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The Interaction of Microwaves with Materials of Different Properties

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Abstract

Electromagnetic radiation, such as microwaves, are all the time reflected, transmitted, and/or absorbed by any kind of matter, glasses, conductors, water, ferrites, and so forth. Magnetic materials absorb greatly microwaves. The more magnetic, the more microwaves are absorbed. The aim of this chapter is to present the fundamental physics of the absorption of microwave power (energy per unit time) by ferrimagnetic and ferromagnetic matter in the nano and micro size scale. The magnetic moments and their collective modes are the basic microscopic absorbers under in-resonance and out-of-resonance conditions. Experimental setups and measurement techniques are described. The profiles of microwave absorption are described and connected to the micromagnetic environment that elicits such absorption. Section by section and the overall microwave power absorption profiles are related to the micromagnetic structures. Emphasis is made on nano- and micromagnets. These interactions of microwaves with nano- and micromagnets serve to infer microscopic magnetic information.

Keywords: microwaves technology, microwaves absorption, magnetic materials, reflection and transmission microwaves

1. Introduction

Microwaves pervade the whole universe; this was discovered by quite an accident by R. W. Wilson and A. A. Penzias in 1964 [1–3]; microwaves seem to bathe the earth and the space from all directions. Microwaves, also, pervade today's world of high technology [4, 5]. They are of tremendous scientific interest, and they are, just, indispensable in today's communication [6], military [7], medical [8], domestic appliances, scientific instruments [9, 10] (electron spin resonance, ESR/ferromagnetic resonance spectroscopy, FMR), microwave passive instruments [11–15], radars, spaceships, satellites, and so forth; they are also found in many industries such as automobile, data, memory and computer processing, and microwave instrumentation [14, 15]; the signal processing in the range of 5–50 GHz is quite

interesting for security, military, and communication applications [15, 16]. Modern microwave communication especially mobile communication and satellites requires high performance band-stop filter having high frequency selectivity, smaller size, high stop band attenuation, and low insertion loss [15, 17]. A good account of different applications is found in [17].

Most impressive, they are already playing an important role in the development of smart cities along with smart transportation, smart energy, smart health care, and so forth [18]. **Figure 1** shows an electromagnetic spectrum, making emphasis on the microwave region and the definition of its different bands. **Figure 2** shows an assortment of pictorial representations of some of the modern applications of microwaves.
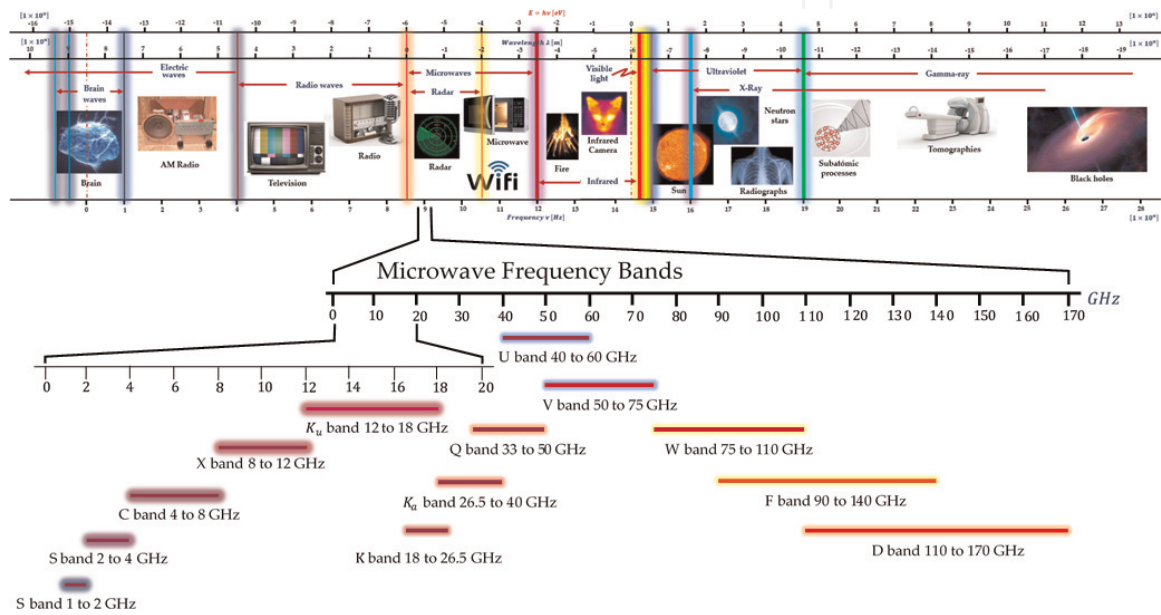
Figure 1.
The electromagnetic spectrum, making emphasis on the microwave region and its different bands.
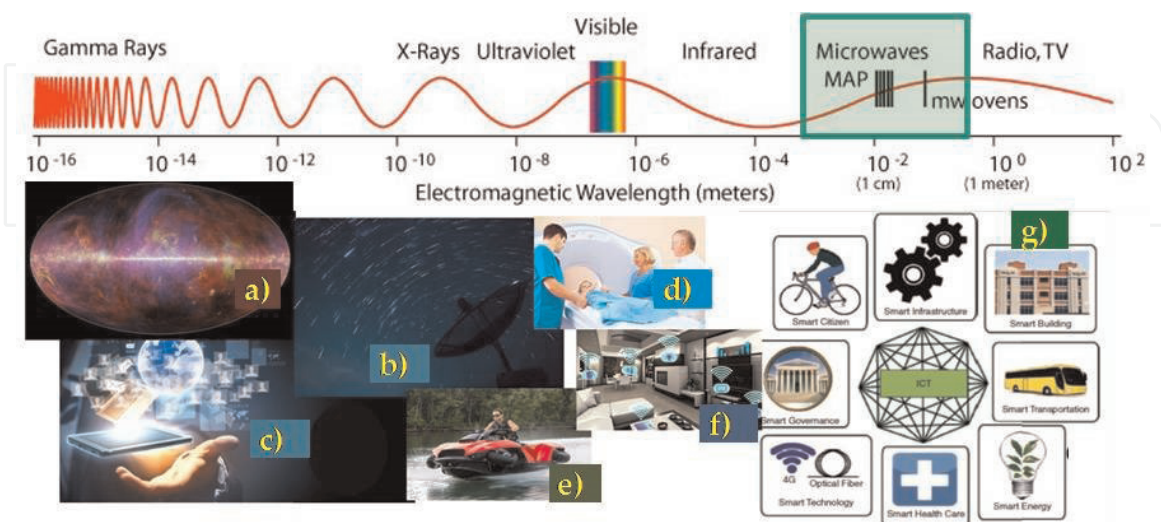
Figure 2.
The microwaves in the electromagnetic spectrum range from 300 MHz (1 m) to 300 GHz (1 mm) [3]. There are microwaves present in: (a) and (b) the whole universe, a microwave view captured by the European Space Agency's Planck satellite [19]; (c) the digital technology [20, 21]; (d) biomedical use [22]; (e) controversial proposition to propel starships [23]; (f) in telecommunications, Wi-Fi antennas; and (g) in the development of smart cities [18].
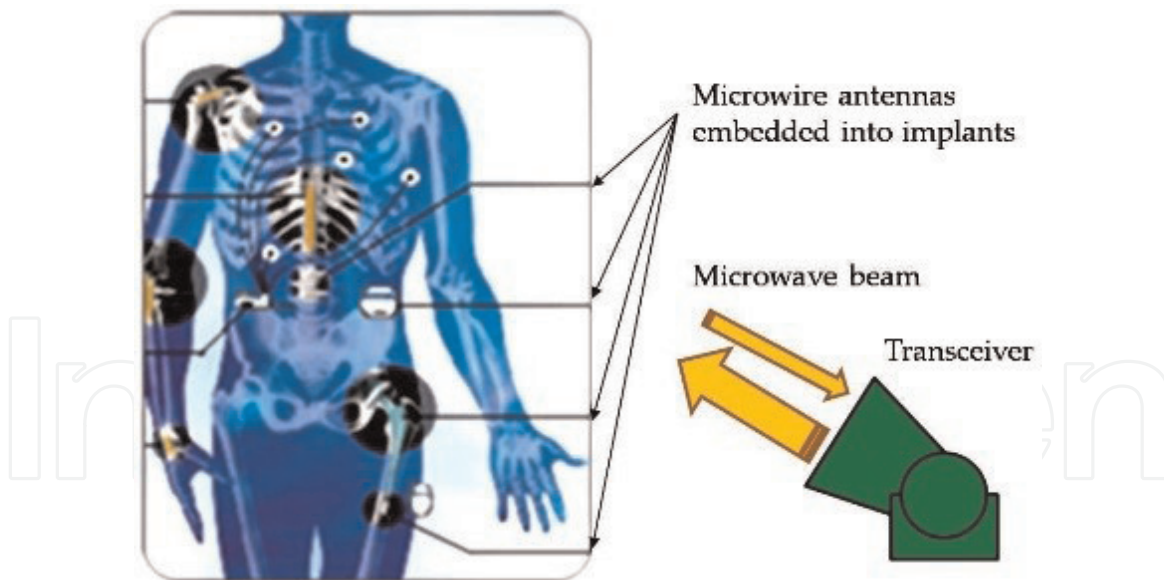
Figure 3.
Microwaves as the signals coming in and out from magnetic microwire sensors implanted in injured-surgery patients in order to follow postoperatory recovery [8]. The transceiver houses, both, the microwave source and the microwave detectors. Probably with the capacity to detect anisotropic distribution of signals.

In **Figure 3**, we show one of the most impactful applications of microwaves as the signals coming in and out from magnetic microwire sensors implanted in injured-surgery patients in order to follow postoperatory recovery [8]. The microwave beam should penetrate a considerable section of tissue then "hit" the magnetic wire, film, or rod, reflecting in many directions. Some microwaves will get back to the horn entrance of the transceiver, then detected and processed. The technology already exists and is already in use in atmospheric sciences [21] and in gun radars to detect speedy objects. These applications cannot be carried out with laser, for example, as laser light cannot penetrate tissue as microwaves do. It should be noted that in all the above examples, microwaves and radar work in open spaces and "hit" a target, and then some of the reflected beams are detected. Absorption in the medium itself and by obstacles reduces the reading at the detectors. There are also a great number of uses of microwaves inside tubes, pipes, and cavities. More controlled energy flux is attained and precision measurements can be done. We treat them after we give the fundamentals of the physics involved.

But, why are they (microwave) everywhere in this world and out of this world? It is because of the peculiarity of their electromagnetic properties and the way they interact with matter. They started to propagate through the universe at the epoch of recombination in the cosmic evolution. The cosmic microwave background (CMB) is the most ancient relic we have today of the beginning of the universe in the form of a big bang [24, 25]. It is the oldest electromagnetic radiation, older than visible light [26]. When atoms and nuclei appeared for the first time in the universe, microwaves started to interact with them immediately. Microwaves interact with atoms, nuclei, protons, electrons, molecules, clusters of molecules, and so forth. At the macroscopic scale, microwaves interact with all kinds of matter: rocks, gases, clouds, liquids (water and oceans), dielectrics, plasmas, ionosphere, metals, magnetic matter, and so on. It gets reflected, transmitted, and very frequently absorbed. Microwaves make atoms rotate (rotational excitation) and make electric dipoles jiggle frenetically, and when electric dipoles are part of dielectric materials, microwaves heat them. Microwaves make magnetic dipoles rotate and jump up magnetic energy states. The free electrons in metallic objects absorb greatly microwaves.

2. The electrodynamic properties of matter interact strongly with microwaves

Microwaves interact with matter, microscopically, through its constituent atoms, conduction electrons if present, and atomic magnetic dipoles if present. Yet, macroscopically, the effects of microwaves on matter are well described by the four Maxwell equations and the electrodynamic properties of matter: ϵ (electric permittivity), μ (magnetic permeability), and σ (electrical conductivity).

