in the associated research and development, especially during World War II. Figure 1 is the electromagnetic wave spectrum. Based on the wavelength, electromagnetic wave is classified into radio wave, microwave, infrared, visible light, ultraviolet, X-rays and gamma rays.

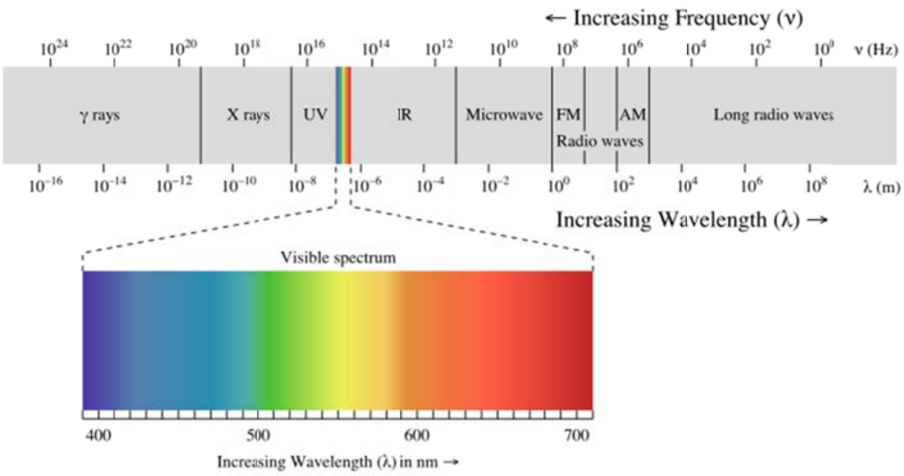


Figure 1.1 The electromagnetic spectrum.

In the first half of the 20th century the development and research efforts of electromagnetic wave have been directed toward meet the requirement for military, such as detective system, warning system, directed energy weapons. Radar, for example, the abbreviation of "Radar Detection and Ranging", is a system using radio waves to detect objects and secretly developed by many countries for wars. Subsequently the higher frequencies, microwaves, are applied to radar for higher directivity and higher resolution [1]. The development of microwave highly influences and improves the performance of radar [2].

The selection of frequency for applications of radar is just based on the reflection, transmission and absorption effects of electromagnetic waves. Not all electromagnetic spectrums can penetrate atmosphere to the surface of the earth. Figure 2 shows that radio waves and the lower-frequency microwaves can transmit through Earth's atmosphere but some spectrum are absorbed totally and other are absorbed partially, such as visible light. Also, radio waves and medium length microwaves can penetrate clouds, dust, smoke, snow, and rain so that they are suitable to be used near the ground.

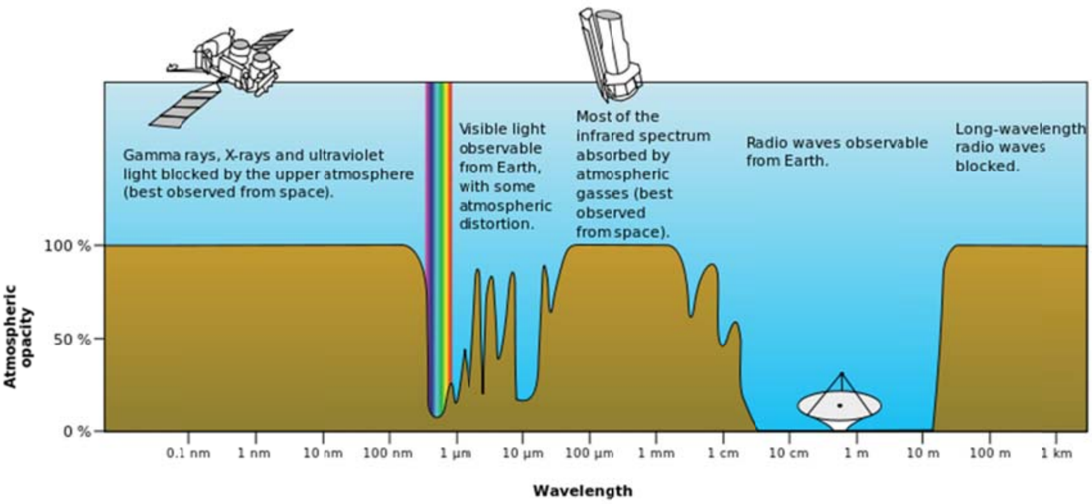


Figure 1.2 Earth's atmospheric transmittance to various wavelengths of electromagnetic radiation [3].

Dielectric heating is also a major application of electromagnetic waves. The common sub-categories of dielectric heating like electronic heating, radio frequency heating and microwave heating are the process in which a high-frequency alternating electric fields heats dielectric materials. Because waves can get into dielectrics with a depth larger considerably than a conductor, the molecule dipoles within them rotate rapidly with the electric field, which causes friction and heat. The use of high-frequency electromagnetic waves for heating dielectric materials had been proposed in 1930s. For example, Bell Telephone Laboratory tendered "*Method and apparatus for heating dielectric materials*" in 1939 [4]. A lot of electromagnetic wave equipments and inventions largely apply the reflection and absorption effects of waves. Hence, we will investigate comprehensively these effects in this thesis.

Moreover, many theories and technologies are as well devised or invented in this duration and are still in use today, such as satellite communication, television, microwave oven, and telecommunication. After World War II most applications of microwave which are military originally expanded to industries and general use, such as speed measurements, sensor, controller and data transformation as well as to medical applications, like disease sensing, RF surgery (diathermy) and clinical treatments.

In this paper, we put our focus mainly on the microwave band. Microwave have frequencies with 300 GHz to as low as 0.3 GHz and corresponding wavelengths with 1 mm to 1 m in free space, which is shorter than radio waves as its name. The establishment of microwave spectrum is specified by the dimensions of corresponding waveguide. It is arduous to fabricate very tiny waveguides for frequencies more than 300 GHz. On the other side, for the lower-frequency microwaves the applicable waveguides are too ponderous to move. Therefore it is appropriate to specify microwave frequencies at this range. The development and applications of microwave technology for several areas can be reviewed in [5], which lists the important milestones in microwave fields over a period of approximately 100 years, up to 1980.

With the advancement of science the frequencies studied have come higher from radio waves to microwaves, millimeter waves and even over 1000 GHz, the terahertz radiation (1 THz), which is the wave with frequencies between far infrared and microwaves, so experiments on the high-frequency and high-power electromagnetic wave will receive more attention and interests. For this reason, we address and discuss the absorption performances of the wave absorber and anechoic chamber for high-frequency microwaves.

Wave behavior in materials and the derivation of generalized permittivity are reviewed in chapter 2, where the power loss mechanisms of electromagnetic waves in conductor and dielectric materials are also discussed, respectively. The reflection and transmission of a wave are dependent significantly of physical properties of substances. Chapter 3 examines the reflection and transmission coefficients of microwave emitted from free space to different media and shows the results of theoretical calculations. In chapter 4, the simulation results of wave absorbers calculated through High Frequency Structure Simulation (HFSS) codes are discussed. Finally, these will be compared with the experiment results presented in chapter 5.

Chapter 2

Plane Wave Propagation in Dielectrics and Conductors

Energy can be propagated in the form of electromagnetic wave in free space or through various substances. To fully understand the behaviors of electromagnetic wave in media, it is necessary to dissect the fundamental physical properties of these media. We arrange them into dielectrics and conductors in the discussion according to the main characteristics of electrons in them.

A conductor contains a lot of electric charges which can move easily when an electric field is applied. These free electrons dominate the conductive property of the conductor. Generally speaking, conductors are metallic but there are also many nonmetallic conductors, such as graphite, solution of salts and plasma. Graphite, particularly in microwave application, is usually mixed into alcohol to make wave absorbing material, which has excellent adhesion to metal, glass and plastic substrates. Moreover, other carbon materials, such as carbon fiber composites and flexible graphite, and carbon-containing compounds are also used for electromagnetic wave absorption [6, 7].

Unlike conductors, dielectrics have no free electron. The physical properties of dielectric materials are different from conductors and of course their interaction with electromagnetic wave is distinguishing, too. Lossy dielectric or high dielectric loss materials are the common absorbing materials because waves can penetrate them and are absorbed. The loss mechanism of dielectrics is explained at Sec. 2-2.

In electromagnetic analyses of materials, the most common and important parameters are permittivity (ε), permeability (μ), and conductivity (σ) or resistivity (ρ), which characterize the physical properties of substances. In this chapter, we first give a brief review of the derivation of the generalized permittivity for matters and then discuss the behavior of electromagnetic wave in dielectrics and conductors.

2.1 The Generalized Permittivity

For general matter, it can be assumed that there are *N* molecules per unit volume and *Z* electrons per molecule. The electrons in one molecule are divided into *j* groups, each of which has electron number f_j. The generalized permittivity can be expressed by the bound electrons and free electrons:

$$\varepsilon = \varepsilon_0 + \frac{Ne^2}{m} \sum_{j(\text{bound})} \frac{f_j}{\omega_j^2 - \omega^2 - i\omega\gamma_j} + i\frac{Ne^2 f_0}{m\omega(\gamma_0 - i\omega)} \tag{2.1}$$

where ω_j is the binding frequency and γ_j is the collision frequency, respectively. The constant ε_0 is known as the permittivity of free space. The second term in this equation is due to the bound electrons, while the imaginary component is the contribution of the free electrons accounting for the conductivity. Based on the model for electrical conductivity proposed by Drude in 1900,

$$\sigma = \frac{f_0 Ne^2}{m(\gamma_0 - i\omega)} \tag{2.2}$$

and Eq. (2.1) is also written as a concise type with real and imaginary part divided as

$$\varepsilon = \varepsilon' + i(\varepsilon'' + \frac{\sigma}{\omega}) \tag{2.3}$$

or

$$\varepsilon = \varepsilon_b' + i(\varepsilon_b'' + \frac{\sigma}{\omega}) \tag{2.4}$$

where the subscript "b" refers to the bound electron. The complex permittivity of materials plays a very powerful role on the electromagnetic wave reflection and absorption [8, 9], especially that of ferrite materials [10]. The real component of permittivity results in the dispersion and refraction, while the imaginary component counts for the lossy (absorption) factor of a matter, including the dielectric damping loss (ε_b'') and the conductivity loss (σ / ω). The physical properties of substances considerably depend on the behavior of electrons.

2.2 Plane Waves in a Dielectric Material and Loss Tangent

According to the lossy property of dielectric materials, there are the lossless and the lossy dielectrics. The loss tangent is a parameter for dielectric materials that quantifies the dissipation of electromagnetic energy.

Eq. (2.3) can be also expressed as

$$\begin{aligned} \varepsilon &= \varepsilon' + i(\varepsilon'' + \frac{\sigma}{\omega}) = \varepsilon'[1 + i(\frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'})] \\ &= \varepsilon'[1 + i\tan\delta] \end{aligned} \tag{2.5}$$

and

$$\tan\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \tag{2.6}$$

The loss tangent is the ratio of the imaginary component to the real component. For lossless materials, such as free space, since there is no power loss as waves travel in it and the loss tangent is zero, the permittivity only has the real part. Nevertheless, the lossy dielectric material has a complex permittivity, the imaginary part of which interprets the power loss in the medium. With the requirement of the energy conservation the imaginary component of permittivity must be minus. The complex permittivity of dielectrics is complicated and studied as the function of frequency and temperature, etc [11].

Because the permittivity of dielectrics has real and imaginary component, the wave number can be written as

$$k = \sqrt{\mu\varepsilon}\omega = \mathrm{Re}\sqrt{\mu\varepsilon}\omega + i\,\mathrm{Im}\sqrt{\mu\varepsilon}\omega \tag{2.7}$$

and we define it as

$$k = \beta + i\frac{\alpha}{2} \tag{2.8}$$

where the parameter $\beta = k_r$ is the phase constant and α is the power attenuation constant. Thus a plane wave can be expressed as

$$\overline{E} = E_0 e^{-i(kz+\omega t)} = E_0 e^{-\alpha z/2} e^{-i(\beta z+\omega t)} \tag{2.9}$$

The intensity of a wave depends on the imaginary part of wave number or the permittivity of material. In addition, from Eq. (2.7) we can know that waves travel at different speeds in various media.

Intrinsically, a lossy dielectric material is an electrical isolator or very poor conductor of electricity which can be polarized by an applied electric field. Figure 2.1 shows electric field interaction with an atom. When a dielectric is placed in an external electric field, its charge carriers tend not to drift through the material as they do in conductor since there is no loosely bound or free electron within dielectric materials, while only slightly shift from their average equilibrium positions. Positive charges are displaced toward the field and negative charges shift in the opposite direction as shown in figure 2.1(b), which result in the dielectric polarization. This dipole moment creates an internal electric field [Fig. 2.1(c)] which reduces the overall field within the dielectric itself [12]. The rotation of the dipole moment following the alternating field direction causes the thermal energy by friction, which is applied in the dielectric heating. Microwave oven works with 2.45 GHz microwaves to force water or other polar molecules in food to rotate and then heat the food.

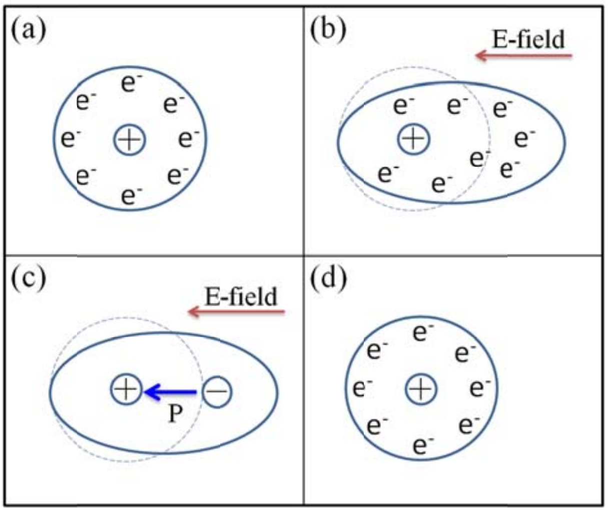


Figure 2.1 The interaction of electric fields and a basic atom

In addition to the well-known application to the capacitors as the intervening medium, dielectric materials are also applied in microwave engineering as wave absorbing materials. The anechoic chamber is usually designed with such dielectric absorbers on its wall and hence it can effectively reduce reflection and diffraction of electromagnetic waves to create a no-reflecting environment. More details on wave absorbers can be viewed in chapter 4.