The interactions of microwaves with matter are of many kinds. The general electrodynamic properties of matter, ϵ, μ, and σ, determine completely their behavior when microwaves "hit" them. More specifically, the electric permittivity, ϵ, carries information on the polarization of a dielectric specimen (water, vapor, clouds, wood, glass, and so on) and is related to the number of electric dipoles as $\chi = N\alpha/(\epsilon_0 - N\alpha b)$ and $P = (\epsilon - \epsilon_0) E$, and $\epsilon = (1 + \chi) \epsilon_0$, with $P = \epsilon_0 \chi E$ and α the molecular polarizability of the medium and is generally anisotropic, i.e., $\alpha_x \neq \alpha_y \neq \alpha_z$; hence χ in general is anisotropic and is represented by a tensor in matrix form. Electric dipoles absorb greatly microwaves because these cause the electric dipoles to execute damped oscillations at the GHz frequency. The damped motion brings with it a complex $\epsilon = \epsilon' - i\,\epsilon''$ which is also a function of frequency [27, 28], in which ϵ'' takes account of the energy losses.

The magnetic permeability, μ, carries information on the magnetization capacity of a material that carries a number N of magnetic dipoles. They are related by $\mu = \mu_0(1 + \chi_m)$, $\mathbf{M} = \chi_m \mathbf{H}$, $\mathbf{M} = (\mu_r - 1)\mathbf{H}$, and $\mathbf{M} = \sum \mathbf{m}_i$, where $\mathbf{m}_i$ are microscopic, atomic magnetic moments (spin, S; orbital, m) [29, 30]. Magnetic dipoles absorb microwave energy because they precess with damping under the torques produced by the microwave's magnetic field; according to the Landau-Lifshitz [30] equation of motion: $\mathbf{M}'(t) = \gamma\mathbf{M}\times\mathbf{H}(\omega) - \alpha\mathbf{M}\times(\mathbf{M}\times\mathbf{H}(\omega))$, in which $\mathbf{H}(\omega)$ is the magnetic field component of the microwaves, γ is the gyromagnetic ratio, and α is the damping constant. The precession velocity and hence $\mathbf{M}'$ is different for different $\mathbf{H}(\omega)$. The higher the frequency, the higher the losses. The damped precessions bring with them the loss of microwave energy making the magnetic permeability complex and frequency-dependent, $\mu(\omega) = \mu'(\omega) - i\mu''(\omega)$. In addition, the response of $\mathbf{M}$ to $\mathbf{H}(\omega)$ is almost always direction-dependent, i.e., given H in direction x produces M_x, but the same H applied along y or z produces $M_y \neq M_z \neq M_x$, and this responses are properly described with a tensor $\boldsymbol{\chi_m}(\omega)$, or tensor $\mu(\omega)$. When the magnetic material is ferro- or ferrimagnetic and it is not magnetically saturated, its magnetic structure is comprised of domains and domain walls; the magnetization, M_a, within a domain, a, has a magnitude and a direction, **a**; the magnetization, M_b, within domain b, has another magnitude and another direction, **b**, and so on. The walls in between the domains have a considerable amount of magnetic energy [30, 31] and can move in translational or rotating dissipative and anisotropic motion following the LL damped equation of motion given above. An iconic set of magnetic materials that has been used in multiple microwave applications since its invention is the so-called microwave ferrites [11–15]. These materials present two magnetic structures and are very poor semiconductors; many authors approximate them as insulators. In any case, their conductivity is very small. However, metals have the largest conductivities and show particular interactions with microwaves. The conductivity of a metal, or conducting material, presents millions of "free" electrons to the actions of the electric, $J = \sigma E$, and magnetic fields, $q\mathbf{v}\times\mathbf{B}$, of the microwaves, and the Lorentz force makes them jiggle rapidly in the resistive medium they are, generating Joule losses and eventually heat. The higher the frequency of the microwaves, the conductivity can become frequency-dependent. In general, the responses $\epsilon(\omega)$, $\mu(\omega)$, and $\sigma(\omega)$ are heavily dependent on the frequency of the

microwaves. This is the dispersion characteristic of matter. As an example, clouds, water vapor, hot air, and sea water have quite different electrodynamic properties; that is why weather radar of longest wavelength (L-band, $\lambda \approx 1$ m, $\nu \approx 1.24$ GHz) is used routinely to penetrate clouds, and weather radar of shorter wavelengths (C-band, $\lambda \approx 0.25$ m, $\nu \approx 3.2$ GHz) is used to detect forests, and even X-band radar is used to measure altitude with respect to sea level due to its highest reflectivity on the surface of the ocean. The ϵ, the μ, and the σ of a material take away, absorb, energy any time they are microwave bathed, much the same way as when we heat coffee or meals in the microwave oven.

We describe here, in a nutshell form, the fundamental physics involved in the interactions of microwaves with matter with emphasis on magnetic matter. Today science and technology are able to produce, control, direct, and amplify microwaves in the laboratory and in devices and high-technology instruments and equipments [9, 11, 19, 21]. The electromagnetism of microwave devices and instruments is an integral part of today's technological world. And the electrodynamics of microwaves is governed by Maxwell's equations as applied to ϵ, μ, and σ materials. We present these equations and the partial differential wave equations that are obtained from them with the expressions of their solutions.

3. Maxwell's equations are the universe of electromagnetic (electrodynamic) phenomena

Richard Feynman (from Feynman's Lectures, Vol. 2, Chap. 21): "So here is the center of the universe of electromagnetism, the complete theory of electricity and magnetism, and of light; a complete description of the fields produced by any moving charges; and more. It is all here. Here is the structure built by Maxwell, complete in all its power and beauty. It is probably one of the greatest accomplishments of physics. To remind you of its importance, we will put it all together in a nice frame:"

$$\nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}(\rho_f - \nabla \cdot \mathbf{P}) \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2}$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial \mathbf{t}} = \mathbf{0} \tag{3}$$

$$\nabla \times \mathbf{B} - \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial \mathbf{t}} = \mu_0 \left(\mathbf{J}_f + \frac{\partial \mathbf{P}}{\partial \mathbf{t}} + \nabla \times \mathbf{M} \right) \tag{4}$$

He states such definite statements once he obtains the general solutions for the electric potential, V, and the vector potential, **A**, for charges in motion. We have changed Feynman's notation φ for V to denote electric potential, and we use MKS units. In these equations ρ's are charge densities, **J**'s are free currents, **P** is the polarization vector, **M** the magnetization vector, and **E** and **B** the electric and magnetic fields. We already defined ϵ, μ, and σ above.

We are not concerned here in the detail deduction of Maxwell's equations, nor the deduction of electromagnetic waves from them. Reflection and refraction and absorption of microwaves in conducting magnetic and dielectric materials are

presented in graphical form along with the principal equations that govern them. The deduction of such results is too long, and they are developed in a number of excellent, well-established textbooks [27–33]. The deduction of electromagnetic fields and waves from Maxwell's equations does not impose any restriction on the wavelength-frequency, as shown in **Figure 1**. The result is quite general, but we are interested and focused on microwaves interacting with ϵ, μ, and σ matter. But real materials, the air, ocean, hurricanes, semiconductors, ferrites, conductors, submarines, cars, planes, ferrous materials, steel, and magnets, which are of technological relevance, are dispersive, anisotropic, and absorb microwave energy [19, 28, 31]; then the adequate ϵ and μ become complex (dispersion and dissipation effects taken into account) and tensorial (anisotropy effects taken into account) [28, 31, 32]:

$$\boldsymbol{\epsilon_{ij}} = \begin{bmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33} \end{bmatrix} = \begin{bmatrix} \epsilon_x & 0 & j\epsilon_{13} \\ 0 & \epsilon_y & 0 \\ -j\epsilon_{31} & 0 & \epsilon_z \end{bmatrix} \tag{5}$$

$$\boldsymbol{\mu_{ij}} = \begin{bmatrix} \mu_{11} & \mu_{12} & \mu_{13} \\ \mu_{21} & \mu_{22} & \mu_{23} \\ \mu_{31} & \mu_{32} & \mu_{33} \end{bmatrix} = \begin{bmatrix} \mu & 0 & jk \\ 0 & 1 & 0 \\ -jk & 0 & \mu \end{bmatrix} \tag{6}$$

All the elements of both material electrodynamic tensors are in general dependent on frequency, $\boldsymbol{\epsilon_{ij}}(\omega)$ and $\boldsymbol{\mu_{ij}}(\omega)$. In what follows we will continue to use just the symbols ϵ and μ. However, we understand their complexity. Using all four field vectors **E**, **D**, **B** and **H**,

$$\nabla \cdot \mathbf{D} = \rho_f \tag{7}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{8}$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = \mathbf{0} \tag{9}$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J_f} \tag{10}$$

Remember that **D** is $\epsilon_0\mathbf{E} + \mathbf{P}$ and $\mathbf{P} = \epsilon_0\chi_e\mathbf{E}$, while **B** is $\mu_0(\mathbf{H} + \mathbf{M})$, and $\mathbf{M} = \chi_m\mathbf{H}$, and $\mu = \mu_0\mu_r = \mu_0(1 + \chi_m)$. Notice that the material's electrodynamics response is within **D** and **B**. In fact, the fields **D** and **B** are valued inside the material bodies. We are interested in microwave fields that in free space and in ϵ, μ, and σ matter, the field components **E** and **H** are sinusoidal functions of time and orthogonal to each other. In such case we can replace the time derivative by factors of $j\omega$. Setting also $\mathbf{D} = \epsilon\mathbf{E}$ and $\mathbf{B} = \mu\mathbf{H}$,

$$\nabla \cdot \epsilon\mathbf{E} = \rho_f \tag{11}$$

$$\nabla \cdot \mu\mathbf{H} = 0 \tag{12}$$

$$\nabla \times \mathbf{E} + j\omega\mu\mathbf{H} = 0 \tag{13}$$

$$\nabla\times\mathbf{H}-j\omega\epsilon\mathbf{E} = \mathbf{J}_f \tag{14}$$

From Maxwell' equations inhomogeneous wave equations are obtained for the fields **E** and **H**. The procedure is taking the rot ($\nabla\times$) of the two rot Maxwell equations, rearranging terms and using the divergence equations; we find for a medium ϵ, μ, and σ nearby $(\rho_f, \mathbf{J}_f)$ microwave source:

$$\nabla^2\mathbf{E}-\epsilon\mu\frac{\partial^2\mathbf{E}}{\partial t^2} = \nabla\left(\frac{\rho_f}{\epsilon}\right)+\mu\frac{\partial\mathbf{J}_f}{\partial t} \tag{15}$$

$$\nabla^2\mathbf{B}-\epsilon\mu\frac{\partial^2\mathbf{B}}{\partial t^2} = \mu\nabla\times\mathbf{J}_f \tag{16}$$

Far from the microwave sources (centimeters, meters, kilometers, and, even, light years), we can safely drop the "source" terms, and homogeneous partial differential equations are left:

$$\nabla^2\mathbf{E} - \epsilon\mu\frac{\partial^2\mathbf{E}}{\partial t^2} - \mu\sigma\frac{\partial\mathbf{E}}{\partial t} = 0 \tag{17}$$

$$\nabla^2\mathbf{H} - \epsilon\mu\frac{\partial^2\mathbf{H}}{\partial t^2} - \mu\sigma\frac{\partial\mathbf{H}}{\partial t} = 0 \tag{18}$$

It should be stressed that these identical wave equations describe attenuated waves. This comes naturally from the third term that includes magnetic permeability, electric conductivity, and the first time derivative of each field. The solutions of these equations are readily obtained by separation of variables [27]. The detailed deduction of these mathematical expressions is lengthy and elaborated; after such work, we find the fields to be transverse and plane-polarized for which the x-direction for **E** is chosen; hence **H** (($j\omega\mu$)**H** = $\nabla \times$ **E**) goes along the y-direction and propagates along the z-direction with a flux of energy density **S** = **E** $\times$ **H** [27] and an impedance Z = E/H. The solutions are summarized in **Table 1**.

Here we show in the form of a table (deductions are given in [27, 28, 31]) the solutions for E and H for propagation in free space and in a dielectric material and in a conducting material. In this concise form, we highlight the most relevant features and parameters of the solutions. When we put back the solutions found for a σ, μ, and ϵ material into the wave equations, we obtain the dispersion relation: $(-k^2 + \omega^2\epsilon\mu - j\omega\sigma\mu)\mathbf{E} = 0$, which is shown in the third column for each

Propagation	Equation	Dispersion Relation	Impedance Z[ohms]	Some Parameters
Vacuum	$E = E_m \exp j(\omega t - kz)$ $H = H_m \exp j(\omega t - kz)$	$(-k^2 + \omega^2\epsilon_0\mu_0)E = 0$	$Z_0 = \frac{E}{H} = \frac{k}{\omega\epsilon_0} = \frac{\omega\mu_0}{k} = \frac{1}{\epsilon_0 c} = \mu_0 c = \left(\frac{\mu_0}{\epsilon_0}\right)^{1/2}$	$k \to$ real $Z \to$ real Skin Depth $\delta = 0$ No losses
Nonconductors	$E = E_m \exp j(\omega t - kz)$ $H = H_m \exp j(\omega t - kz)$	$(-k^2 + \omega^2\epsilon\mu)E = 0$	$Z = \frac{E}{H} = \left(\frac{\mu}{\epsilon}\right)^{1/2} = 377\left(\frac{\mu_r}{\epsilon_r}\right)^{1/2}$	$k \to$ real $Z \to$ real Skin Depth $\delta = 0$ No losses
Magnetic Conductors, possibly dielectric	$E = E_m \exp(-\alpha z) \exp j(\omega t - \beta z)$ $H = H_m \exp(-\alpha z) \exp j(\omega t - \beta z - \theta)$	$(-k^2 + \omega^2\epsilon\mu - j\omega\sigma\mu)E = 0$	$Z = \frac{E}{H} = \frac{k}{\omega\epsilon - j\sigma} = \frac{\omega\mu}{k}$ $= \left(\frac{\mu}{\epsilon}\right)^{1/2}\frac{\exp j \arctan(\alpha/\beta)}{(1 + \mathcal{D}^2)^{1/4}}$ $\approx 377\left(\frac{\mu_r}{\epsilon_r}\right)^{1/2}\frac{\exp j \arctan(\alpha/\beta)}{(1 + \mathcal{D}^2)^{1/4}}$	$k = \beta - j\alpha \to$ necessary complex α gives absorption; $\alpha \neq \beta$ $z \to$ necessary complex $\delta = \frac{1}{\alpha} = \left(\frac{2}{\sigma\mu\omega}\right)^{1/2}$
Very Good Conductors	$E = E_m \exp\left[j\left(\omega t - \frac{z}{\delta}\right) - \frac{z}{\delta}\right]$ $H = \left(\frac{\sigma}{\omega\mu}\right)^{1/2} E_m \exp\left[j\left(\omega t - \frac{z}{\delta} - \frac{\pi}{4}\right) - \frac{z}{\delta}\right]$	$(-k^2 + \omega^2\epsilon_0\mu_0 - j\omega\sigma\mu_0)E = 0$	$Z = 377\left(\frac{\mu_0}{\epsilon_0}\right)^{1/2}\frac{1}{(1 + \mathcal{D}^2)^{1/4}}$	$k = \beta - j\alpha \to$ necessary complex α gives absorption; $\alpha = \beta$ $z \to$ becomes real $\delta = \frac{1}{\alpha} = \left(\frac{2}{\sigma\mu_0\omega}\right)^{1/2}$

Table 1.
Wave solutions in different media (no bounds considered).

electrodynamic medium. A summary of **E** and **H** solutions, along with the dispersion relations, impedance, attenuation, and skin depth, is presented in **Table 1** for different materials characterized by particular sets of electrodynamic properties (σ, μ, ϵ).

In the ideal case of propagation of microwaves in air, the phenomenon of attenuation (absorption of microwave energy, $E = h\nu$, in the form of photons) does not take place. In reality, quite a substantial attenuation of microwaves takes place when they propagate in air (molecules that constitute the air readily absorb microwaves. Such energy excites efficiently rotation and vibration degrees of freedom). The Wi-Fi technology [5, 6, 16] knows very well this fact, that is why there exist in the market potentiators of Wi-Fi signal to cover adequately a room of several meters square. The problem of attenuated signal becomes worse if panels, wall, wood, and metals come in the way of the propagation. The microwave engineer, designer, and scientist know that the main factor which causes attenuation in microwave propagation is water, H_2O. War technology for decades has faced the problem of the no radar signal penetration in the oceans to a depth enough to detect submarines. So, in order to propagate microwaves in the atmosphere or in the ocean, for at least 1 m, or longer distances, it is mandatory to guide such electromagnetic GHz waves or increase considerably their power content, Poynting vector, $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ being proportional to its power content per unit area.

3.1 Microwaves in spaces with obstacles: propagation, reflection, refraction, and absorption

In the modern microwave Wi-Fi, military, radar communication systems, the microwaves have to travel through "free space" to reach detectors and receivers, but it is pretty common in urban areas that the propagation encounters obstacles, such as buildings, windows, walls, bridges, metallic structures, and fog. At the surface of those obstacles, reflection, absorption, refraction, and dispersion of the microwaves occur. When microwaves hit obstacles, energy is irremediably lost at these obstacles. This fact could be used to detect that precisely an obstacle is present and fine measurements of the reflected or refracted microwave energy could give valuable information on the electromagnetic character (ϵ, μ, σ) of such obstacle. This is how radar in air and other atmospheric microwave instruments detect objects (the obstacles themselves). But many other times, obstacles, like walls, wood floors, and concrete structures, attenuate, disperse, and deviate the microwaves, and reception at the desired site is deficient or completely lost. In such cases midway potentiators are used to increase the signal power to compensate the losses at the obstacles. These examples are meant to show how important are the reflection, absorption, refraction, and dispersion of microwaves in real-world applications. The laws that govern these phenomena are Snell law and Fresnel laws of reflection and refraction. They are obtained as a consequence of the boundary conditions applied to the interface, any interface between two media as shown in **Figure 4**. The reflected (transmitted) waves carry an energy R(T) per unit of incident energy. Appropriate detectors (common radiometers, photocells, diodes) measure with ease R and T, also depicted in **Figure 4**. These radar and Wi-Fi microwaves hit all the time buildings, hot air, street floors, and so forth, and, at all times, they are reflected, absorbed, and refracted [16–20] as illustrated in **Figure 4**.

3.2 Boundary conditions that microwaves fulfill at the interface between any two media

The general boundary conditions the electromagnetic fields, **E**, **D**, **H** and **B**, must satisfy at the interface of any two (σ, μ, ε) media which are easily obtained
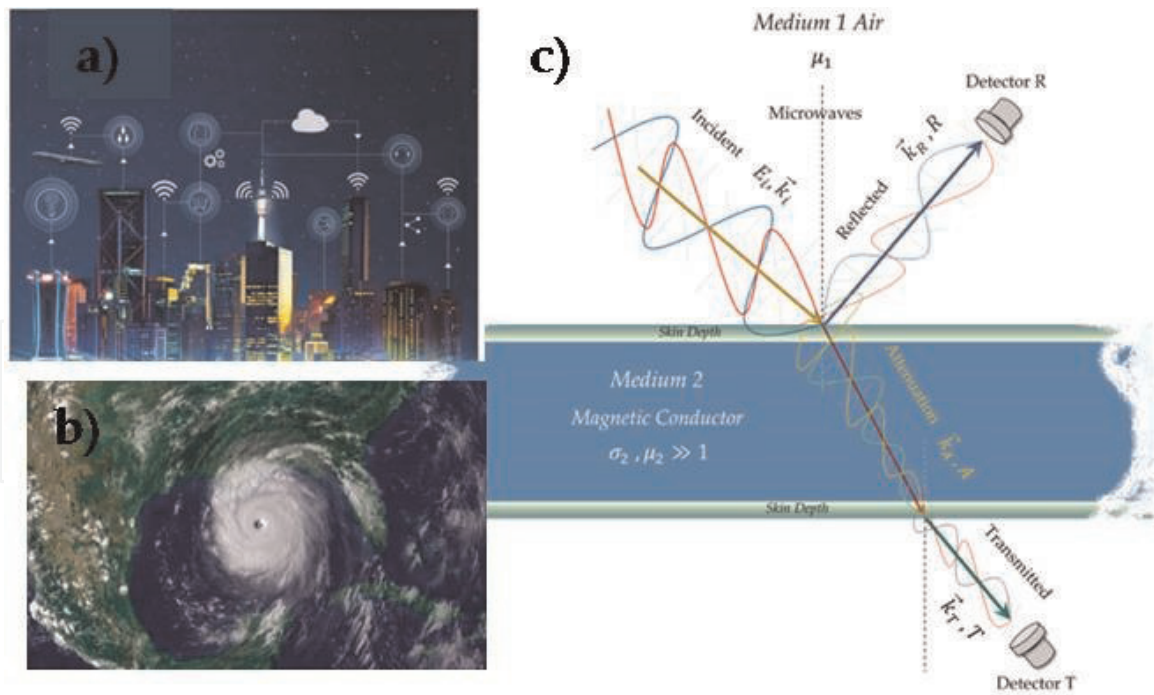
Figure 4.
Microwaves bounce back from virtually any material. (a) The Wi-Fi signal being reflected and refracted from anything can be in an urban city area. Wi-Fi and radar signals are commonly present in the air in any city. These microwaves hit buildings, windows, fog, hot air, street floors, and so forth; at all times they are reflected (R), absorbed (A), and refracted (T) [16–20], (b) satellite weather radar detecting and following 2005 Katrina hurricane trajectory just about to land [21], and (c) abstraction of any process in which microwaves hit a body of matter.

from applying Gaus law to a small cylinder placed through the two media and from applying Ampere's circuital law to a closed (rectangular) trajectory, again, crossing through both media. The results are [27–29] $E_{1t} = E_{2t}$; $H_{1t} = H_{2t}$, i.e., the tangential components of **E** and **H** must be continuous through the interface. And $D_{1n} = D_{2n}$; $B_{1n} = B_{2n}$, i.e., the normal components of **D** must be continuous, provided the interface does not carry any charge and the normal components of **B** must be continuous. All this is represented in **Figure 5**.

Since medium 1 sustains the incident and reflected fields, $E_1 = E_i + E_r$; $D_1 = D_i + D_r$; $H_1 = H_i + H_r$; and $B_1 = B_i + B_r$. In medium 1 a sum of vector fields must be formed. In medium 2 there are only the transmitted fields E_t, D_t, H_t, and B_t.

When boundaries are present on purpose or as an inevitable obstacle, the incident microwaves reflect and refract, and the formal treatment will conduct us to Snell law and the Fresnel equations for incidence with **H** parallel to the plane of incidence as shown in **Figures 6** and **7** to the Fresnel equations with **H** perpendicular to the plane of incidence as shown in **Figure 8**.

In **Figure 6a**, medium 1 is the space where we want to propagate some microwave signal and medium 2 being a window, a wall, water, wood, concrete, metallic sheets, a building in front of us, etc. A very common situation is when sunlight shines and goes through a glass window; in this case most of the light goes through and illuminates the room. And yet, part of it is reflected, and part is absorbed (the energy of which heats up the glass window itself). A second very common situation generated by the modern wireless communication technology is the Wi-Fi signal (it plays exactly the same role as the sunshine in the above illustration). The typical Wi-Fi signal is around 2.3 GHz, and the newest cable boxes are delivering to our home rooms ≈ 5.2 GHz with about 1 W power.