2.3 The Condition for Good Conductors and Skin Depth

A conductive material allows the free electrons to flow easily from one atom to another when it is in an electric field. Free electrons dominate the electrical conductive property of a conductor. The contribution of free electrons to the permittivity is much larger and more important than that of bound electrons, i.e., $\sigma/\omega >> \mathrm{Im}(\varepsilon_b)$, so we may assume ε_b to be real.

$$\varepsilon = \varepsilon_b + i\frac{\sigma}{\omega} \tag{2.10}$$

A good conductor is defined by

$$\frac{\sigma}{\omega\varepsilon_b} >> 1 \tag{2.11}$$

The value, $\sigma/\omega\varepsilon_b$ of copper whose conductivity is 5.9×10^7 /(Ω-m) is greater than one for a widespread frequencies ranging from radio waves to X-ray. Clearly, copper is a good conductor. However, a substance can display distinguishing characteristics at different frequencies. For example, the conductivity of water fresh is about 0.01 /(Ω-m). From Eq. (2.11) water is a good electrical conductor for 60 Hz wave ($\sigma/\omega\varepsilon_b \approx 3\times10^6$) so this is the reason why it is dangerous to touch the socket with humid hand, while it is dielectric for 2.45 GHz microwave ($\sigma/\omega\varepsilon_b \approx 7.34\times10^{-2}$), which is the frequency used specifically on microwave oven.

The power of electromagnetic wave attenuates and diminishes to closely zero when wave penetrates a high conductivity medium with an extremely short distance. The distance is called the length of penetration or skin depth, which is denoted by δ. For a good conductor, we have

$$\sqrt{\varepsilon} = \left(\varepsilon_b + i\frac{\sigma}{\omega}\right)^{\frac{1}{2}} \approx \left(i\frac{\sigma}{\omega}\right)^{\frac{1}{2}} = \sqrt{\frac{\sigma}{2\omega}}(1+i) \tag{2.12}$$

and hence the wave number

$$k = \sqrt{\mu\varepsilon}\,\omega = \sqrt{\frac{\mu\sigma\omega}{2}}(1+i) = \frac{1+i}{\delta} \tag{2.13}$$

where

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \tag{2.14}$$

is skin depth, which is dependent of the conductivity (or resistivity) of substances and the frequency of incident wave.

Figure 2.2 illustrates that skin depth is as a function of the resistivity of media for microwave frequencies, 1, 10, 30 and 100 GHz. Take copper ($\rho=1.72\times10^{-8}$ Ω-m) for the reference. First, at the right part of this figure, the skin depth of copper at 30 GHz is about 6.61×10^{-6} m so the imaginary component of the wave number is very large [Eq. (2.13)], which means that the power in the wave falls immediately to zero when wave just pierces into the skin of copper. However, a wave can penetrate deeply into materials with high resistivity (dashed lines), so dielectrics can be uniformly heated everywhere inside.

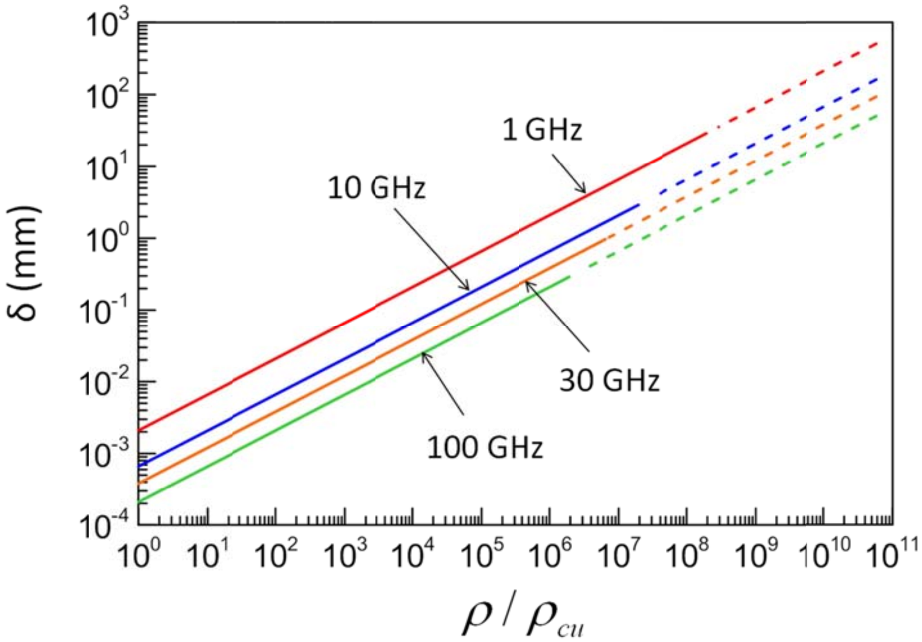


Figure 2.2 Skin depths (δ) of substances differentiated based on the value ($\sigma/\omega\varepsilon_b$) greater than 5 (solid line) and little than 5 (dashed line) are as the function of the resistivity of substances with that of copper as a reference for microwaves. Substances with the value ($\sigma/\omega\varepsilon_b$) greater than 5 are good conductors.

In terms of frequency, high frequency is less penetrative than lower frequency. Radio frequency dielectric heating at intermediate frequencies, due to its greater penetration over microwave heating, shows greater promise than microwave systems as a method of uniformly preparing certain food items, and also killing parasites and pests in certain harvested crops. But, the power absorbed is directly associated with the frequency, so high frequency heating can rapidly reach required temperature (this will be explained in chapter 4). The wavelengths of RF are far longer than the cavity used, and thus make use of near-field effects and not electromagnetic waves. However, modern heater like microwave oven makes use electromagnetic waves with electric fields of much higher frequency and shorter wavelength than RF heaters. Typical domestic microwave ovens operate at 2.45 GHz, present as far-field type EM radiation in small cavity system like what we use today.

By Eq. (2.13), electromagnetic waves in metals can be written as

$$\mathbf{E} = E_0 e^{ikz - i\omega t}\mathbf{e}_x = E_0 e^{-\frac{z}{\delta}} e^{i(\frac{z}{\delta} - \omega t)}\mathbf{e}_x \tag{2.15}$$

so the relationship between power and skin depth is

$$P \propto e^{-2z/\delta} \tag{2.16}$$

As indicated in Fig. 2.3, the power of wave depends on the displacement (z) in the metals. The "z" is normalized by skin depth, δ. After EM wave enters a conductor with two skin depth, the power reduces to only 1.8%.

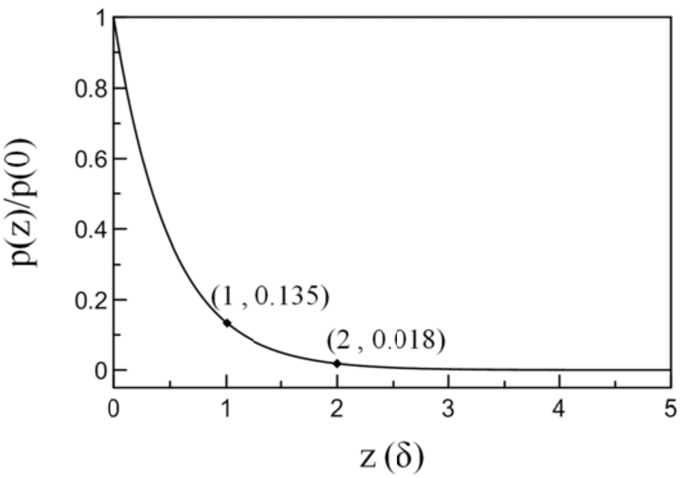


Figure 2.3 The power in a wave attenuates with the displacement (z) in the conductor. The displacement is normalized by skin depth (δ).

2.4 Frequency Dependent Behavior of Materials

In general, comparing with the collision frequency γ_0 of matter, we can separate the frequencies into two parts, low-frequency $(\omega << \gamma_0)$ and high-frequency $(\omega >> \gamma_0)$. For a good conductor like copper, its collision frequency is about 4×10^{13} s^{-1}. If $\omega << \gamma_0$, Eq. (2.2) will become to

$$\sigma = \frac{Ne^2 f_0}{m(\gamma_0 - i\omega)} \approx \frac{f_0 Ne^2}{m\gamma_0} = \sigma_{copper} = 5.8\times10^7 \tag{2.17}$$

We can neglect the effect of frequency, and then the conductivity of copper is a constant. However, for the broad frequency,

$$\sigma = \frac{Ne^2 f_0}{m(\gamma_0 - i\omega)} = \frac{Ne^2 f_0}{m\gamma_0(1 - i\frac{\omega}{\gamma_0})} = \frac{5.8\times10^7}{1 - i\frac{\omega}{4\times10^{13}}} \tag{2.18}$$

which has an important dependence on frequency. Therefore

$$\varepsilon = \varepsilon_0 + i\frac{\sigma}{\omega} = \varepsilon_0 + i\frac{5.8\times10^7}{\omega(1 - i\frac{\omega}{4\times10^{13}})} \tag{2.19}$$

The permittivity of copper divided to real part and imaginary part varies with frequency as shown in Fig. 2.4. The imaginary component has dominant influences at the low frequency region. However it is much smaller in magnitude than real component at high frequency region because in fact the real part is negative at frequencies over 2.6×10^{15} (Hz).

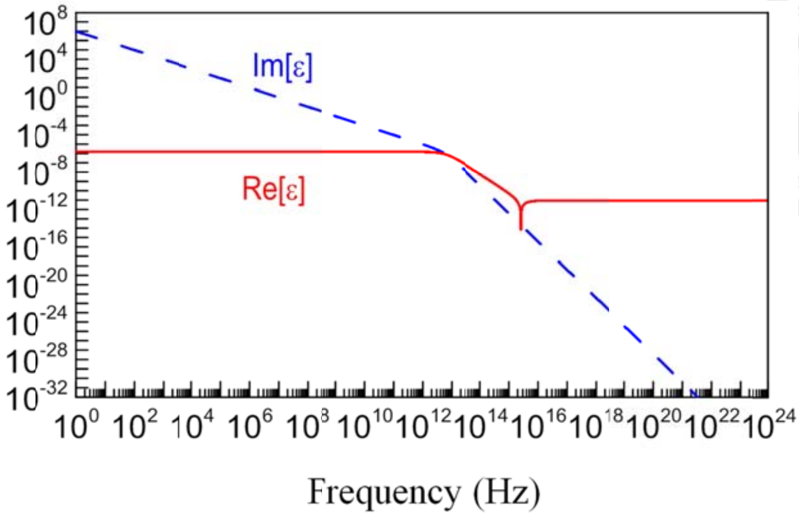


Figure 2.4 The real part (solid line) and imaginary part (dashed line) of permittivity of copper. The real part is negative at frequencies over 1.6×10^{15} Hz.

Substituting the real and imaginary parts into Eq. (2.7) then the wave number can be calculated and shown in Fig. 2.5.

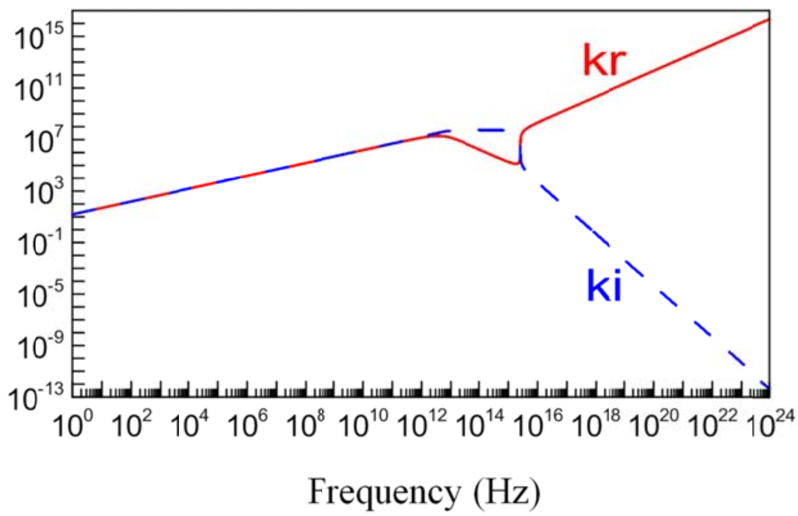


Figure 2.5 The real part (solid line) and imaginary part (dashed line) of wave number in copper.

The permittivity of a dielectric material is more complicated than that of a conductor. It involves some polarization mechanisms, including electronic, ionic, dipolar and interfacial polarizations which are strongly frequency dependent. The general frequency dependence of the different polarization mechanisms in dielectrics is shown in Fig. 2.6. The vibration of atoms and ions in dielectric materials is dependent on the thermal energy available and frequencies of these vibrations correspond to the infrared region of electromagnetic spectrum. Since electronic and ionic polarization as the two small peaks shown in solid lines occur in the visible and infrared frequencies, they are able to polarize almost in phase with the alternating electromagnetic field and do not generally contribute to microwave absorption. Molecules with permanent dipolar moments, such as water, may have considerable mass and, therefore, orientation polarization typically takes place near radio frequencies and microwaves [13].