When the obstacle (medium 2) is made of materials that are also ferromagnetic or ferrimagnetic (ferrites), the absorption will increase considerably because the magnetic moments of the material absorb energy from the Wi-Fi waves.
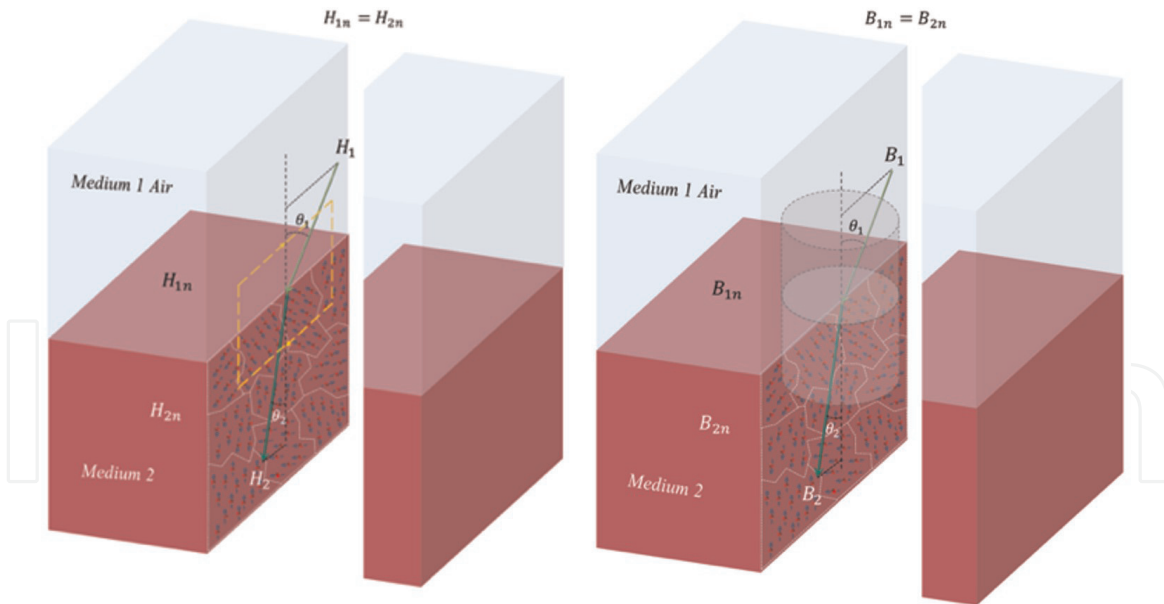
Figure 5.
*Boundary conditions for the magnetic field **H** and for the magnetic induction. The condition $B_{1n} = B_{2n}$ is obtained from $\nabla \cdot \boldsymbol{B} = 0$, and $H_{1t} = H_{2t}$ is obtained from Ampere's circuital law. Similar vector diagrams for the **D** and **E** vectors are considered, and the conditions, $D_{1n} = D_{2n}$ and $H_{1t} = H_{2t}$, are obtained.*
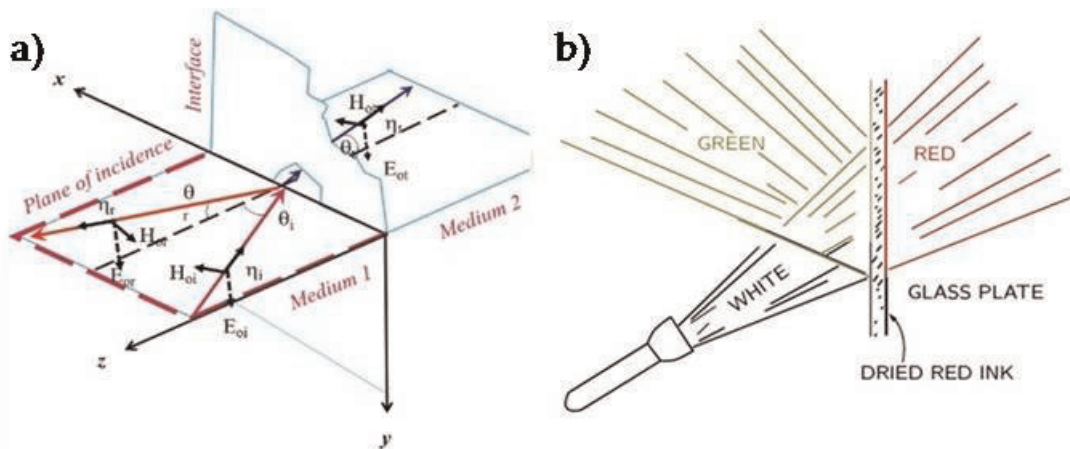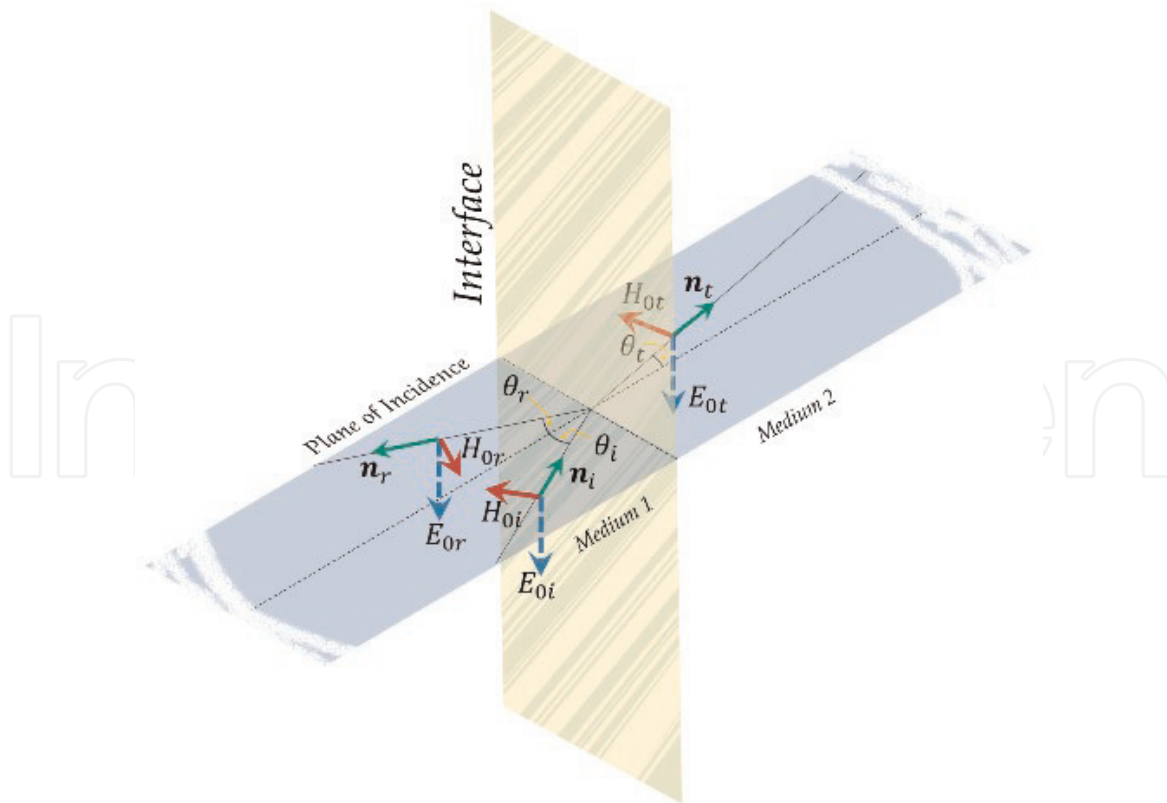

Figure 6.
*Incident, reflected, and transmitted microwaves at any kind of interface. (a) **H** parallel to the plane of incidence. $\boldsymbol{n}_i$, $\boldsymbol{n}_r$, and $\boldsymbol{n}_t$ are unitary vectors normal to the respective front-plane waves and pointing in the propagation direction, $\boldsymbol{k} = k\boldsymbol{n}$. θ_i, θ_r, and θ_t are, respectively, the incident, the reflected, and the transmitted direction of the waves with respect to the dotted line axis. (b) Feynman's Lintern. A white light beam incident on a glass that has been coated with red paint refracts red light and reflects the green component; hence $\omega_t \neq \omega_r$.*

Conductors (materials with free electrons) will absorb Wi-Fi wave energy by virtue of the term JE which becomes Joule heating. Abstracting the cases mentioned above, we consider, as the first case, the incidence of a plane electromagnetic wave on the interface of two media as shown in **Figure 7**; the incident electric field is of the form

$$\mathbf{E_i} = \mathrm{E_{0i}} \exp j\omega_i \left(t - \frac{\mathbf{n_i} \cdot \mathbf{r}}{u_1} \right) \mathbf{n_i} \tag{19}$$

The reflected and the refracted waves are $\mathbf{E_r} = \mathbf{E_{0r}} \exp j\omega_r \left(t - \frac{\mathbf{n_r} \cdot \mathbf{r}}{u_1} \right)$ and

$\mathbf{E_t} = \mathbf{E_{0t}} \exp j\omega_t \left(t - \frac{\mathbf{n_t} \cdot \mathbf{r}}{u_2} \right)$, where u_1 and u_2 are the velocities of the waves in mediums 1 and 2, respectively. The E_{0i}, E_{0r}, and E_{0r} are the amplitudes of the respective

Figure 7.
The incident wave with magnetic vector in the incidence plane. Snell laws demand that the reflected and transmitted magnetic vectors are also in the same plane. The arrows indicate the directions of the vectors involved. The Poynting vectors $S_{i,r,t} = E_{i,r,t} \times H_{i,r,t}$ point always in the direction of propagation of that particular wave, and its magnitude indicates how much electromagnetic energy is flowing in that direction.

waves. For linear, isotropic, homogeneous media (LIH), and nondispersive, it is readily shown that the three vector fields E_i, E_r, and E_t are identical functions of time [27–29, 32–34], $\omega_i = \omega_r = \omega_t$. For dispersive media, at least [27–29, 32–34] two frequencies are different $\omega_i \neq \omega_t \neq \omega_r$.

As the simple example illustrated in **Figure 6b**, given by Feynman [29], shows "A large imaginary part of the index of refraction (or equivalently a large imaginary component of k, k") means a strong absorption. So there is a general rule that if any material gets to be a *very good absorber at any frequency (let's say red)*, the waves are strongly reflected at the surface, and very little gets inside to be absorbed. You can see this effect with strong dyes. Pure crystals of the strongest dyes have a metallic shine. Red ink absorbs out the greens of transmitted light, so if the ink is very concentrated, it will exhibit a strong surface reflection for the frequencies of green light (see **Figure 6b**).

But in our case the three fields must be identical functions of space and time at any point on the interface [27–29, 32, 33]. From such requirement, it follows that $\theta_i = \theta_r$ the angle of incidence is equal to the angle of reflection. This is the law of reflection. It is also obtained that $[\sin\theta_t / \sin\theta_i] = [n_1/n_2]$, with n = k/λ. This equation is the well-known Snell law. With these results at hand, we now write:
$E_i = E_{0i} \exp j[\omega t - k_1(x\sin\theta_i - z\cos\theta_i)]$, $E_r = E_{0r} \exp j[\omega t - k_1(x\sin\theta_i - z\cos\theta_i)]$, $E_t = E_{0t} \exp j[\omega t - k_2(x\sin\theta_t - z\cos\theta_t)]$; the respective magnetic fields are $H_p = (k/\omega\mu)E_p$, with p = i, r, t.

Now we proceed to determine the quantities E_{0i}, E_{0r}, E_{0t} that assure the continuity of the tangential components of **E** and **H** at the interface:
$E = E_0 \exp j(\omega t - k_\eta \cdot r)n_\eta$ and $H = (k_\eta/\omega\mu_{1,2})E_0 \exp j(\omega t - k_\eta \cdot r)n_\eta$, with $k_\eta = k_i$, k_r, k_t with η = i, r, t the propagation vectors and $\mu_{1,2}$ the magnetic permeability of medium 1 or medium 2.

We have four unknowns: (E_{0r}, H_{0r}) and (E_{0t}, H_{0t}). And we have four equations, which are the four boundary conditions. E_{0i} and H_{0i} are taken as known since they are the primary waves that we send-propagate from a "controllable" source. We would find the unknowns normalized by E_{0i} and H_{0i}. Of course the problem can be inverted, and we could start knowing the transmitted waves and would like to determine the initial fields, E_i, H_i, that come from an unknown (potentially fundamental) source. Present cosmological problems are exactly of this type [3, 35, 36]. Continuity of the tangential components of **E** requires

$$E_{0i} + E_{0r} = E_{0t} \tag{20}$$

At any point and at any time at the interface. Likewise, continuity of the tangential component of the magnetic field requires $H_{0i} \cos \theta_i - H_{0r} \cos \theta_i = H_{0t} \cos \theta_t$ which becomes $\frac{k_1}{\omega \mu_1}(E_{0i} - E_{0r}) \cos \theta_i = \frac{k_2}{\omega \mu_2} E_{0t} \cos \theta_t$. But $k = n/\lambda$, so

$$\frac{n_1}{\mu_1}(E_{0i} - E_{0r}) \cos \theta_i = \frac{n_2}{\mu_2} E_{0t} \cos \theta_t \tag{21}$$

Algebraic Eqs. (20) and (21) are readily solved for unknowns E_{0r} and E_{0t}:

$$\frac{n_1}{\mu_1} E_{0i} \cos \theta_i - \frac{n_1}{\mu_1} E_{0r} \cos \theta_i = \frac{n_2}{\mu_2} E_{0t} \cos \theta_t \tag{22}$$

Using (20) $E_{0i} + E_{0r} = E_{0t}$ and after some algebra, we obtain [27]: the amplitude of the fields E_{0r}/E_{0i} and E_{0t}/E_{0i}:

$$\left(\frac{E_{0r}}{E_{0i}}\right)_N = \frac{\frac{n_1}{\mu_{r1}} \cos \theta_i - \frac{n_2}{\mu_{r2}} \cos \theta_t}{\frac{n_1}{\mu_{r1}} \cos \theta_i + \frac{n_2}{\mu_{r2}} \cos \theta_t} \tag{23}$$

$$\left(\frac{E_{0t}}{E_{0i}}\right)_N = \frac{2\frac{n_1}{\mu_{r1}} \cos \theta_i}{\frac{n_1}{\mu_{r1}} \cos \theta_i + \frac{n_2}{\mu_{r2}} \cos \theta_t} \tag{24}$$

where N indicates that E is normal to the incidence plane and/or H is in the plane of incidence.

In the case the three H vectors are perpendicular to the plane of incidence, **Figure 8**, we have: $H_{0i} - H_{0r} = H_{0t}$. In terms of **E** fields

$$\frac{n_1}{\mu_1}(E_{0i} - E_{0r}) = \frac{n_2}{\mu_2} E_{0t} \tag{25}$$

$$(E_{0i} + E_{0r}) \cos \theta_i = E_{0t} \cos \theta_t \tag{26}$$

After some algebra and rearranging terms, we obtain E_{0t}/E_{0i}. Hence:

$$\left(\frac{E_{0r}}{E_{0i}}\right)_P = \frac{-\frac{n_2}{\mu_{r2}} \cos \theta_i + \frac{n_1}{\mu_{r1}} \cos \theta_t}{\frac{n_1}{\mu_{r1}} \cos \theta_t + \frac{n_2}{\mu_{r2}} \cos \theta_i} \tag{27}$$

$$\left(\frac{E_{0t}}{E_{0i}}\right)_P = \frac{2\frac{n_1}{\mu_{r1}} \cos \theta_i}{\frac{n_1}{\mu_{r1}} \cos \theta_t + \frac{n_2}{\mu_{r2}} \cos \theta_i} \tag{28}$$

Here P denotes that the $\mathbf{H}_i$, $\mathbf{H}_r$, $\mathbf{H}_t$ are all parallel to the interface. In the case of normal incidence with all the **H** vectors parallel to the interface, $\theta_i = \theta_t = 0$ (**Figure 8**), and $\cos \theta_i = \cos \theta_t = 1$ in the above equations.
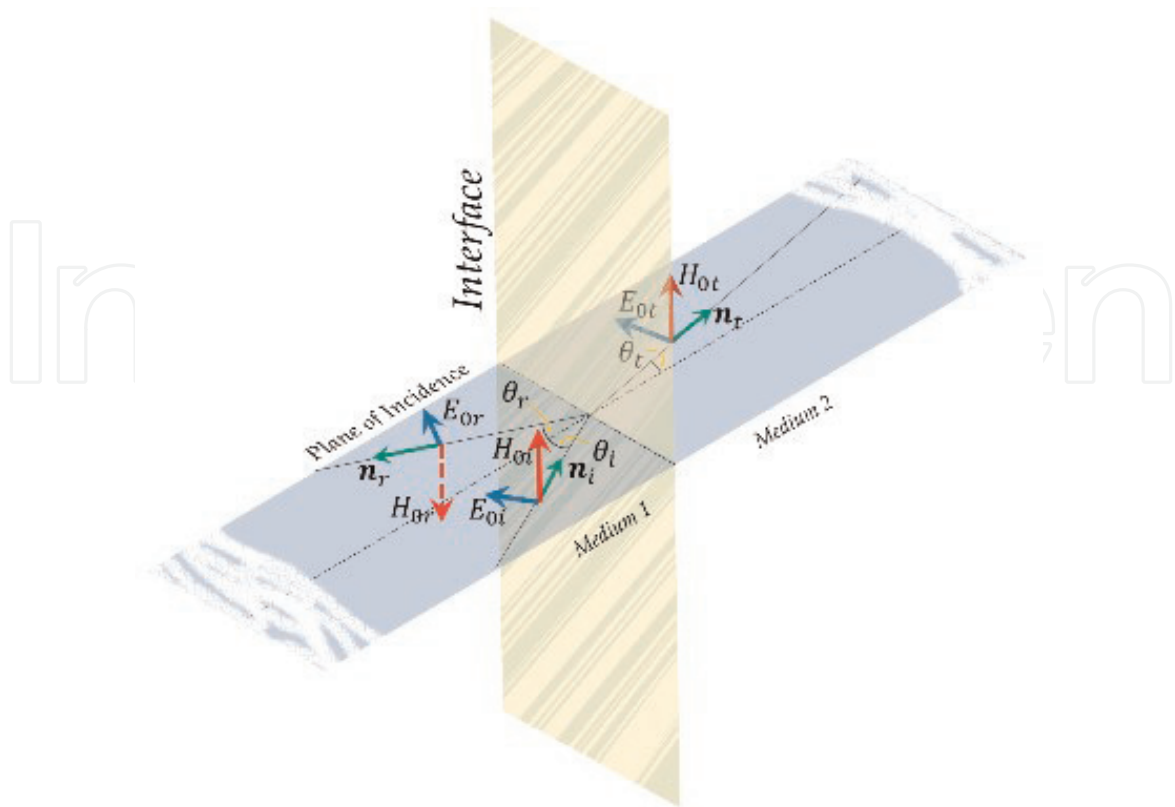
3.3 The coefficients of reflection (R) and transmission (T) and conservation of energy $(\mathbf{R} + \mathbf{T} = \mathbf{1})$

$$R = \left[\frac{\mathbf{S}_{r \ av} \cdot \mathbf{n}}{\mathbf{S}_{i \ av} \cdot \mathbf{n}}\right] = \frac{E_{0 \ r}^2}{E_{0 \ t}^2} \tag{29}$$

$$T = \left[\frac{\mathbf{S}_{t \ av} \cdot \mathbf{n}}{\mathbf{S}_{i \ av} \cdot \mathbf{n}}\right] = \left(\frac{\epsilon_{r \ 2}}{\epsilon_{r \ 1}}\right)^{1/2} \frac{E_{0 \ t}^2 \cos \theta_t}{E_{0 \ t}^2 \cos \theta_i} = \frac{n_2 E_{0 \ t}^2 \cos \theta_t}{n_1 E_{0 \ t}^2 \cos \theta_i} \tag{30}$$

$$R_N = \left\{\frac{\left(\frac{n_1}{n_2}\right) \cos \theta_i - \cos \theta_t}{\left(\frac{n_1}{n_2}\right) \cos \theta_i + \cos \theta_t}\right\}^2 \tag{31}$$

$$T_N = \frac{4\left(\frac{n_1}{n_2}\right) \cos \theta_i \cos \theta_t}{\left\{\left(\frac{n_1}{n_2}\right) \cos \theta_i + \cos \theta_t\right\}^2} \tag{32}$$

Figure 8.
Both media are dielectric and magnetic, and the magnetic field component H_i is parallel to the interface, and so the reflected and the transmitted magnetic components, H_r, H_t, are also parallel to the interface.

$$R_P = \left\{ \frac{-\cos\theta_i + \left(\frac{n_1}{n_2}\right)\cos\theta_t}{\cos\theta_i + \left(\frac{n_1}{n_2}\right)\cos\theta_t} \right\}^2 \tag{33}$$

$$T_p = \frac{4\left(\frac{n_1}{n_2}\right)\cos\theta_i \cos\theta_t}{\left\{\cos\theta_i + \left(\frac{n_1}{n_2}\right)\cos\theta_t\right\}^2} \tag{34}$$

And obviously $R_N + T_N = 1$, and $R_p + T_p = 1$. With these equations we calculate the energy content in the reflected wave and in the transmitted wave in terms of the incident wave for both cases: the so-called parallel incidence and the normal incidence. For normal incidence as in geophysics altimeter radars, $\theta_i = \theta_r = \theta_t = 0^0$, and the R and T coefficients become $R = \{(n_1 - n_2)/(n_1 + n_2)\}^2$ and $T = (4n_1)/\{(n_1 + n_2)\}^2$.

The whole subject of reflection, refraction, and absorption of microwaves at the interface of air and a conducting (σ), magnetic (μ), and dielectric (ϵ) medium is summarized qualitatively in **Figure 4**. The most relevant mathematical expressions are given above. Depending on the application at hand, reflection and transmission count with sensitive methods for their measurement, and in consequence quantitative determinations of absorption of microwave power is readily available.
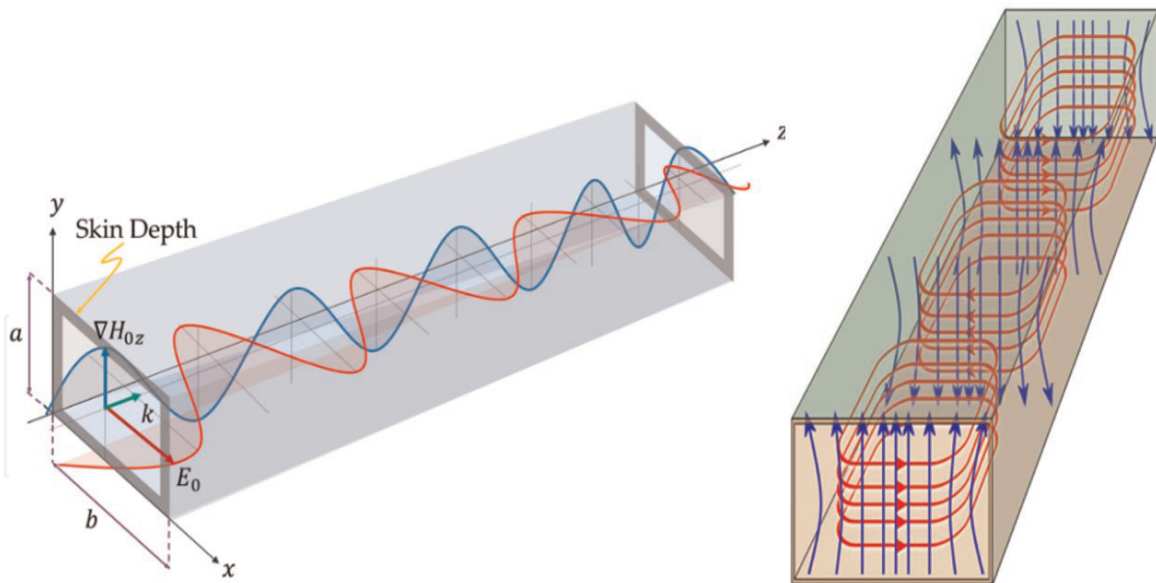
4. Waveguides

When research in this area does not involve necessarily open spaces, and transmission losses should be avoided, what can we do to reduce losses, dispersion, and uncontrolled reflections of microwaves while propagating? Or what can be done to control and measure such dispersions, absorptions, and reflections? The answer is whenever possible, guide the microwaves (**Figure 9**).

It is well known that very good conductors (metallic) reflect electromagnetic waves with a minimum of losses (these losses are due to Joule effect on the free electrons that are within the skin depth only) (see **Table 1**). And this skin depth is very small (microns, fractions of microns) for good conductors. So, multiple reflections on hollow metallic pipes are preferred choice to deliver microwaves from here to there (**Figures 9** and **10**).

Since the beginnings of the microwave technology, previous to world war II, it is well known that metallic hollow pipes with internal, mirror-polished walls can sustain propagation of some particular electromagnetic (EM) modes, TM (transverse magnetic), and TE (transverse electric) and cannot sustain other EM modes [27–29, 37, 38].