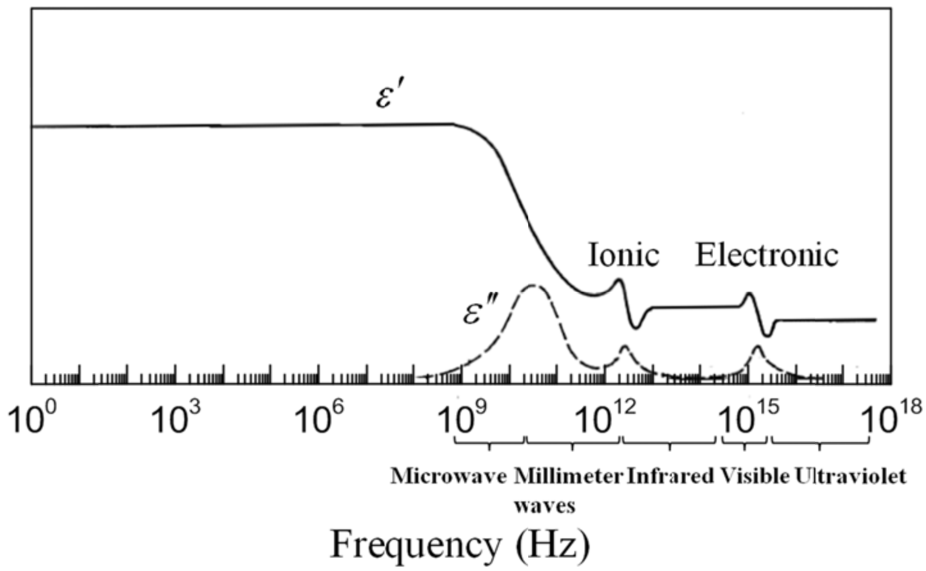


Figure 2.6 Frequency dependence of real (solid lines) and imaginary (dashed lines) parts of permittivity for a dielectric material and the contributions on power loss by the various polarization mechanisms [14].

2.5 Ferrite Materials

The ceramic-like materials, ferrites, can be classified according to the crystal configuration, the manufacturing process or the composition, for example, spinel Ni-Zn ferrite, spinel Mn-Zn ferrite, hexagonal barium ferrite, etc, or sintered ferrite, ferrite composition, soft ferrite and hard ferrite. A unique characteristic of ferrite material is that its dielectric constant is studied as a function of frequency, composition, (magnetic materials) loading and temperature [15]. Moreover, ferrites have the advantages, such as mold ability, high resistivity, lower price and greater heat resistance.

The soft ferrites are most often used as materials for ferrite wave absorbers. The typical ferrite wave absorber is a ferrite tile blacked with a conductive metal plate. Each ferrite has two matching frequencies, fm1 and fm2, and two matching thicknesses, tm1 and tm2, respectively. The former is attributable to ferrites' complex permeability. Therefore, if the frequency of the wave to be absorbed is specified, a particular ferrite material can be chosen to accomplish this absorption [16, 17]. Ferrite nanoparticles are also used as the component of radar-absorbing materials which coated in stealth aircraft to avoid being detected and also used for the electromagnetic compatibility measurement to diminish the reflected wave. After World War II, The use of microwave band increases annually and, hence, the requirement of the microwave absorbers are more and more for the development of the microwave technology. Many countries invest a large amount of time and resources to study the properties of ferrite materials and try to find the novel types. The historical development and the applications of ferrite materials have been reviewed in [18].

In addition to the utility for wave absorbing materials, ferrites are also characterized by their ferromagnetic. Since the resistivity of ferrite may be in the proximity of insulator, electromagnetic wave can get into inside to produce magnetic effects, which is a characteristic applied widely to microwave devices, especially nonreciprocal devices. Figure 2.6 show the familiar nonreciprocal devices, the isolator and circulator.

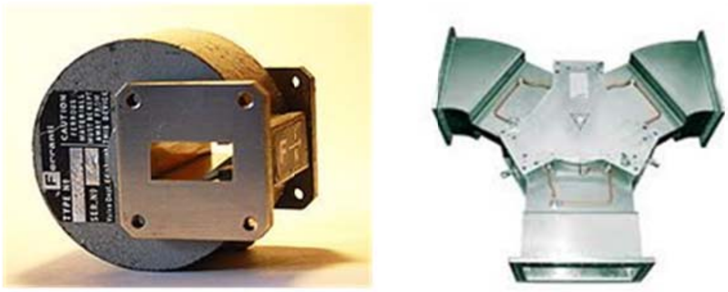


Figure 2.7 The common nonreciprocal devices, Isolator (left) and three-port circulator (right)

Chapter 3

Effects of Wave Reflection, Transmission and Absorption

The effects such as reflection, diffraction, scattering, refraction, transmission and absorption of electromagnetic waves are critical importance in the study of how EM waves move in media. When waves interact with objects or materials through which they travel these electromagnetic phenomena happened depending on the composition of the material and the wavelength of wave.

As a wave is reflected or diffracted, there is some loss of energy which generally passes into the medium and is absorbed because the photons hit the atoms or molecules and lead them to vibrate. Reflection coefficient is one of important parameters and reveals how much wave (or power) is reflected in electromagnetic wave experiments and measurements. For different purposes, sometimes we hope that waves can be reflected totally back without any signal loss when they impact objects so that we can receive complete information. However, sometimes absorbing the power of wave and decreasing the reflection are possibly the requirements for experiments and some devices, for example, wave absorbers and anechoic chambers.

In last chapter, we have reviewed some derivations on the permittivity, which is one of significant factors in reflection of waves. And the calculations on the reflection and transmission coefficients will be shown and discussed in this chapter. This section begins with the derivation of reflection and transmission coefficient and then tries to find the favorable materials to absorb the power in electromagnetic waves.

3.1 Reflection of EM Waves on Flat Surfaces of Substances

The surfaces of matters existing in the world are almost rough, which is the reason for scatter of waves. For simplicity, we neglect the effect of scatter and consider that the wave is emitted to a flat substance. The reflection and transmission coefficients for a plane wave emitted from free space to a flat surface of medium is given by [19, Eq. (7.39)&(7.41)]. According to the boundary conditions, there are two separate situations. The first one is that E-field of the incident wave is parallel to the plane of incidence as shown in Fig. 3.1

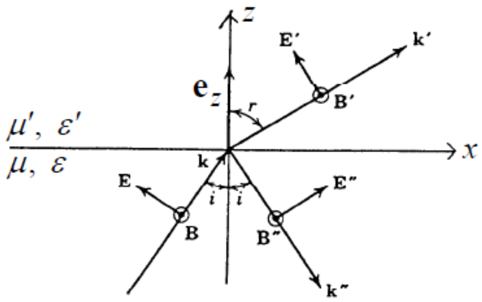


Figure 3.1
Refraction and reflection with polarization parallel to the plane of incidence

$$\begin{cases} \Gamma = \dfrac{E_0''}{E_0} = \dfrac{\dfrac{\mu}{\mu'} n'^2 \cos i - n\sqrt{n'^2 - n^2 \sin^2 i}}{\dfrac{\mu}{\mu'} n'^2 \cos i + n\sqrt{n'^2 - n^2 \sin^2 i}} \\ \mathrm{T} = \dfrac{E_0'}{E_0} = \dfrac{2nn' \cos i}{\dfrac{\mu}{\mu'} n'^2 \cos i + n\sqrt{n'^2 - n^2 \sin^2 i}} \end{cases} \tag{3.1}$$

and the other situation is that E-field of the incident wave is perpendicular to the plane of incidence. The reflection and transmission coefficients are given by

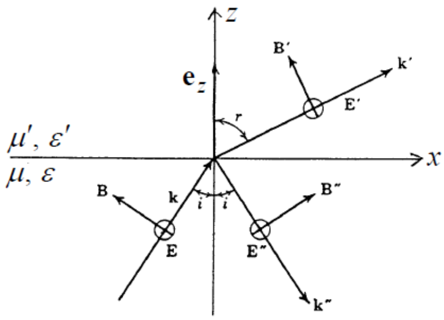


Figure 3.2
Refraction and reflection with polarization perpendicular to the plane of incidence

$$
\begin{cases}
\Gamma = \dfrac{E_0''}{E_0} = \dfrac{n\cos i - \dfrac{\mu}{\mu'}\sqrt{n'^2 - n^2\sin^2 i}}{n\cos i + \dfrac{\mu}{\mu'}\sqrt{n'^2 - n^2\sin^2 i}} \\
\mathrm{T} = \dfrac{E_0'}{E_0} = \dfrac{2n\cos i}{n\cos i + \dfrac{\mu}{\mu'}\sqrt{n'^2 - n^2\sin^2 i}}
\end{cases}
\tag{3.2}
$$

where n and n' are the indices of refraction. These two cases, parallel and perpendicular polarizations, can reduce to the same for normal incidence.

$$
\begin{cases}
\Gamma = \dfrac{E_0''}{E_0} = \dfrac{\sqrt{\dfrac{\mu\varepsilon'}{\mu'\varepsilon}} - 1}{\sqrt{\dfrac{\mu\varepsilon'}{\mu'\varepsilon}} + 1} = \dfrac{Z' - Z}{Z' + Z} \\
\mathrm{T} = \dfrac{E_0'}{E_0} = \dfrac{2}{\sqrt{\dfrac{\mu\varepsilon'}{\mu'\varepsilon}} + 1} = \dfrac{Z' - Z}{Z' + Z}
\end{cases}
\tag{3.3}
$$

where

$$
\begin{cases}
Z = \sqrt{\dfrac{\mu}{\varepsilon}} \\
Z' = \sqrt{\dfrac{\mu'}{\varepsilon'}}
\end{cases}
\tag{3.4}
$$

are the impedances of the media.

The reflection coefficient can be counted by substituting Eq. (2.4) into Eq. (3.3) with the two assumptions for simplicity that permeability of media $\mu = \mu' = \mu_0$ and that $\varepsilon_b \approx \varepsilon_0 = 8.85\times10^{-12}$ farad/m for all media.

$$\varepsilon = \varepsilon_0 + i\frac{\sigma}{\omega} \tag{3.5}$$

Figure 3.3(a) shows that the reflection coefficient for a variety of materials whose resistivity is ρ (=1/σ) at microwave frequencies. We have used the resistivity of copper (ρ_{cu} =1.72×10^{-8} Ωm) as a reference value. The reflection coefficients have a significant dependence on the resistivity (or conductivity) of materials. It is conspicuous that microwaves are almost totally reflected when they meet a good conductor but penetrate when they meet a dielectric. In the region with fractional reflection, there is an evident tendency that the reflection coefficient decreases gradually as the frequency of incident wave increases, especially in the middle of this figure. This verifies again that one substance can be a conductor or dielectric material at different frequencies, which is aforementioned at Sec. 2.3.

Also, the corresponding transmission coefficient is shown in Fig. 3.3(b). The transmission coefficient of matter with large resistivity is nearly 1. This indicates good dielectrics are closely transparent to the microwaves.

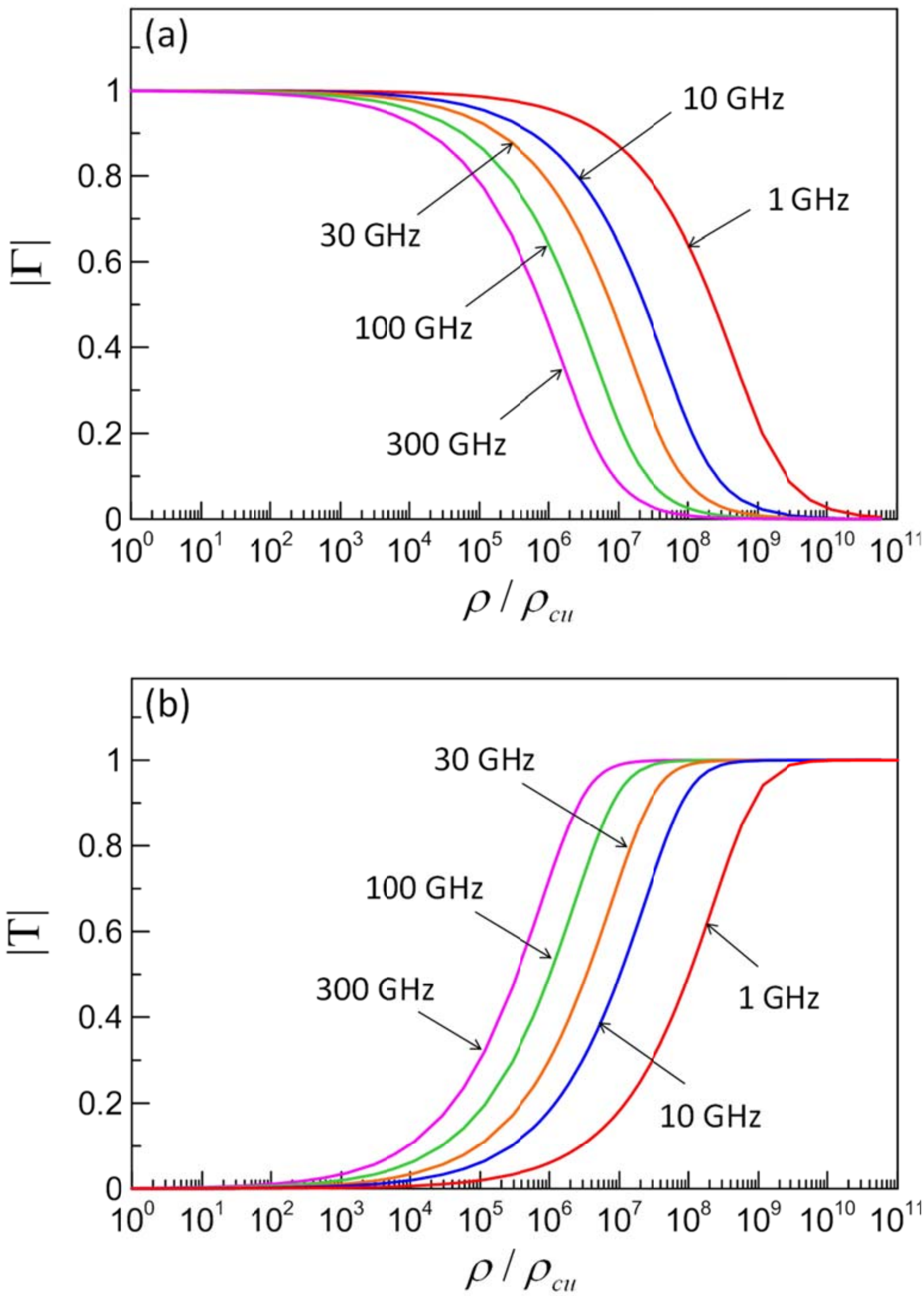


Figure 3.3 The reflection (top) and transmission (button) coefficients of microwaves incident from free space to a wide variety of materials ranging from good conductor to good dielectrics with the assumption that relative permittivity (ε_r) is 1.