A universal condition is that one significant dimension, ξ, of the hollow pipe be exactly a multiple of an integer number of half the wavelength of the microwave to be transmitted through it. Hence $\xi = n\lambda/2$ determines the "size" of the cross section of a rectangular or a cylindrical waveguide. $\lambda_g = c/\nu_{nm}$ is the wavelength inside the waveguide. All the theory is consequence of the solutions to Maxwell's equations, under boundary conditions at the walls of the mirror-polished metallic surfaces of the microwaveguide. The particular deductions of the mathematical expressions of the valid **E** and **H** fields inside the waveguides are involved and lengthy. We give in **Table 2** some rectangular waveguides with their band, frequency operation, cutoff frequencies, and internal dimensions (**Figure 10**). A typical rectangular Q-band waveguide connected to a Q-cylindrical resonant cavity is shown in **Figure 10b**.
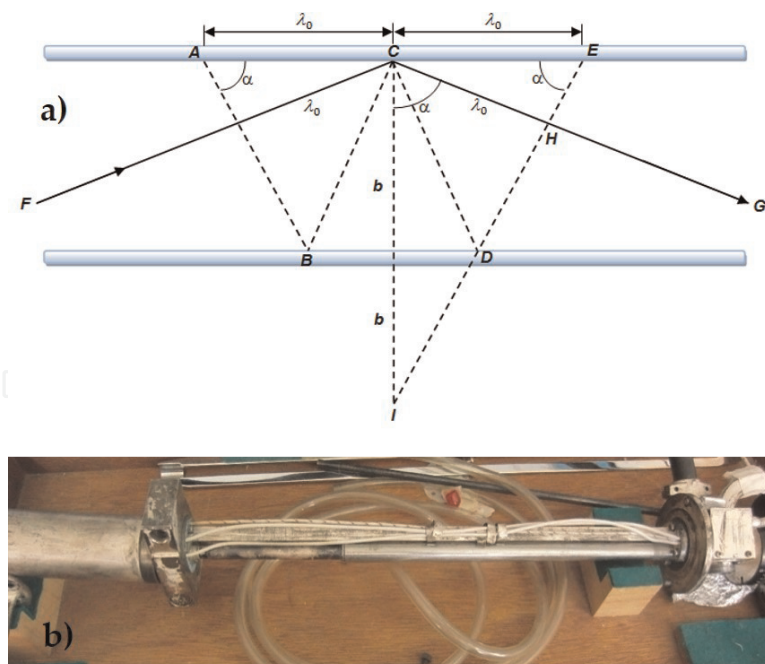
Figure 9.
*Rectangular waveguides made of very good conducting metals (copper, silver, gold, and brass) sustaining different patterns of **E** and **H** modes propagating along the guides. If the guide is perfectly conducting the electric field intensity, **E** is zero in the conductor, and **E** is either normal or zero at the surface. For a TE wave, it is shown that ∇H_{0z} is tangent to the wall.*

| Standard sizes of rectangular waveguide					
Waveguide name	Frequency band name	Recommended frequency band of operation (GHz)	Cutoff frequency of lowest-order mode (GHz)	Cutoff frequency of next mode (GHz)	Inner dimensions of waveguide opening (mm)
EIA					
WR650	L-band (part)	1.15–1.72	0.908	1.816	165.1 × 82.55
WR340	S-band (part)	2.20–3.30	1.736	3.471	86.36 × 43.18
WR229	C-band (part)	3.30–4.90	2.577	5.154	58.17 × 29.08
WR90	X-band	8.20–12.40	6.557	13.114	22.9 × 10.2
WR42	K-band	18.00–26.50	14.051	28.102	10.7 × 4.32
WR22	Q-band	33.00–50.00	26.346	52.692	5.86 × 2.84
WR19	U-band	40.00–60.00	31.391	62.782	4.78 × 2.39
WR15	V-band	50.00–75.00	39.875	79.75	3.76 × 1.88
WR12	E-band	60.00–90.00	48.373	96.746	3.10 × 1.55
WR10	W-band	75.00–110.00	59.015	118.03	2.54 × 1.27
WR8	F-band	90.00–140.00	73.768	147.536	2.03 × 1.02
WR6, WR7, WR6, 5	D-band	110.00–170.00	90.791	181.583	1.65 × 0.826

Table 2.
*Some of the most common rectangular waveguides and their frequency ranges and frequency cutoffs and inner dimensions (mm). The waveguide name WR stands for waveguide rectangular, and the number is the inner dimension width of the waveguide in hundredths of an inch (0.01 inch = 0.254 mm). The different microwave bands are given and can be correlated with the bands shown in **Figure 1** (Taken from Wikipedia).*

Once we know the electromagnetic patterns that can be formed and sustained in hollow metallic pipes, as the one we show in **Figure 11**, how can we use them to probe material's properties? The fundamental idea of how to measure

Figure 10.
A plane electromagnetic wave propagating in a rectangular hollow waveguide. (a) The lines AB and CD are parallel to wave fronts for the wave propagating to the right and upward. Similarly, BC and DE are parallel to wave fronts traveling to the right and downward. The angle α is the angle of incidence; the broken line FCG represents a ray reflected at C. (b) A laboratory Q-band cylindrical waveguide.
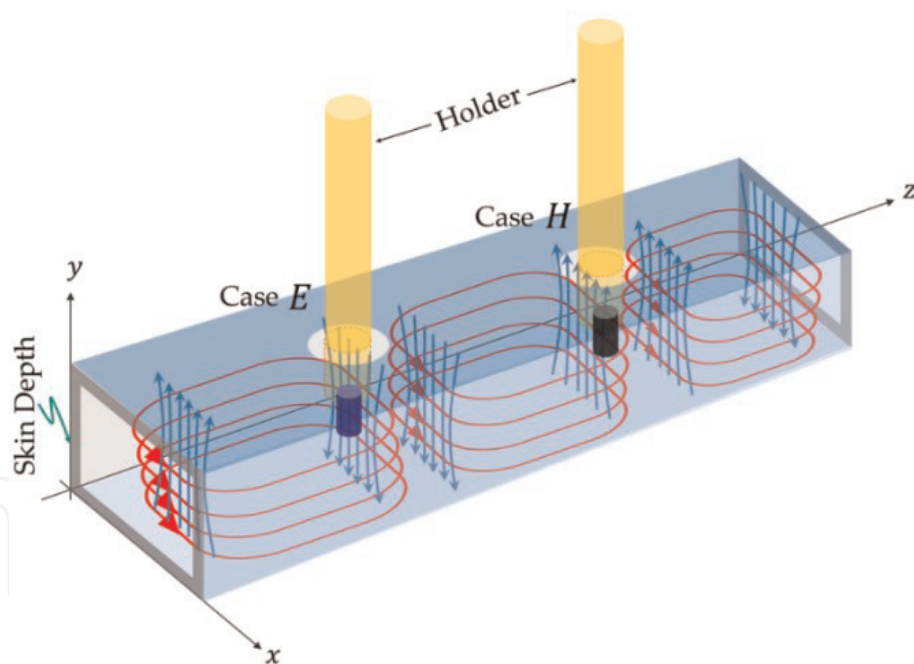
Figure 11.
Fundamental idea of how to measure electrodynamic properties (ϵ, μ, σ) of matter by making it interact with microwaves inside a waveguide. Measuring transmission, reflection, or dispersion will give so much information on ϵ, μ, and/or σ of the material.

electrodynamic properties (ϵ, μ, σ) of matter by making it interact with microwaves inside a waveguide is as follows. We just put the material specimen of interest inside the waveguide, at some place where the electric field is predominant if the electrodynamic expected response is diamagnetic, $\epsilon(\omega)$, or where the magnetic field dominates, if the magnetic response, $\mu(\omega)$, is to be explored. In this way the specimen will get excited electrically or magnetically, and predominantly the response would be ϵ(dielectric) or μ(magnetic) and by electron conductivity if the specimen is conductive, even if it is poor conductor (as ferrites).

To insert the specimen in the location we want, a hole is made on top of the guide and a material (dielectric, ϵ; magnetic, μ; and/or conductor, σ) is introduced; depending on the position of the hole **E** or **H**, the material will interact strongly with the **E** or the **H** component, see **Figure 11**, of the microwaves, and reflection, absorption, dispersion, and transmission will occur, and their measurement can be carried out.

Waveguides are used mainly to measure microwave transmission and energy transmission, T. A greater performance in the interaction of microwaves with (ϵ, μ, σ) materials is achieved when electromagnetic resonant cavities house the microwaves and the material to be studied.

5. Electromagnetic cavities

Closed metallic boxes are a particular case of a bounded space but are an important one. When the wavelength of a particular microwave (v.gr. 3 cm, 11 cm, or 8 mm) is trapped inside a box made of very good conductors (copper, silver, gold), the microwave bounces back and forth between the walls, and a pattern of standing waves is formed. The energy absorption at the walls is very small, and by virtue of this property, such a box is, really, a container of electromagnetic energy, concentrated electromagnetic energy in a closed, finite space. The same way we store a beverage in an aluminum can, we can store electromagnetic energy in a similar can (see **Figure 12**).

In electromagnetic cavities, the microwaves inside form maxima and minima at known distances, and the electromagnetic energy is stored efficiently. The main quantities that describe the electromagnetic behavior of a cavity are the standing wave electromagnetic fields **E** and **H** that form inside the cavity, its power and its figure of merit, the Q of the cavity. All these quantities are obtained from the **E** and **H** solutions to Maxwell's equations under boundary conditions at the internal metallic walls. Each component of the fields (**E**, **H**) obeys a homogeneous wave equation, as the ones given before.

They are solved by separation of variables, the boundary conditions are periodic, and the separation constants become integer numbers: $(k_1, k_2, k_3) \Rightarrow (n, l, m)$ in Cartesian coordinates, or (χ'_{mn}, m, k), where χ'_{mn} are the roots of the normal Bessel functions $J'_{mn}(\chi'_{mn}, r = a)$, in spherical coordinates [28, 37, 38]. The
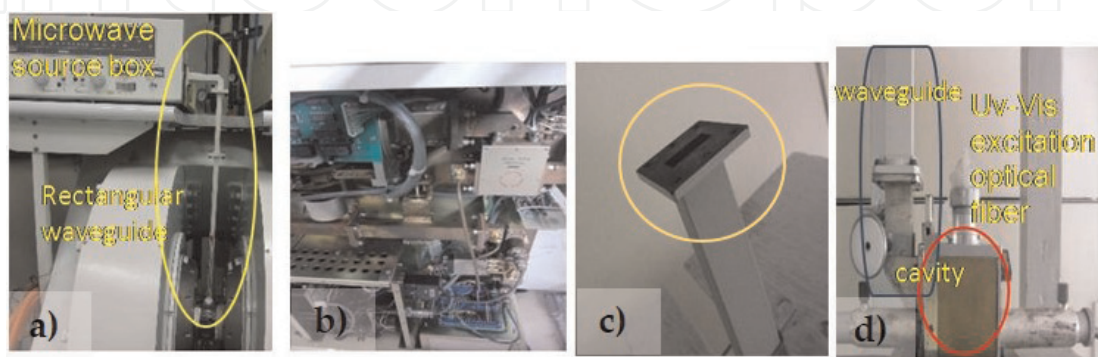

Figure 12.
A metallic can is commonly used to contain and to store a beverage. Similarly, a metallic can is used to sustain and store electromagnetic fields in the form of standing waves.

electrodynamic power of the EM fields inside the cavity is given by
$|\mathbf{E} \times \mathbf{H}| = S = V.W/vol = Power/u.area$, and the power absorbed by a purely magnetic material is $P = \omega H_1^2 \chi''$.

If we are interested in the quantitative study of microwave dispersion, absorption, and reflection by some kind of materials, we produce standing wave patterns inside a resonant cavity, put inside the material to be studied, let the microwaves interact with it, and then measure its absorption by its reflection and its frequency shift (dispersion) by the change of the energy in the cavity (through the Q of the cavity) without and with material sample.