Through reflection coefficient [Fig. 3.3] and skin depth [Fig. 3.4], we can know clearly that how thick a wave absorbing material is needed if we want to use it to accomplish the absorption for a specified-frequency wave. Especially, for high frequency, the skin depth reduces to very small and the lossy material required is only a thin layer. This has great help for fabricating high-frequency wave absorbers.

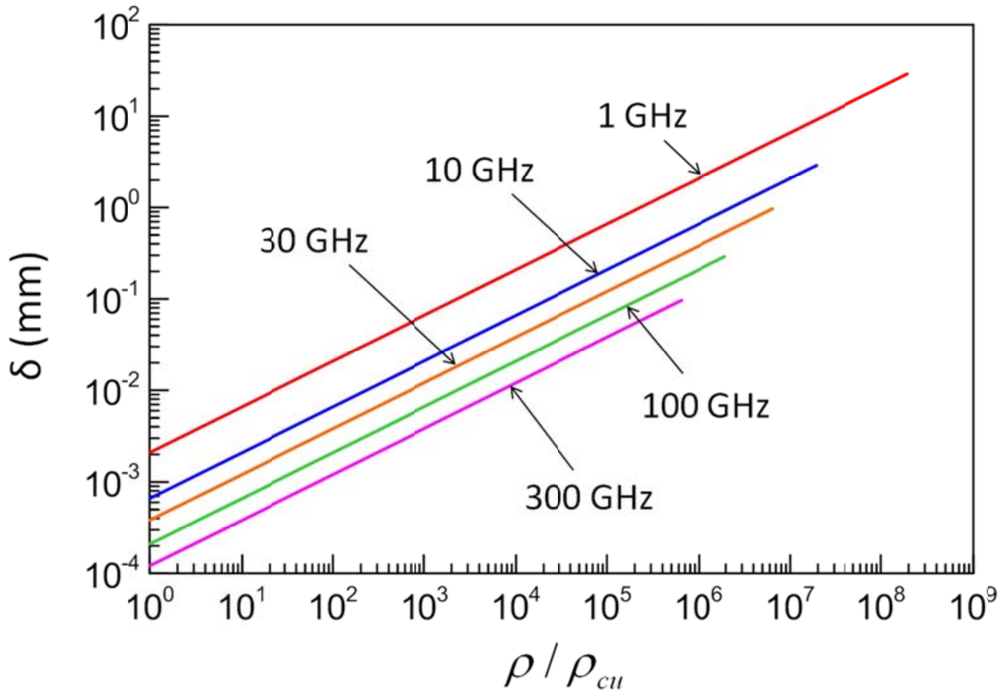


Figure 3.4 Skin depth of substances at microwave frequencies

For a good dielectric material,

$$\frac{\sigma}{\omega\varepsilon_r\varepsilon_0} << 1 \tag{3.6}$$

the imaginary part of its permittivity are negligible at microwaves or the higher frequencies.

$$\varepsilon = \varepsilon_r\varepsilon_0 + i\frac{\sigma}{\omega} \approx \varepsilon_r\varepsilon_0 \tag{3.7}$$

where ε_r is the relative permittivity. Thus the reflection and the transmission coefficients [Eq. (3.3)] can converge to a value only related to relative permittivity.

$$\Gamma = \frac{E_0''}{E_0} = \frac{\sqrt{\frac{\mu\varepsilon'}{\mu'\varepsilon}} - 1}{\sqrt{\frac{\mu\varepsilon'}{\mu'\varepsilon}} + 1} = \frac{\sqrt{\varepsilon_r} - 1}{\sqrt{\varepsilon_r} + 1}$$

$$\mathrm{T} = \frac{E_0'}{E_0} = \frac{2}{\sqrt{\frac{\mu\varepsilon'}{\mu'\varepsilon}} + 1} = \frac{2}{\sqrt{\varepsilon_r} + 1} \tag{3.8}$$

As shown in Fig. 3.5, the reflection coefficients of good dielectrics with $\varepsilon_r = 2$ converge toward about 0.172.

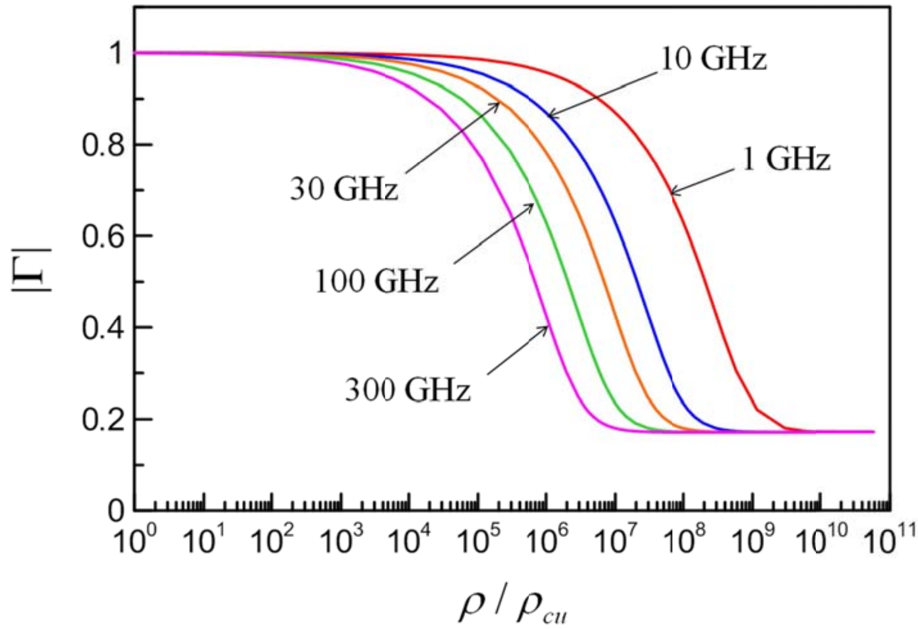


Figure 3.5 The reflection coefficients converge on 0.172 at "good dielectric region" as relative permittivity is two. The resistivity is normalized by that of copper.

3.2 Waves Incident with an Angle on Matters

Practically, the situation of a plane wave emitted obliquely onto a material interface is much more common than that of a plane wave emitted perpendicularly. Once the incident angle is nonzero, Eq. (3.3) is not appropriate any more for calculating reflection and transmission coefficients. It is necessary to use Eq. (3.1) or (3.2) for the cases that electric fields perpendicular or parallel to the plane of incidence, respectively. We consider the lossless materials. The calculated results [Fig. 3.6] illustrate that the parallel polarization has less reflection than perpendicular polarization at any incident angles except that 0 degree, which is normal incidence case, and that 90 degree, which means there is no wave emitted to the matter and of course the reflection coefficient is 1 (the transmission coefficient is 0).

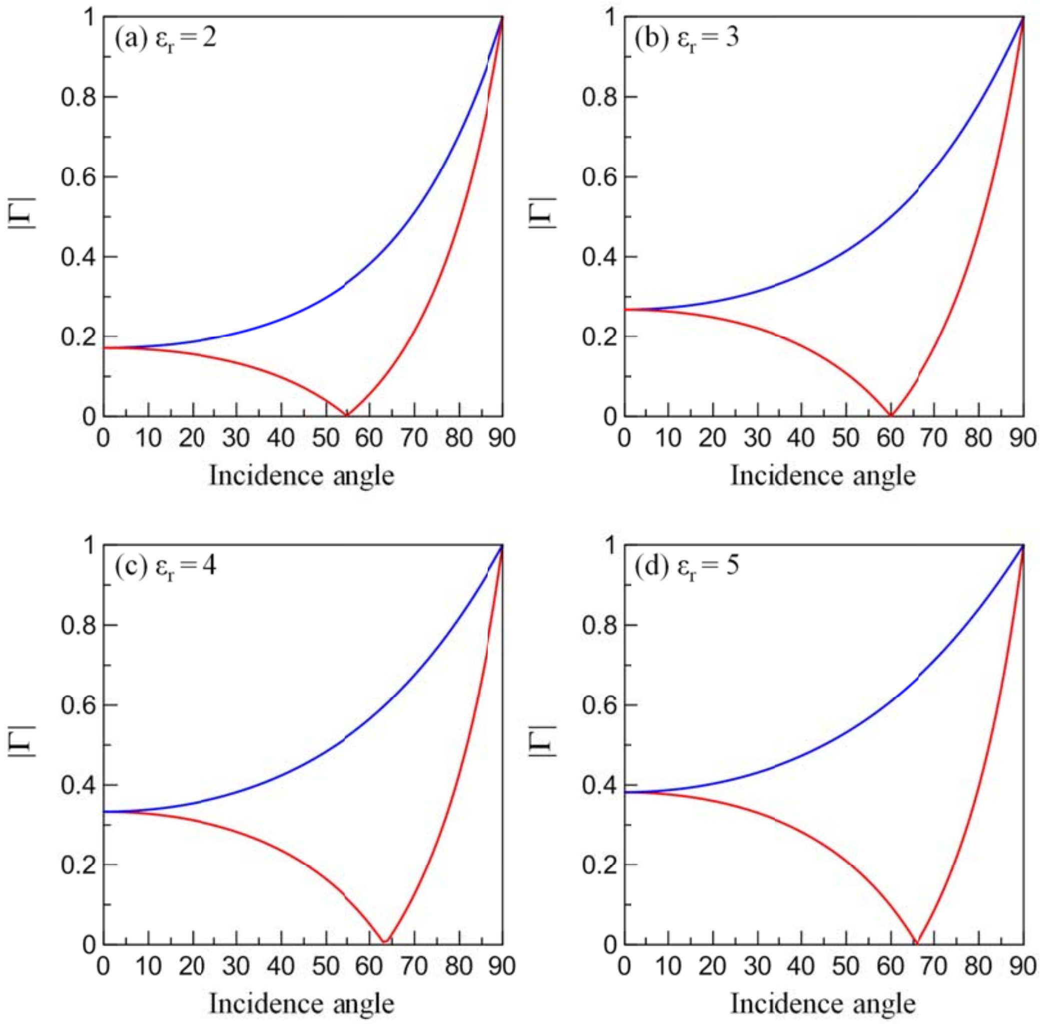


Figure 3.6 The reflection coefficients for perpendicular (blue lines) and parallel (red lines) polarizations of a plane wave obliquely incident on dielectrics

3.3 Reflection of Power in Electromagnetic Waves

In general, power is the magnitude we measure and observe in electromagnetic experiments and measurements. The power in an electromagnetic wave is proportional to the square of the amplitude. Therefore based on Eq. (3.3) and

$$\begin{cases} \dfrac{\text{Reflected power}}{\text{Incident power}} = |\Gamma|^2 \\ \dfrac{\text{Transmitted power}}{\text{Incident power}} = 1 - |\Gamma|^2 \end{cases} \tag{3.9}$$

the reflection and transmission of the power of a wave emitted from vacuum to various substances can be calculated by using the generalized permittivity $\varepsilon = \varepsilon_b + i\dfrac{\sigma}{\omega}$ [Eq. (2.6)] with the assumption that $\varepsilon_b \approx \varepsilon_0 = 8.85 \times 10^{-12}$ farad/m and

$$\sigma = \frac{Ne^2 f_0}{m(\gamma_0 - i\omega)} \tag{3.10}$$

where γ_0 is the collision frequency of matter. Thus, if the frequency of incident wave is much lesser than the collision frequency, we obtain

$$\sigma \approx \frac{Ne^2 f_0}{m\gamma_0} \tag{3.11}$$

The conductivity is just a real constant.

Figure 3.7 are plotted as the function of the resistivity ρ with ρ normalized to that of copper (ρ_{cu} =1.72×10^{-8}Ω-m) from good conductors to dielectrics. The wave frequencies cover a wide range. Although the reflection for good conductors is close to perfect reflection, there is still some transmission that can be seen in Fig. 3.7 (below). Conductor material absorbs about 15 times more at 10^{12} Hz than at 10^{10} Hz, that is to say, it absorbs much more infrared radiation than microwave frequencies. This is why the temperature of the walls of a modern microwave oven are cooler than those of a conventional oven and is also why the microwave oven is more frugal of the electricity.

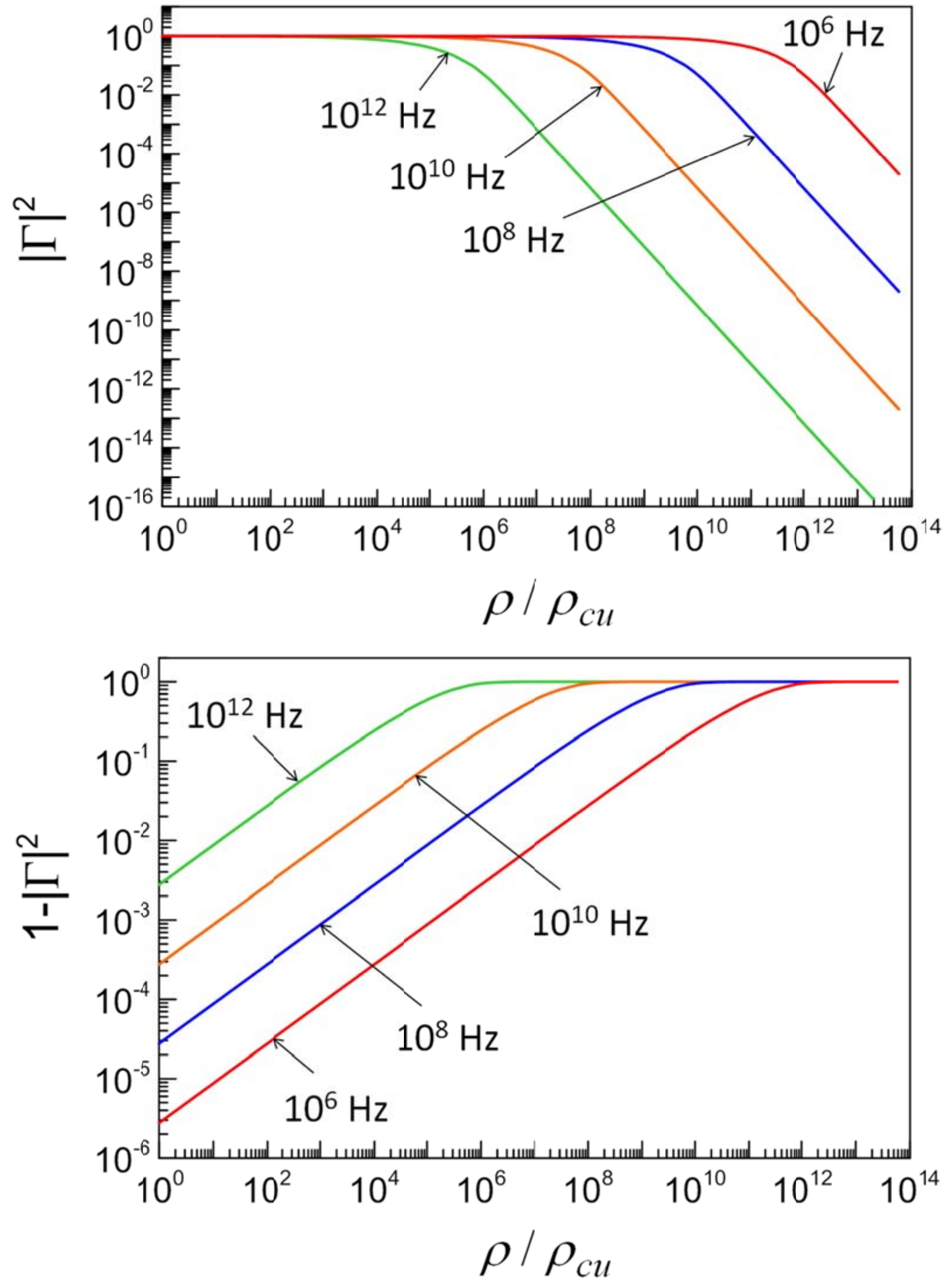


Figure 3.7 The reflection (top) and transmission (bottom) of the power in electromagnetic waves. Γ is the reflection coefficient.

3.4 Waves Emitted from Vacuum to Copper

Following frequency-dependent electrical conductivity, Eq. (2.18),

$$\sigma = \frac{Ne^2 f_0}{m(\gamma_0 - i\omega)} = \frac{Ne^2 f_0}{m\gamma_0 (1 - i\frac{\omega}{\gamma_0})} = \frac{5.8\times10^7}{1 - i\frac{\omega}{4\times10^{13}}}$$

and Eq. (2.19),

$$\varepsilon = \varepsilon_0 + i\frac{\sigma}{\omega} = \varepsilon_0 + i\frac{5.8\times10^7}{\omega(1 - i\frac{\omega}{4\times10^{13}})}$$

the reflection and transmission of waves emitted from free space to solid copper can be calculated. Figure 3.8 shows the calculation results. The frequencies range from long waves to gamma rays.

The point mentioned last paragraph can be also illustrated in the “good conductor regime”. For long waves and radio waves, the power absorbed by copper is much smaller than one percent of the incident power.

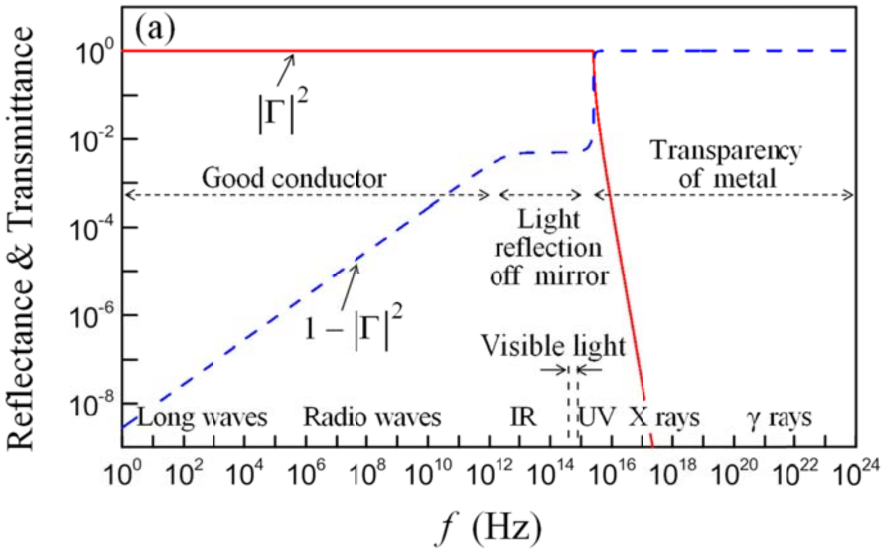


Figure 3.8 The reflection and transmission of waves emitted from free space to solid copper. The frequencies range from long waves to gamma rays.

In the light reflection off mirror regime, theory predicts total reflection if copper has no loss, and there are evanescent fields inside the copper. In reality, copper has a very small resistivity (ρ_{copper}=1.72×10^{-8}Ω-m), which results in approximately 0.5 percent of wave absorption by the evanescent fields. In the transparency of metal regime applicable to ultraviolet, X-rays and gamma rays, theory predicts total transmission if copper has no loss. But practically, the small copper resistivity results in a negligibly small reflection as shown in the right zone of Fig. 3.8.

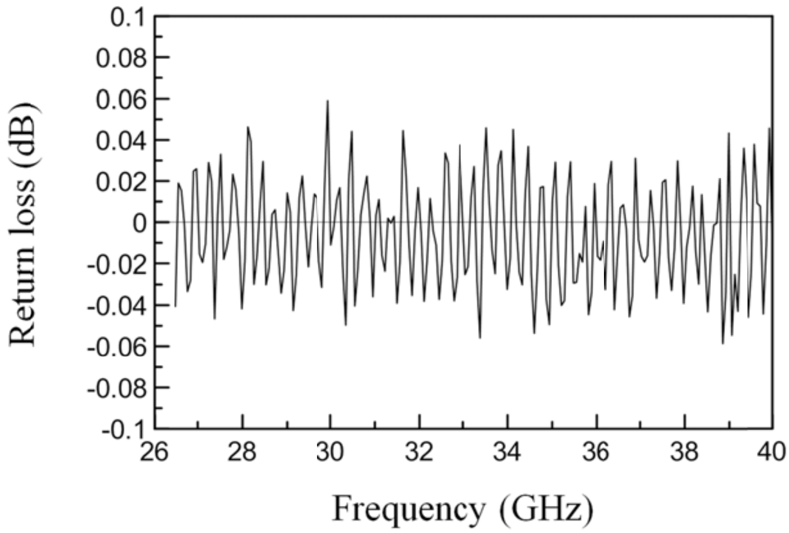


Figure 3.9 The copper measurement result through Network Analyzer.

Figure 3.9 shows the return loss of copper measured by Network Analyzer. The return loss of -0.02 means that there is 99.54 percent of incident power in the wave reflected and the rest, 0.46 percent, transmits into copper and is absorbed.

Chapter 4

The Absorbers for Microwaves Frequencies

4.1 Introduction

Electromagnetic wave experiments and measurements in laboratory usually need a high quality no-reflecting environment, such as electromagnetic wave anechoic chambers or shielded room installations, which play an important role in the work of electromagnetic interference and compatibility tests. They are usually composed of many wave absorbers lined on walls. Absorbers in anechoic chamber can absorb the power of electromagnetic waves and efficiently reduce the reflected wave that could give rise to influences on the result of EM wave measurement.

The dimensions of an anechoic chamber are based on the measured sample as well as the sizes of wave absorbers, or more correctly, based on the wavelength of the absorbed wave. The room of an anechoic chamber for radio waves is usually as large as an auditorium, but for microwaves it can be reduced greatly. Because studying on microwaves have extensively involved millimeter waves and even the higher frequency waves, terahertz waves, the needs for corresponding wave absorbers and measurement equipments are increasing. Hence, we will discuss the absorber for high frequency. In the following discussion the electromagnetic spectrums are focused on microwaves, whose wavelengths range from one meter to one millimeter, and equivalently, frequencies between 300 MHz and 300 GHz. For a 30 GHz microwave, its wavelength is 1 cm and thus the dimensions of appropriate chamber can be smaller than a cubic meter. The cost of making one is inexpensive and it can be placed in a general laboratory.

After the first absorber invested in Netherlands in 1930s, substantially, the discovery of novel wave absorbing materials and the progress of manufacturing techniques greatly benefit and strengthen the performance of wave absorber and of course anechoic chamber. In that time, they were studied mostly by military organizations and communication companies and the commercialized production of absorbers first appeared in 1950s. The early development of the absorber and anechoic chamber has been systematically reviewed in [20].

The absorption competence of a wave absorber depends primarily on materials used, shapes and designs. Shape is a very significant factor affecting the performance of absorbers. There are also simulation studies to optimize the absorber geometry for better performance [21, 22]. Following the conclusions in Chapter 2 and 3, we have understood what kind of materials used as microwave absorbers can possess the optimal performance. In this section we will introduce the structures of absorbers in the beginning and then compare and discuss dimensional factors influencing the performances of wave absorbers simulated through High Frequency Structure Simulation (HFSS) codes.

4.2 The Structures and the Material of Wave Absorbers

Our purpose is to examine the dynamics of high-frequency microwave absorption and efficient absorber structures that can tolerate high power while also possessing a structural simplicity for laboratory fabrication.

Here, we introduce two various wave absorbers, the pyramidal absorber and the wedge-shaped absorber. The features and physical specifications of them are shown in Table 4.1.

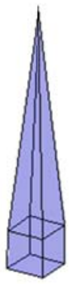
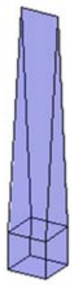
Shape	Pyramid	Wedge
		
Bottom	3.56 × 3.56 × 3.5 (mm^3)	
Total high	23.53 (mm)	
Taper angle	5 (°C)	
Absorbing area	144.85 (mm^2)	

Table 4.1
The dimensions of the pyramid and wedge shaped absorbers

The purpose of this simulation is to look for what kind of absorber has the optimal performance. In order to diminish the dimensional distinctions between these two absorbers which may influence the reflection and absorption, most parts of the absorbers are set to be the same, particularly the absorbing area. The power of microwave is fixed at 1 watt.

The sizes of the base are specified according to the inside dimensions of Ka-band waveguide. In the simulation, these absorbers are settled in the Ka-band waveguide whose fundamental mode TE_{10} cutoff frequency is 21.081 GHz so that most mode conversions are avoidable when the used frequencies are under double cutoff frequency. Figure 4.1 shows the field distribution of TE_{10} mode in a rectangular waveguide. The red vectors represent the magnitude and direction of electric field and blue dashed lines are magnetic field. More plots of modal field distribution in rectangular waveguide can be seen in [23].

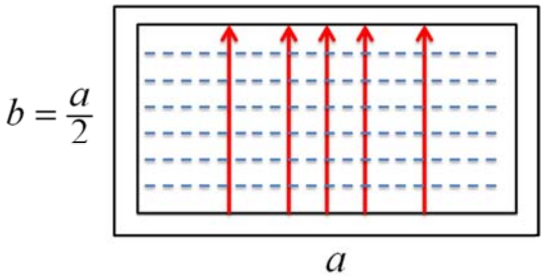


Figure 4.1 Field plot of TE_{10} mode in a rectangular waveguide with inner dimensions a, b. Electric field are red vectors (solid lines) and magnetic field are blue lines (dashed lines).

Besides the standard dimensions as shown in Fig. 4.2, we also simulate absorbers whose the length is changed and stretched to find the performance of a column absorber, which is closer to the actual situation in an anechoic chamber. The "L" is the changed dimension of absorber and waveguide and the taper angles of these three wave absorbers are fixed at 10 degrees.