Examples of real microwave laboratory X-band and Q-band waveguides and cavities are as follows: the schematic representations of **E** and **H** field patterns in **Figures 9, 10** and **11** are propagated in real waveguides shown in **Figure 13**. This equipment performs high precision microwave measurements; typically the microwaves are combined with static magnetic fields to excite and saturate the magnetic specimen; hence, electromagnets are part of these equipments. The microwave circuitry includes the source, circulators, attenuators, splitters, and so forth. Some waveguides are shown to be connected through flanges to more waveguides that make 90° turns and then connected to more microwave waveguide "plumbing" until it reaches the heart of the microwave source. At the bottom end, the waveguides terminate in a rectangular cavity that hosts a specimen to be studied. Details of the microwave X-band source box are shown; an isolated open end of another waveguide is also shown. Cavities and waveguides can stand several small holes without degrading their performance; hence, several probes can be inserted. The last panel in **Figure 13** shows a rectangular cavity which is also fed in its inside with UV-vis light through an optical fiber that enters the microwave cavity space to excite simultaneously the electronic levels and the electron spins of the atoms of the specimen, the collective magnetization, and/or the domain walls of a ferromagnetic specimen. There are also dual (twin) cavities which simultaneously receive microwaves; one is empty and the other is loaded with a specimen; in real time the different absorption measurements are registered. The fact that cavities and waveguides can stand holes in their walls and insertion of different small measurement, excitation, or conducting devices, multiplies greatly the number of experimentations with ϵ, μ, and σ and electronic and vibronic states that can be performed. Basically, the universal measurement in all these cases would be the reflected microwaves and from them the absorptive characteristics of the sample under study.

Figure 13.
*Common rectangular X-band waveguides and cavities and microwave source box used in laboratory. (a) typically the microwaves are combined with static **H** fields Electromagnets are part of these equipments, (b) the inside of a microwave source box that delivers in a precise fashion microwaves from a few microwatts up to 180 mW, (c) view of the open end of a waveguide built with a flange to connect with other waveguides, and (d) a waveguide terminated in a rectangular TE_{011} cavity which is also fed with UV-Vis light through an optical fiber.*
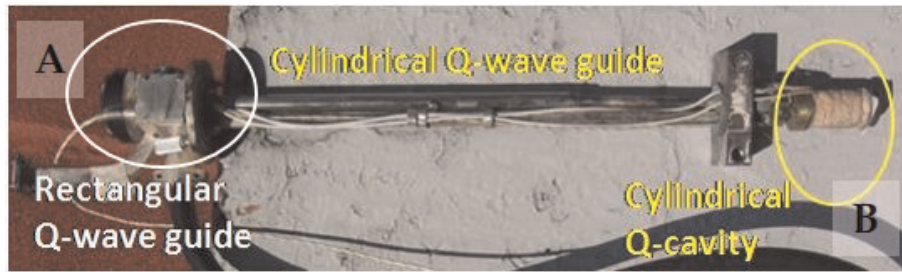
Figure 14.
Multiple reflections on the inner metallic wall of a wave guide allow the propagation of microwaves long distances, A, a laboratory Q-Band cylindrical wave guide connected on the upper part to a rectangular portion of another wave guide and connected at the bottom, B, to a cylindrical resonant cavity.

The same kind of experimental setups we just briefly described for X-band waveguides and cavities can be very well carried out at other frequencies with the appropriate K, Ku, Q, L, and S microwave equipment. The hoses that carry water and the electric cables that carry electricity can bend and give ≥90° turns, and pipes can be splitted, reduced in size, and so forth. The same with optical fibers and the same with microwave plumbing. Microwave circulators make the **E** and **H** fields go round in a circle and leave at the "aperture" of another piece of waveguide. The coupling of a waveguide with a geometry with another waveguide of another geometry is quite possible as we show in **Figure 14** for Q-band waveguides. The cylindrical waveguide connects to the right at the bottom with a cylindrical Q-band cavity, and connects to the left with a rectangular waveguide. The hole to insert a sample is at the center of the top wall (**Table 3**).

5.1 Circular cavity resonators

As a way of example, next we give some cylindrical frequency parameters and some standing wave patters (**Table 3**) allowed to propagate in these cavities for an

Wave Type	TM_{01}	TM_{02}	TM_{11}	TE_{01}	TE_{11}
Field distributions in cross-sectional plane, at plane of maximum transverse fields					
Field distributions along guides					
Field components present	$E_{\eta 1}\,E_{r1}\,H_\phi$	$E_{\eta 1}\,E_{r1}\,H_\phi$	$E_{\eta 1}\,E_{r1}\,E_\phi,\,H_{r1}\,H_\phi$	$H_{\eta 1}\,H_{r1}\,E_\phi$	$H_{\eta 1}\,H_{r1}\,H_\phi,\,E_{r1}\,E_\phi$
ρ_{nl} or ρ'_{nl}	2.405	5.52	3.83	3.83	1.84
$(k_c)_{nl}$	$\dfrac{2.405}{a}$	$\dfrac{5.52}{a}$	$\dfrac{3.83}{a}$	$\dfrac{3.83}{a}$	$\dfrac{1.84}{a}$
$(\lambda_c)_{nl}$	$2.51a$	$1.14a$	$1.64a$	$1.64a$	$3.41a$
$(f_c)_{nl}$	$\dfrac{0.393}{a\sqrt{\mu\varepsilon}}$	$\dfrac{0.877}{a\sqrt{\mu\varepsilon}}$	$\dfrac{0.609}{a\sqrt{\mu\varepsilon}}$	$\dfrac{0.609}{a\sqrt{\mu\varepsilon}}$	$\dfrac{0.293}{a\sqrt{\mu\varepsilon}}$
Attenuation due to imperfect conductors	$\dfrac{R_s}{a\eta}\dfrac{1}{\sqrt{1-(f_c/f)^2}}$	$\dfrac{R_s}{a\eta}\dfrac{1}{\sqrt{1-(f_c/f)^2}}$	$\dfrac{R_s}{a\eta}\dfrac{1}{\sqrt{1-(f_c/f)^2}}$	$\dfrac{R_s}{a\eta}\dfrac{(f_c/f)^2}{\sqrt{1-(f_c/f)^2}}$	$\dfrac{R_s}{a\eta}\dfrac{1}{\sqrt{1-(f_c/f)^2}}\left[(f_c/f)^2+0.420\right]$

Table 3.
*Concentrate of the basic properties of some cylindrical cavities that sustain some E and H modes (patterns of standing waves). The blue dashed lines are **H** lines and the red ones are **E** lines. The second row shows how they propagate along the waveguide. The field components are shown and parameters like the cut-off frequency, the attenuation due to imperfect conductance, the cut-off wave length are also shown.*

air-filled circular cylindrical cavity resonator of radius a and length d. The resonant frequencies are

$$(f_r)_{TM_{mnp}} = \frac{1}{2\pi\sqrt{\epsilon\mu}} \sqrt{\left(\frac{\chi_{mn}}{a}\right)^2 + \left(\frac{p\pi}{d}\right)^2} \text{ and } (f_r)_{TE_{mnp}} = \frac{1}{2\pi\sqrt{\epsilon\mu}} \sqrt{\left(\frac{\chi'_{mn}}{a}\right)^2 + \left(\frac{p\pi}{d}\right)^2}$$

where the boundary condition at the lateral wall, r = a, imposes $J_{mn}(\chi_{mn}) = 0$ and the χ'_{mn} are the roots n of the m Bessel function; hence $J'_{mn}(\chi'_{mn}) = 0$

Zeros of $J_n(x)$, x_{np}				Zeros of $J'_n(x)$, x'_{np}			
p \ n	n = 0	n = 1	n = 2	p \ n	n = 0	n = 1	n = 2
1	2.405	3.832	5.136	1	3.832	1.841	3.054
2	5.520	7.016	8.417	2	7.016	5.331	6.706

Above we show just a few roots of $J_n(\chi_{mn})$ and of $J'_n(\chi'_{mn})$. For TE_{001} mode sustained in an empty cavity, m = 0, n = 0, p = 1, so $\chi'_{mn} = 3.832$, a = 3.65 cm/2 = 1.825 cm, and d = 4.38 cm with $\epsilon = \epsilon_0$ y $\mu = \mu_0$.

## 5.2 The quality factor of a resonant cavity

It is a fundamental quantity in the theory and evaluation of microwave cavities. The quality factor of the cavity is defined by

$$Q = \frac{2\pi(\text{Time} - \text{average energy stored at a resonator frequency})}{\text{Energy dissipated in one period}} \tag{35}$$

Q becomes an extremely useful parameter to measure the performance of a cavity and to make quantitative the losses in it when it is empty and/or when it is loaded with a material sample of interest. The higher the Q, the higher the quality of the metallic cavity as reservoir of electromagnetic energy. A cavity with a Q of 17,000, 33,000, or 100,000 will lose energy in a fraction of 1/17,000 or 1/33,000 or 1/100,000 of the initial energy content per cycle. So, these devices are really very good at storing microwave energy. Notice that the inverse of Q is a measure of those losses:

Q^{-1} = Energy loss (absorbed, dissipated) per cycle/2π (time-avarage of energy stored at resonant frequency).

Let's call L the inverse of Q; $L = Q^{-1}$. The theory of cavities finds that there are four types, and only four types, of energy losses: (a) by Joule effect on the conducting walls and just within the skin depth, L_σ, (b) by dielectric losses if a dielectric material, $\epsilon = \epsilon' - i\epsilon''$, is introduced in the cavity, L_ϵ. This means that the dielectric material absorbs microwaves by virtue of its polarized atoms/molecules, (c) by magnetic losses if a magnetic material, $\mu = \mu' - i\mu''$, is introduced in the cavity, L_μ [27–33]. This means that the magnetic material absorbs microwaves by virtue of its magnetic moments that precess with friction (damping) according to the Landau-Lifshitz equation of motion [LL], or the magnetic domain walls move back and forth trying to follow H(ω) [30], L_μ, (d) any holes or apertures in the cavity, from which some microwave energy can escape, Lh. And the losses are additive, hence: $L_Q = L_\sigma + L_\epsilon + L_\mu + L_h$, in terms of Q^{-1} becomes $1/Q = 1/Q_\sigma + 1/Q_\epsilon + 1/Q_\mu + 1/Q_h$. For an empty cavity: $Q = \frac{\omega W}{P_L}$ where $W = W_E + W_H$ is the
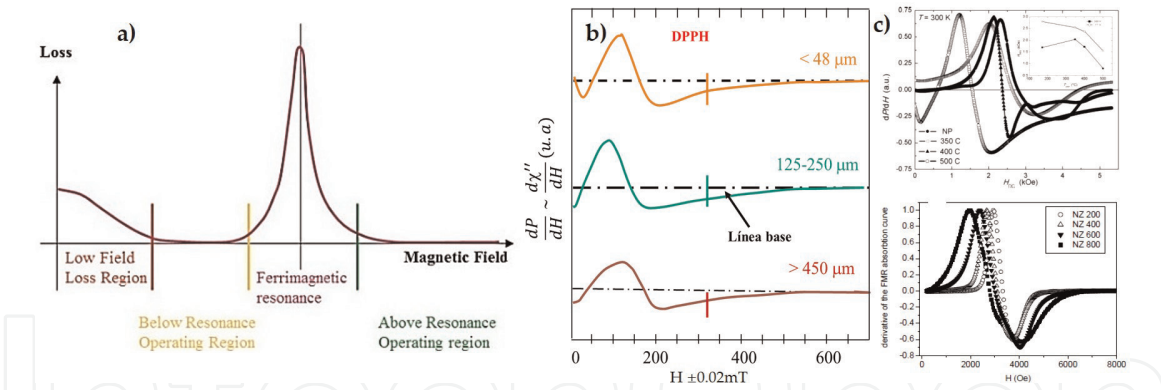
Figure 15.
A variety of ferrites with different sizes and fabrication procedures absorb energy in similar ways. (a) Profile of absorption contains four distinctive regions. Only one is resonant. (b) The usual representation of the absorption is the derivative of the microwave power with respect to magnetic field. (c) Many other ferrites collapse the yellow region, and the FMR region expands to lower and higher fields.

total electric and magnetic microwave energy and $W_E = \frac{\epsilon}{4} \int |\mathbf{E}|^2 d\tau$; $W_H = \frac{\mu}{4} \int |\mathbf{H}|^2 d\tau$. At resonance: $W = 2W_E = 2W_H$. The power loss per unit area, L_σ, is only due to the conductivity of each wall. In this case $P_{av} = \frac{1}{2}|\mathbf{J}_\sigma|^2 R_\sigma = \frac{1}{2}|\mathbf{H}|^2 R_\sigma$, where R_σ is a superficial resistance $R_\sigma = \frac{b\rho}{\pi(D-\delta)\delta} \approx \frac{b\rho}{\pi D \delta}$, with b, length of cavity; D, diameter of cylindrical cavity; ρ, resistivity ($\rho = 1/\sigma$); σ, conductivity of cavity material; δ, skin depth $\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{2}{\omega\mu\sigma}}$; ν, electromagnetic wave frequency; and $J_s = |\mathbf{J_s}|$, AC current density generated by microwaves inside the cavity wall, generating a power loss P_S. Now, what follows has been found experimentally [39, 40]. If an extra conductor as a wire or a conducting film is introduced in the cavity, a new loss term due to J_{ex} (AC current density generated by microwaves within the skin depth of the extra conductor) appears, P_{ex}. Both terms are of the same type; hence, $P_{\sigma total} = P_\sigma + P_{ex}$, and both power loss integrals are of the same type. $P_\sigma = \oint P_{av} \, ds$, and the new Q is: $Q = \frac{\omega W}{P_\sigma + Px} = \frac{2\pi\nu W}{\oint P_{av} \, ds}$. And so, $1/Q = 1/Q_\sigma + 1/Q_{ex}$. If we continue adding lossy objects inside a cavity, more power loss terms appear and the total loss would be the sum of each loss, $P_{total} = \sum P_i$, where $P_i = P_\sigma + P_\epsilon + P_\mu + P_h$. This analysis on the Q of a loaded cavity and its losses is very powerful to understand what mechanisms are responsible for the total microwave absorption that a magneto conductor exhibits.