The dispersion relation in a waveguide is

$$\omega^2 - k_z^2 c^2 - \omega_{cmn}^2 = 0 \tag{4.1}$$

where

$$\omega_{cmn} = \pi c \left(\frac{m^2}{a^2} + \frac{n^2}{b^2} \right)^{\frac{1}{2}} \tag{4.2}$$

is the cutoff frequency of TE_{mn} waves in a rectangular waveguide with inside dimensions a, b, as shown in Fig. 4.1. If the length of the shorter side of waveguide is fixed, mostly, high-order modes cannot appear in the waveguide except the modes (m, 0), the field distributions of which are analogous to TE_{10} mode [23].

$$\omega_{cm0} = \pi c \frac{m}{a} \tag{4.3}$$

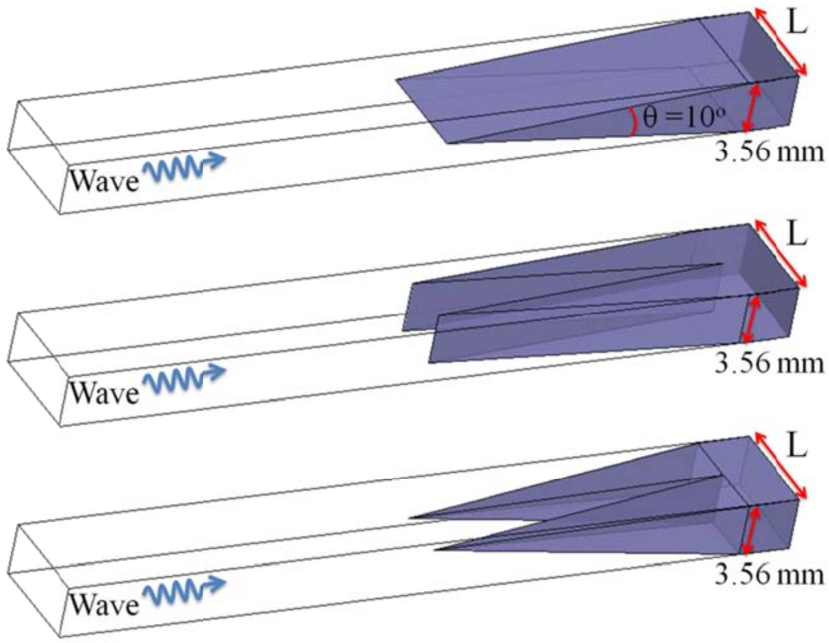


Figure 4.2 The wedge-shaped absorbers (a)-(b) and pyramidal absorber (c) are settled in Ka-band waveguide. The differences between (a) and (b) are the relationships of the directions of fields and the absorbing surfaces. Case (a) is parallel polarization and case (b) is perpendicular polarization. Case (c) is a linear combination of (a) and (b).

In Sec. 3-1 we have calculated the reflection and transmission coefficients of a wave emitted to infinite flat surfaces of substances over a wide resistivity range [Fig. 3-3] and knew that what kind of material is applicable to wave absorbers at microwave band. Now similar calculation will be done again through HFSS for the wedge-shaped absorber-1 [Fig. 4.2(a)].

A conspicuous dip appears at about $\rho/\rho_{cu}=10^5$, particularly in Fig 4.3(a) and (c), and the values of return loss at the proximity of this dip are less than the materials with larger resistivity. However, theoretically the larger the resistivity of absorber is, the better absorption performance is. The fact is that the absorber cannot absorb all power at first contact, which results in some wave reflected. What is more, the reflected wave has the frequency fit for reflection back and forth at the two wedge-shaped spaces. In other word, resonance occurs at the peripheral of absorber and the reflected wave does not go back to wave port so the power measured is less than it should be. Fig. 4.3 makes a description of that material with about $\rho/\rho_{cu} = 10^6$ are good enough to accomplish absorption.

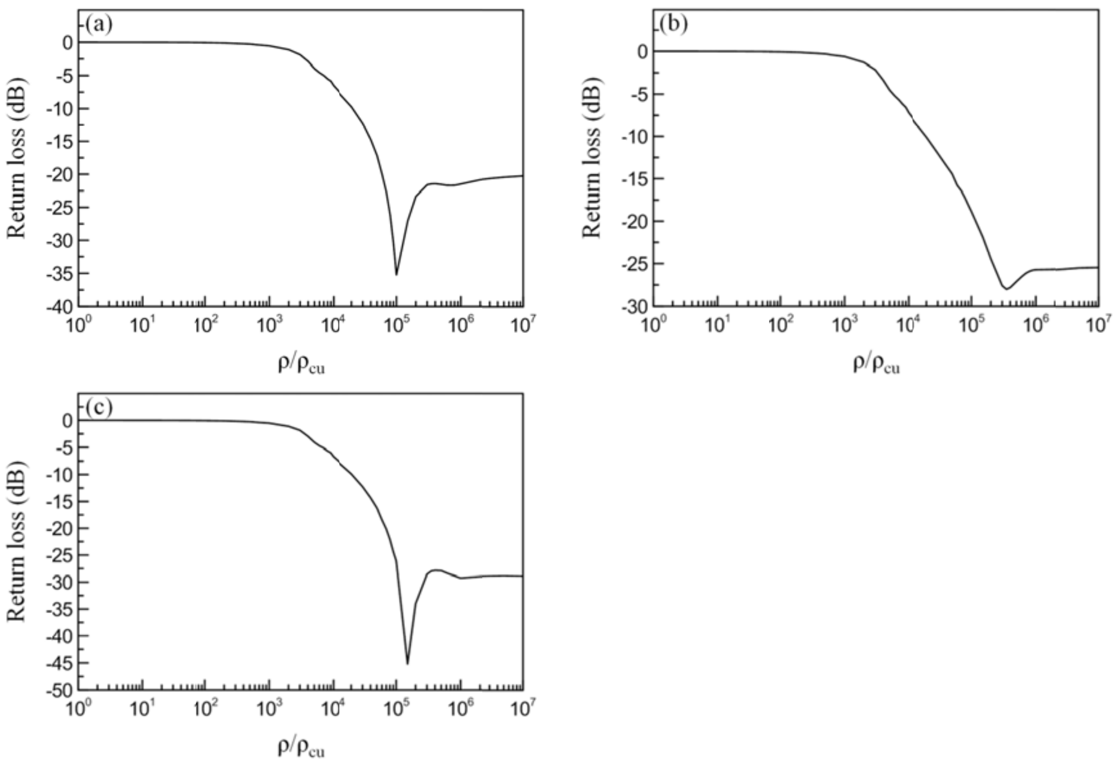


Figure 4.3 The absorption performance of wedge-shaped absorber-1 made of a variety of materials at (a) 24, (b) 26 and (c) 28 GHz.

The lossy material we used as the wave absorbers is a kind of carbon compound comprising graphite and mass isopropyl alcohol. This colloidal graphite compound has high lubricity and good adhesion to metal. We can smear it on a bended conductor sheet to form wave absorbers. The conductivity of this material is approximately 16.67 /(Ω-m) and the ρ/ρ_{cu} is about 3.48×10^6. Nevertheless, it belongs to electrical conductor for frequencies over 20 GHz. Microwaves penetrate dielectric materials more deeply than conductors, which means that there is more power can be absorbed by dielectrics, but most dielectric materials cannot sustain high power. As a result, we select the modest electrical conductive material to serve as our wave absorbers. The dielectric, magnetic, ferroelectric and ferrite materials combined with some are commonly used to make wave absorbing materials [24].

4.3 The Simulation Results of the Three Kinds of Absorbers

A figure of merit for the power loss because of reflection is called the return loss (RL), defined as a ratio in decibels (dB)

$$RL\,(\mathrm{dB}) = 10\log_{10}\left(\frac{P_{re}}{P_{in}}\right) = 10\log_{10}|\Gamma|^2 \tag{4.3}$$

where P_{in} is the incident power and P_{re} is the reflected power, respectively. The reflectivity (S_{11}) of these absorbers is measured by return loss which is always a negative number but minus sign is often omitted. The requirement of reflectivity for an anechoic chamber is at least below -20 dB. Only 1 percent of incident power is reflected. An anechoic chamber with return loss of -40 dB is considered to be excellent, which means only one of ten thousand of incident power is reflected.

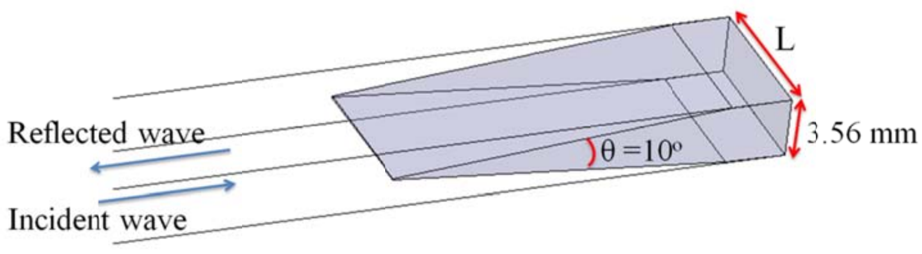


Figure 4.4 The diagram of the wave and wedge-shaped absorber in waveguide. The "L" is the changed dimensions in the simulation.

Figure 4.5 and 4.6 respectively show the simulation results of wedge-shaped absorber-1 [Fig. 4.2(a)] and wedge-shaped absorber-2 [Fig. 4.2(b)], plots of return loss versus frequency ranging from 22 to 28 GHz. The "L" is the length of wave absorbers as shown in Fig. 4.4 and the ρ/ρ_{cu} of used material is about 3.48×10^{6}.

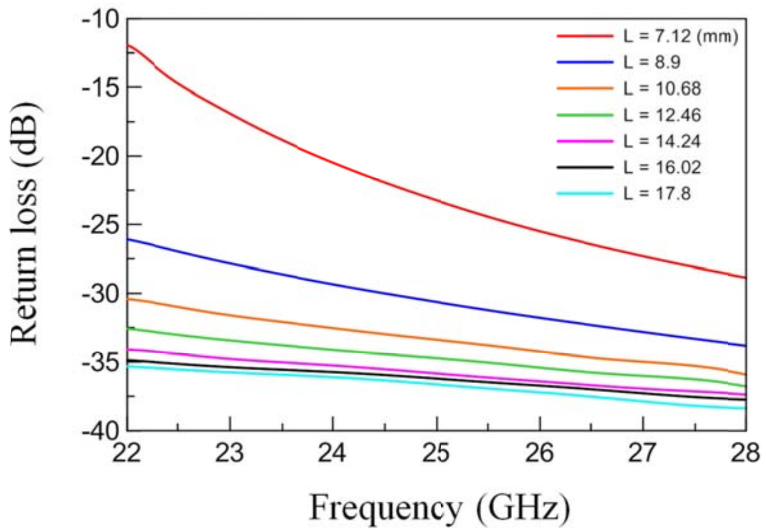


Figure 4.5 The return loss of wedge-shaped absorber-1 [Fig. 4.2(a)] for 22 to 28 GHz microwaves. A return loss of -35 dB is equal to reflectivity of 0.03%.

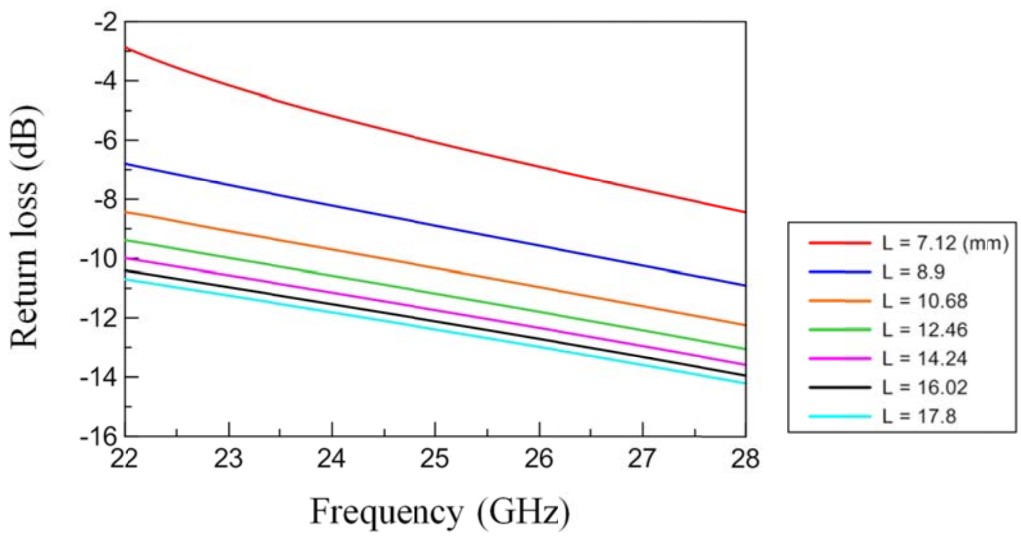


Figure 4.6 The return loss of wedge-shaped absorber-2 [Fig. 4.2(b)] for 22 to 28 GHz microwaves. A return loss of -14 dB is equal to reflectivity of 4%.

First, there is a clear tendency for every curve toward less reflection (more absorption) when the frequency of incident wave is enhanced increasingly. This is well demonstrated by the following equation. The time-averaged power absorbed on the surface of a good conductor is

$$\frac{dP_{abs}}{da} = -\frac{1}{2}\mathrm{Re}[\mathrm{E}\times\mathrm{H}^{*}]\cdot\mathbf{e}_{z} = \frac{\mu\omega\delta}{4}\left|\mathrm{H}_{\parallel}\right|^{2} \tag{4.4}$$

and by substituting Eq. (2.14) into Eq. (4.4)

$$\frac{dP_{abs}}{da} = \sqrt{\frac{\mu\omega}{8\sigma}}\left|\mathrm{H}_{\parallel}\right|^{2} \propto \sqrt{\omega} \tag{4.5}$$

where $\mathrm{H}_{\parallel}$ is the tangential magnetic field that exists just on the surface of the conductor. The power absorbed is proportional to square root of frequency of incident wave and return loss is in the same way.

Equation (4.4) demonstrates a more significant point that the power loss per unit area also depends on the tangential magnetic field ($\mathrm{H}_{\parallel}$), and this can explain the difference of absorption performance between these two models. The tangential magnetic field increases with a reduced cross-sectional area of space in waveguide when wave gets into the zone of absorber [Fig. 4.2(a)]. Therefore this leads to more power being absorbed. For satisfying boundary conditions of electromagnetic fields, the electric field going into absorber can produce a current near the surface of the conductor, which causes the same magnetic field to resist the entrance of the magnetic field outside the surface. However, the effect doesn't appear in wedge-shaped absorber-2 though cross-sectional area also reduces

Secondarily, based on Fig. 4.1 and 4.2(a), the directions of TE_{10} mode electric field are closely parallel to the absorbing surfaces of wedge-shaped absorber-1 (parallel polarization). It is easier to form the electric force lines than the other case of wedge-shaped absorber, wedge-shaped absorber-2 (perpendicular polarization), for which it is more difficult to do that. This is one reason wedge-shaped absorber-1 has the superior performance of absorption in comparison with the result of wedge-shaped absorber-2 [Fig. 4.6].

Hence, that the absorption performance in case (a) is better than in case (b) is consistent with the theoretical calculation in Sec. 3.2, the reflection coefficient under parallel polarization is always less than under perpendicular polarization.

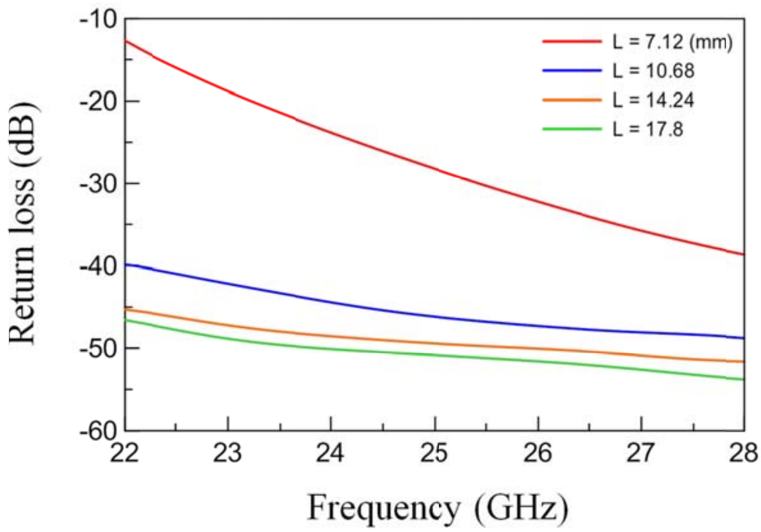


Figure 4.7 The return loss of pyramidal absorber [Fig. 4.2(c)] for 22 to 28 GHz microwaves.

The simulation results of the third model, pyramidal absorbers [Fig. 4.2(c)], can be seen in Fig. 4.7, identically, with different lengths. Geometrically, a pyramidal absorber is the combination of wedge-shaped absorber-1 and absorber-2. But, as a consequence of comparison among Fig. 4.5-7, the pyramidal absorber conspicuously has the optimal absorption performance, which can be attributed to the structural characteristic on the tip. The tip of a pyramidal absorber is a dot and the impedance made by a dot is much less than that made by a line, the tip of a wedge-shaped absorber, which means that the magnitude of the power reflected is less when electromagnetic wave contacts a dot.

Except for the red curve (L = 7.12 mm), everyone is below -40 dB, that is to say, this kind of absorber has 0.01% incident power reflected and absorbs nearly total power in microwaves. This is the main reason why the pyramidal absorbers are widely and usually used in the anechoic chamber. Furthermore, the field distribution of electromagnetic waves in an anechoic chamber is not simple as in the waveguide, especially the waves reflected by the measured sample. Based on such reasons, the pyramidal absorber is the best choice for anechoic chambers.

Another point we can view from Fig. 4.5-4.7 is that the reflection decreases with increasing the longer side of absorber because the absorbing surfaces are expanded. The decrease in the power per unit area makes the performance of absorption better. Additionally, the relative amount in return loss of two next curves also decreases, which means that the return loss will converge on a constant when L is expanded to be infinite. And at this situation the field distribution of the incident wave in the waveguide is similar to that of a plane wave.

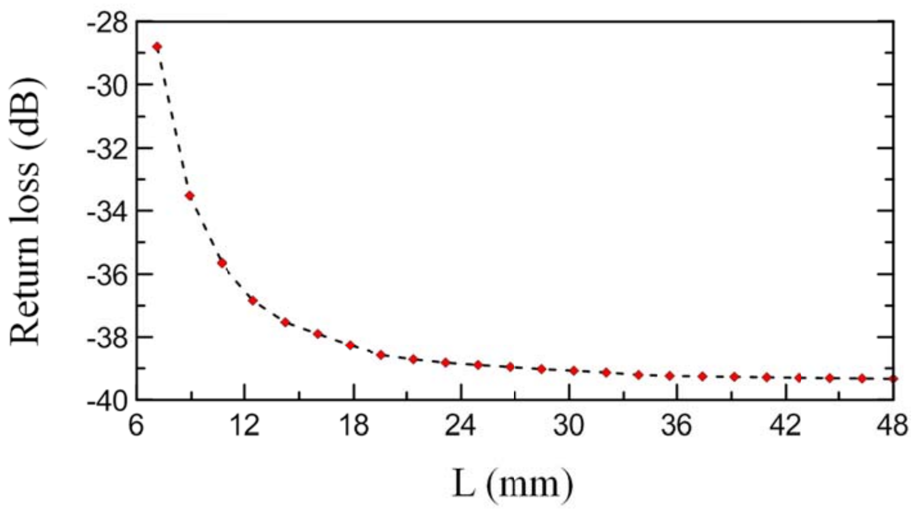


Figure 4.8 The convergence test of wedge-shaped absorber-1 for the lengths at 28 GHz. The length is enhanced from 7.12 mm to 48.0 mm and the width of the wave absorber is fixed at 3.56 mm.

Figure 4.8 shows the result of the convergence test of wedge-shaped absorber-1 for the length at 28 GHz. The length is extended from standard dimension to 48 mm. The magnitude difference of return loss is apparent when L is smaller than 30 mm, but is nearly zero when the length is enhanced to over 36 mm. Finally the return loss converges at -39.34 dB.

4.4 Discussions on Wedge-shaped Absorber-1

For manufacturing absorbers in laboratory, it is relatively easy to make the wedge-shaped absorbers due to the simple shape in spite of that it is not the optimal structure. Therefore in the following discussion the focus will be held on wedge-shaped absorber-1, which has better absorption performance than wedge-shaped absorber-2. The discussion on the latter can be viewed at Appendix A.

At the process of fabrication, there are some dimensional factors effecting the reflection and absorption performance, such as surface roughness, the angle and tip of absorbers, which can be seen in Fig. 4.8.

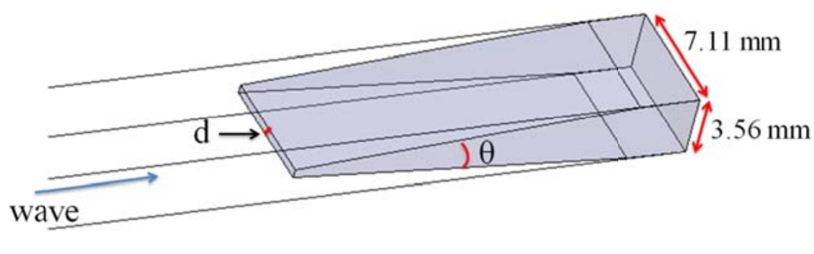


Figure 4.9 The diagram of the changed dimensions, including the taper angle (θ) and tip width (d) of wave absorbers. The band of this waveguide is Ka-band.

Here, we compare some wave absorbers with different taper angles and widths of tips. First, the influences on the reflection due to the angles of the absorbers are shown in Fig. 4.9. The simulation result agrees with the intuition that the larger the angle is, the more the reflected power is since there is obvious discontinuity for larger-angle absorbers. But, in the waveguide, as the angle of an absorber enlarges the absorbing area reduces, which also results in absorption performance weak. Therefore, this is not a scrupulous interpretation.

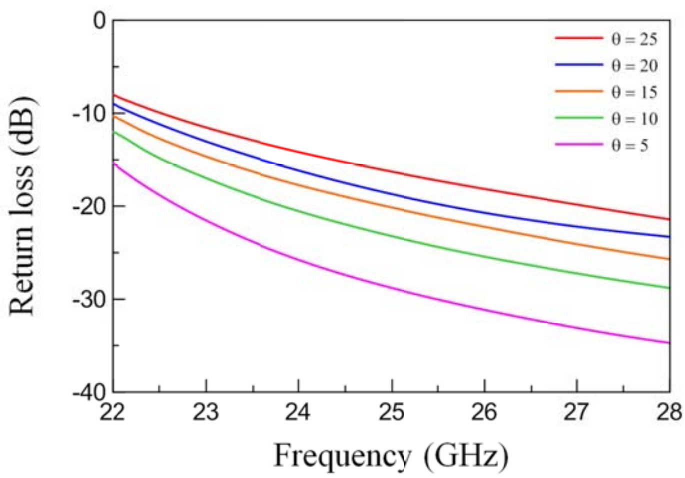


Figure 4.10 Influences of the taper angles of wave absorbers on reflection.

Besides the angle of wave absorber, its tip is also one factor affecting the result. In fact, the tip of a bended conductor sheet is not exactly a line but a little area which is inevitable in fabrication. The actual reflectivity (S_{11}) measured through the Network Analyzer is more than the result of simulation. Consequently, we simulate the absorbers with different widths of tip from 0 mm to 0.5 mm to examine the differences. Figure 4.10 shows the simulation results. Obviously the more reflected waves produced if the tip of the wave absorber is blunt.

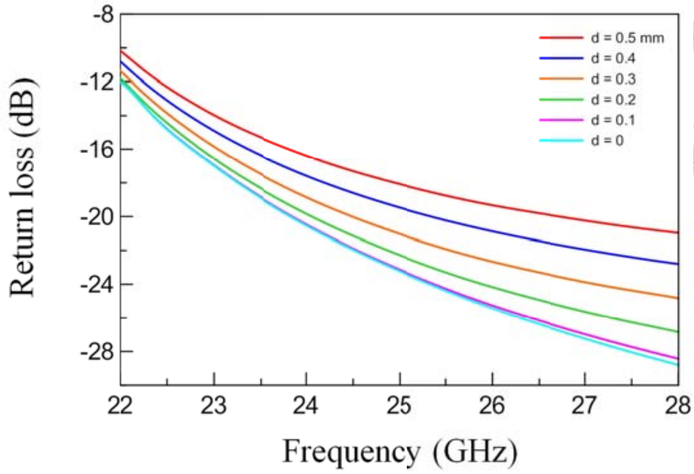


Figure 4.11 Influences of the tip widths of wave absorbers on reflection.

Finally, we extend the microwave frequency to 40 GHz. The TE_{10} cutoff frequency of Ka-band waveguide is 21.081 GHz and the recommended frequency range is from 26.5 to 40 GHz. Figure 4.12 shows the reflectivity performance of wedge-shaped absorber-1 in Ka-band waveguide. The return loss is -26.6 dB (reflectivity of 0.2%) at 26.5 GHz and reduces to -38.3 dB at 40 GHz, about reflectivity of 0.02%. This means that the wave absorber is able to absorb entirely the waveguide band.

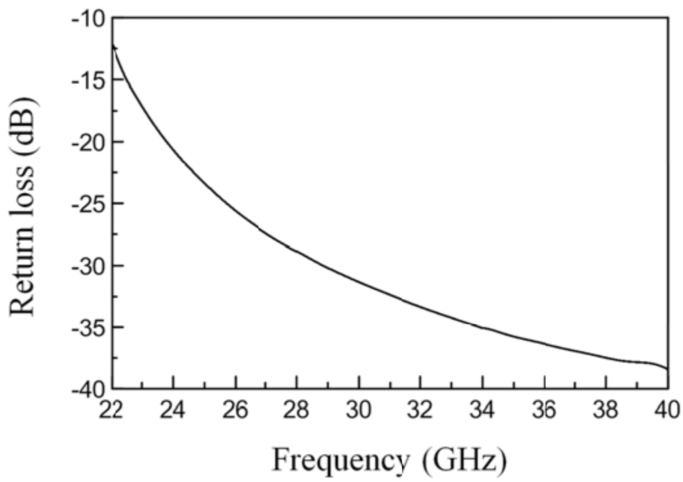


Figure 4.12 The reflectivity performance of wedge-shaped absorber-1 in Ka-band waveguide. The ρ/ρ_{cu} of used material is about 3.48×10^{6}.

4.5 Simulation of Coating Absorbing Materials

In the fabrication of wave absorbers, absorbing material coating is an important process. To understand how much absorbing materials is thick enough, we examine the following simulation. An illustration of the model of a wave absorber is given in Fig. 4.13. The copper wedge is coated with the absorbing material. It is more convenient to control the height (h) of the absorbing material than the thickness normal to the surface [Fig. 4.2(a)]. The appropriate height of absorbing material will be obtained when the absorption performance is as good as that of the wedge-shaped absorber-1 made entirely of the absorbing material.

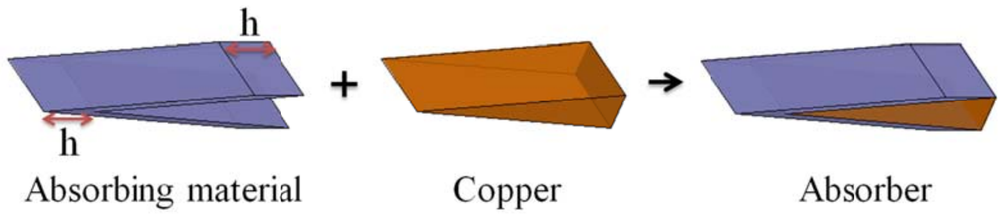


Figure 4.13 The illustration of the model of a wave absorber. The "h" is the height of absorbing material modulated in the simulation.

The used absorbing material is a kind of lossy conductor. Its resistivity is about 0.06 (Ω-m) and the corresponding skin depth is 0.8 mm at 24 GHz [Eq. (2.14)]. Theoretically, the power in the electromagnetic wave reduces to 13.5% when wave penetrates a conductor to one skin depth deep and 1.8% to two times skin depth deep. These have been mentioned at Sec. 2.3.

Figure 4.14 shows that the absorption performance of wave absorbers is related to the thickness of the absorbing material. The curves of h = 1 mm and h = 2 mm reveal that such thickness are too thin to absorb the power. However, evidently, the curve of h

= 5 mm (blue line) is the fittest one to the curve of absorber-1 (red line), which means copper wedge coated with such thick lossy material can afford to accomplish the absorption.

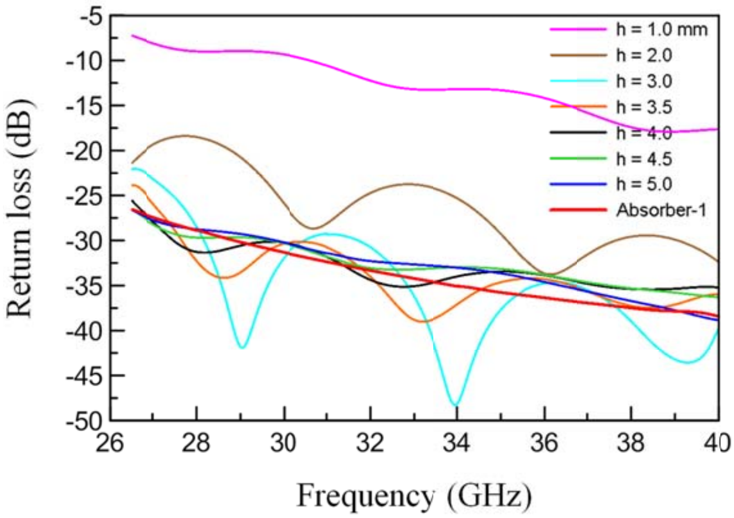


Figure 4.14 The absorption performance of wave absorber is related to the thickness of the absorbing material.

The lossy conductor thickness of absorbers normal to the surface can be obtained by

$$Thickness = h \times \sin\frac{\theta}{2} \tag{4.6}$$

For a Ka-band microwave absorber with 10-degree taper angle, the height of 5 mm means the thickness is only 0.44 mm, about a half skin depth. The absorbing material coating the copper wedge is just a thin layer, which makes the fabrication of wave absorbers easier. This is the benefit of conductivity lossy materials and will become more advantageous at millimeter and terahertz wave regimes.

Chapter 5

The Network Analyzer Measurement of Wave Absorbers

5.1 The Fabrication of Wedge-shaped Absorber

Based on the specification presented in Table 4.1, the wedge-shaped wave absorber can be made by coating the conductivity lossy material on the wedge-shaped conductor as shown in Fig. 5.1. The conductivity of used lossy material is 16.67 siemens per meter and ρ/ρ_{cu} is about 3.48×10^{6}.

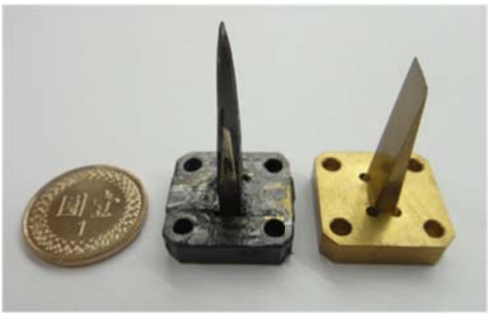


Figure 5.1 Copper wedge-shaped base (right) and wave absorber with a lossy conducting layer (middle).

5.2 The Measurement Results

The measurement results through the network analyzer are shown in the Fig. 5.2.

The reflection decreases as the thickness of lossy conductor increases (from H1 to H2). The thickness for H2 is 0.4 mm. Then we grind the tip and surface of the wave absorber to make them sharp and smooth (A1 and A2). As such, the absorption becomes better. S1 is the simulation result of wave absorber with a lossy layer (h = 0.4 mm). Obvious, they differ greatly in absorption because it is arduous to reconcile the sharp tip of model and the surface roughness of the absorber with the simulation by the manners coating and grinding. Especially, the shape of tip becomes blunt when it is coated with more lossy material. These are the main reasons for the inconsistent results. But we can predict the result of experiment will be better and similar to simulation for higher frequency yielding smaller skin depth.

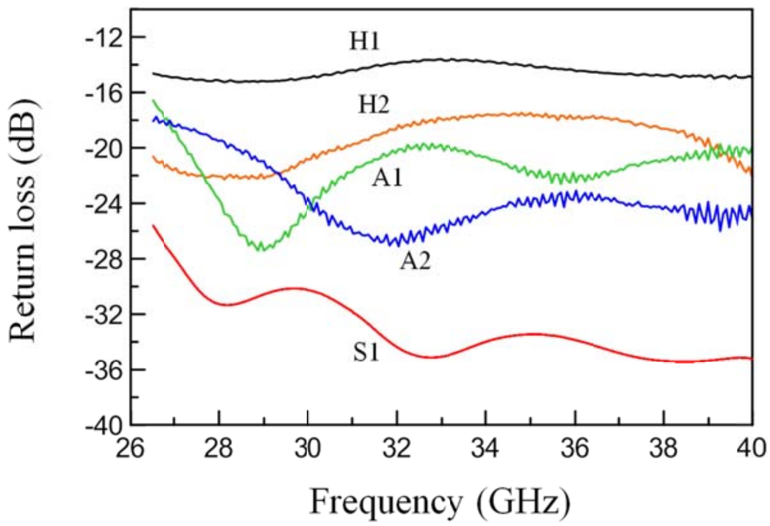


Figure 5.2 The PNA measurement results.

Chapter 6

The conclusion: Summary and Future Direction

Medium with high resistivity can enhance the absorption and reduce the reflection, but meanwhile, it also increases the skin depth, resulting in an increase in the requirement for thickness. However, for simplicity fabrication of high-frequency microwave absorbers, only a few ten of microns lossy material is needed and the higher the operating frequency is, the thinner the required lossy material is. Thus, based on these two conditions, a minimum resistivity of material or the thickness of lossy layer can be found to absorb a specified frequency band. The simulation and experiment results both demonstrate that such wave absorbers with a lossy conducting layer can accomplish the absorption for Ka-band microwaves and also imply this method is certainly applicable at higher frequency bands.

The simulation results also indicate that the shape is the most predominant factor in absorption performance. The geometrical advantage of the pyramidal absorber is its tip, a dot basically, which provides a good impedance match at first contact position and produces the minimum reflection of wave. Moreover, in terms of wedge-shaped absorbers, field polarization is also an important key to the issue. The power absorbed is proportional to the square of tangential magnetic field. Except for exactly 0^{o} and 90^{o}, the parallel polarization possesses the better performance than perpendicular polarization at any incident angles. The simulation results corroborate this argument and are consistent with the theoretical calculation of reflection coefficient in chapter 3. This information has great help for the fabrication of wave absorbers.

Based on this study, it has been well known what kind of materials and shapes are applicable to the high-frequency microwave absorber. But, we have only simulated wave absorbers in the waveguide; in fact, this is barely a fraction of an anechoic chamber. To understand the absorption performance of an anechoic chamber with many wave absorbers lined on the walls, it is necessary to measure under practical condition. The manner presented in this thesis makes the manufacturing of anechoic chambers easier to implement, serving as a convenient tool for high-frequency research and applications.

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Appendix

A. Discussion on Wedge-shaped Absorber-2

The absorption performance of wedge-shaped absorber-2 has been viewed at Sec. 4.3. It is much worse than wedge-shaped absorber-1 mainly because wedge-shaped absorber-2 [Fig. 4.2(b)] separates the cross-sectional area of waveguide into three parts waves cannot get into. Here, we simulate the following two types to examine the differences. These absorbers are analogous to wedge-shaped absorber-2.

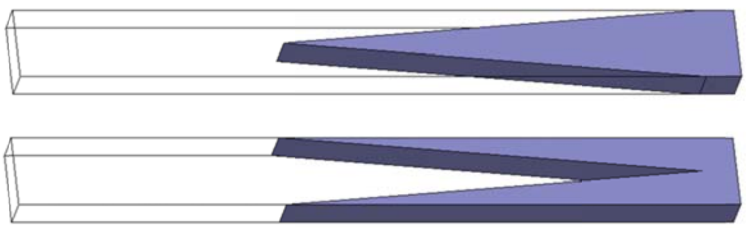

Figure A.1 Two absorbers are settled in Ka-band waveguides. Absorber-2a (top) separates the space of waveguide into two parts. Absorber-2b (bottom) is the complementary to absorber-2a.

The simulation results and the field plots are presented in Fig. A.2. For the absorber-2a, the cross-sectional area of waveguide is separated by absorber-2a into two small parts and, consequently, the cutoff frequency becomes two times of the original. The cutoff frequency for TE_{10} mode is given by

$$\omega_{cmn} = \pi c \left(\frac{m^2}{a^2} + \frac{n^2}{b^2} \right)^{\frac{1}{2}} \Rightarrow \omega_{cm0} = \pi c \frac{m}{a} \qquad \text{(A.1)}$$

where *a* is the length of waveguide and *b* is the width. Therefore, only a little wave can get into the peripheral of the absorber-2a and be absorbed, and most power reflects back to the port, which results in the impotent absorption performance. In the other hand, it is pretty clear that there is more power getting into the peripheral of absorber-2b so naturally the absorption performance is better.

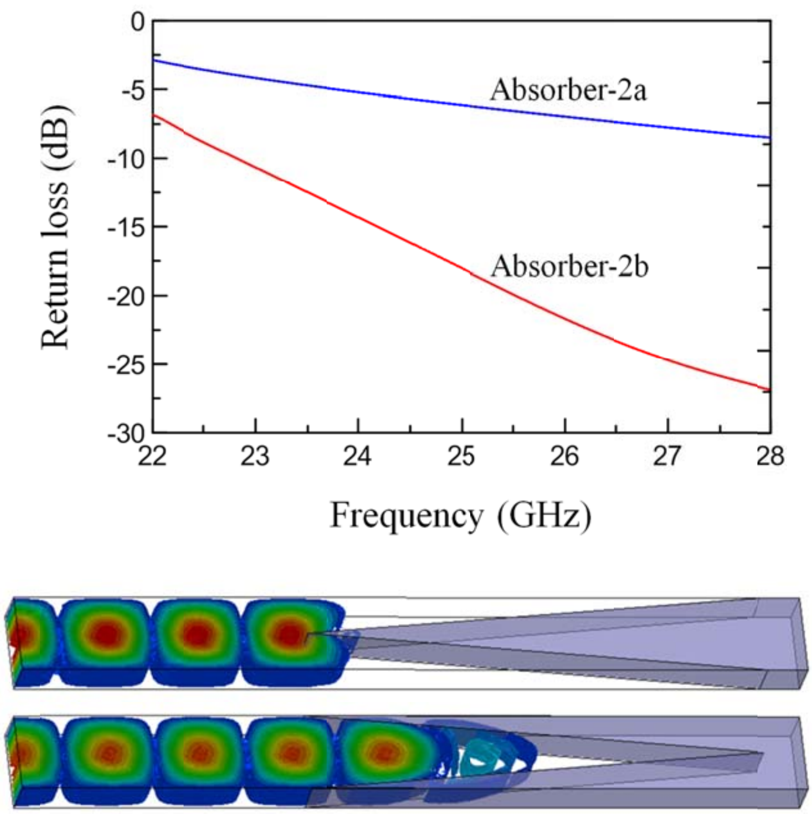

Figure A.2 The simulation results of the absorber-2a and absorber-2b, the plot of return loss versus frequency from 22 to 28 GHz (top) and the field plots at 28 GHz (bottom).

Due to the shape giving rise to the change of cutoff frequency in the waveguide, the type of absorber-2 is not good at absorbing electromagnetic waves. In absorber-1 case, although the cross-sectional area also reduces, the cutoff frequency is unchangeable in progress. Hence, the absorber-1 has the better absorption performance than absorber-2 even if not consider the field polarization. Figure A.3 shows the comparison between the wedge-shaped absorber-1 [Fig. 4.2(a)] and absorber-2.

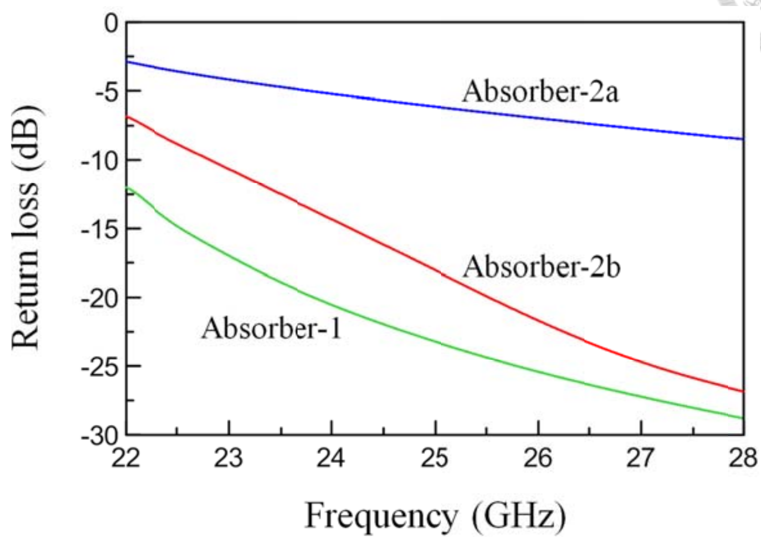

Figure A.3 The comparison between the wedge-shaped absorber-1 [Fig. 4.2(a)] and the absorber-2.