5.3 Examples of experimental measurements of microwave absorption by different magnetic and/or conducting materials

The first example is microwave ferrites. Their name clearly indicates the main function they have and have been studied with microwaves since their very invention. Microwave ferrites are crucial elements in microwave measurement equipment itself and in a pleyade of different microwave devices [17]. Its ability to absorb greatly microwaves under very specific circumstances and do not absorb them under other set of circumstances makes these materials highly controllable, and that is what engineering requires [11].

As microwave device it is desirable to have wide yellow and green regions in **Figure 15** for passive circulator and isolator operation [11, 24]. Ferrites absorb microwave energy in a resonant fashion and under nonresonant conditions, making these responses a very versatile and manageable material. It is very cheap and easy to fabricate [41].
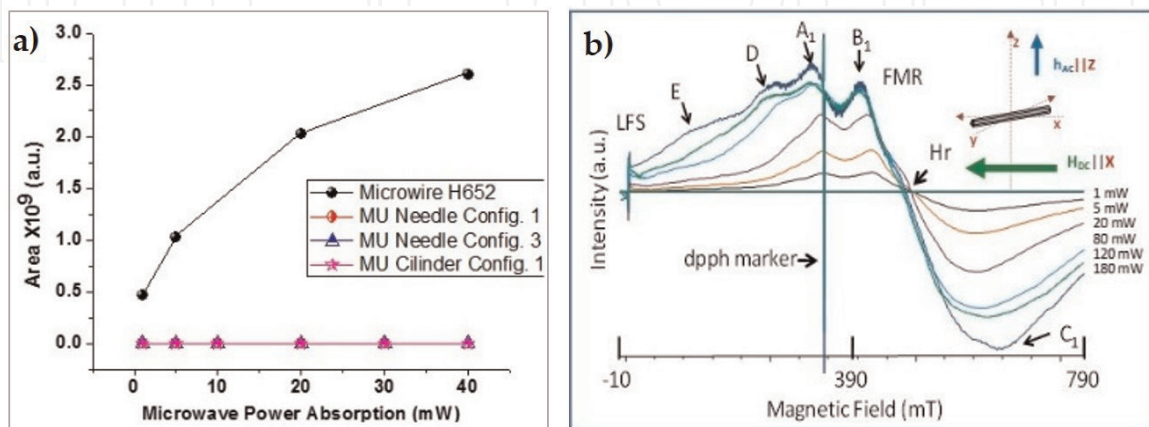
6. Resonant absorption of microwaves

What is microwave energy absorption in a resonant fashion? The phenomenon is really ferromagnetic resonance (FMR). What is the role of microwaves in the ferromagnetic resonance phenomenon? A brief description follows; the most common measurements of the ferrite absorption performance or profile are carried out in equipment as the one shown in **Figure 13**. In addition to the microwave excitation of the ferrite inside the cavity, an extra static magnetic field, H_0, is applied to the ferrite through the magnet poles of the electromagnet also shown in **Figure 13a**. This is why the cavity is seen located at the center of the magnet poles. This field serves to simplify the magnetic structure of domains of the ferrite, and when 250 mT (2500 Oersters) or more are applied, the domain structure has disappeared, and the material becomes magnetically saturated, and the whole sample has the magnetization value M_s, and this M_s as a whole interacts with the microwave magnetic field and absorbs its energy greatly in the form of $\hbar\omega = g\beta H_0$, in which $\hbar\omega$ is the energy of a quantum of the microwave field and the right side $g\beta H_0$ is the magnetic energy splitting of two consecutive magnetic energy levels. This is the well-known Zemann effect, where $\beta = \hbar e/2m_e$ is Bohr magneton and g is the spectroscopic factor (for ferromagnets and ferrimagnets g is close to 2.00 but always larger). To have $\hbar\omega = g\beta H_0$ means that a stimulated transition between two contiguous energy levels, $\Delta E = g\beta H_0$, is taking place and the energy is provided by photons, $h\nu$, with v exactly in the microwave region, of the magnetic component of the microwaves. This is called the resonance condition; it is fully quantum and was discovered without knowing what it was in 1946 by R. Griffiths [34] and explained fully 1 year later by Kittel [32]. When this absorption fullfils the Kittel condition, $h\nu = g\beta H_0$, it is resonant absorption of energy (no more, no less, just exactly the energy content in a microwave photon $h\nu$), meaning that resonant absorption of microwave (photon) energy is performed by the magnetization of a ferromagnetic specimen. When the atomic magnetic moments or uncoupled electron spins are not governed by the strong magnetic exchange interactions, they do not behave collectively, as a unit, and they behave individually. Such is the case of paramagnetic substances. Each atomic magnetic moment, $\mathbf{m_i}$, or electron "spin only", $\mathbf{S}$, can and do absorb microwaves individually obeying also the resonance energy equation, $h\nu = g\beta H_0$. In these cases the phenomenon is called electron paramagnetic resonance (EPR) or electron spin resonance (ESR). In any of these cases, energy from the microwaves is absorbed resonantly and very efficiently. So, FMR, EPR, and ESR are techniques that measure very accurately the absorption of microwaves (quanta, $h\nu$) in the presence of a static magnetic field, H_0, of a magnetic sample located in a microwave cavity.

7. Nonresonant absorption of microwaves

When the microwave experimental setup is as described but the equality $h\nu = g\beta H_0$ is not fullfiled and absorption of microwaves is still registered, then we have a nonresonant absorption of microwaves, and other dissipative process dynamics are taking place. For example, domain walls can be made to oscillate with an external field, and the motion is dissipative, or some conduction "currents" can be operating. So, the same equipment and experimental setup can measure resonant and nonresonant absorption of microwaves. Measurements of this kind, carried out in equipment as in **Figure 13a** on ferrites fabricated with different methods and with different compositions [41], give very frequent absorption profiles as the ones

shown in **Figure 15**. This contains nonresonant and resonant absorption of microwaves. This kind of absorption profile has been known for many years. Here we want to demonstrate that resonant and nonresonant absorption of microwaves coexists in just one measurement that is capturing different microscopic absorption mechanisms at different values of H_0. The information obtained this way is very rich. For passive microwave circulators and isolators, it is highly convenient that the regions below resonance (B/R, yellow) and above resonance (A/R, green) be as wide as possible since no absorption is demanded. The widening of these yellow and green regions is a continuous search by modifying ferrite fabrication parameters and continuously measuring this kind of microwave absorption. Yet, many ferrites do the contrary and absorb in all regions of H_0. On the other hand, the maximum possible absorption is required in order to sensing it from a distance. In a sense a kind of sink is desirable, like an antenna that works by absorbing greatly microwaves. Much the same way radar works. In order to develop potential applications as the one illustrated in **Figure 3**, "sensors" that absorb greatly microwaves in preferred directions are required. Some promising materials are $Fe_{79}B_{10}Si_{11}$ glass-covered amorphous-conducting magnetic microwires (simply FeBSi wires) because they have shown great capacity to absorb microwaves at X-band in an anisotropic fashion [42]. The proposed application in **Figure 3** demands a great global absorption of microwaves in order to detect reflected microwaves from implanted magnetic microwires (glass-covered for them to be biologically inert) in patients that have undergone some kind of orthopedic surgery at the level of knee, shoulder, vertebra, hip, and so on. The microwires are implanted with some specific orientation, and as recovery develops and bone grows, or fractures heal, the microwires would move when pushed by the new processes taking place. Those changes are expected to be informative to the surgeons. The idea of the detection is quite similar as how radar detects moving or static "objects" at a distance. The same idea is used in how the laser gun works detecting a speeding vehicle. A good level of reflected, or perturbed. microwave "signal" coming back to the transducer is required. In laboratory models, FeBSi wires have shown great microwave absorption at some particular orientations. Experiments are carried out with the wires inside microwave cavities in equipment as the one shown in **Figure 13**. Conditions are established for FMR absorption because it is the maximum possible; hence in addition to the X-band microwaves fed to the resonant cavity, an extra static magnetic field is also applied. The physical interactions are as described for ferrites, except that these are amorphous and no long-range order exists and the strong
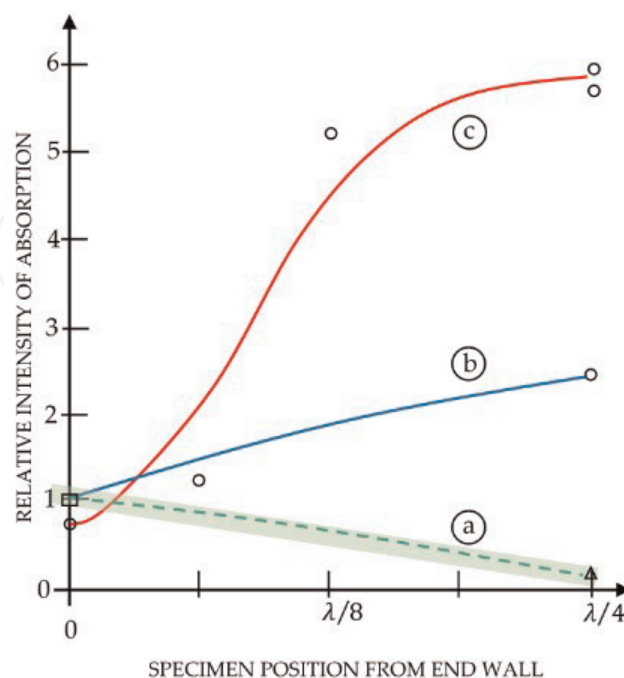

Figure 16.
FMR absorption of microwaves by glass-coated amorphous-conducting ferromagnetic microwires. (a) First derivative of absorption intensity as function of delivered microwave power and (b) the total absorption is a fast-increasing function of power. The Abs% grows to over 1000% for P = 180 mW. The measured absorption for the military material "mu" is shown for comparison, it does not show such effect [42].

crystalline anisotropy does not exist and H_{int} that goes in H_{eff} is different from the H_{int} present in ferrites. A typical absorption profile is shown in **Figure 16**. Here the quantity of interest is the integral of the absorption curve since it gives directly the total microwave power absorbed by the sample. The higher the integral, the better in order to use it as sensor-detector of microwaves. The total absorption resulted in a fast-increasing monotonic function of power. The Abs% grows to over 1000% for P = 180 mW. The measured absorption for the military material "mu" is shown for comparison; it does not show such effect. This is a kind of amplification effect [42].

In, yet, another application, the cavity microwave magnetic field near an extra inserted conducting perturbation is greatly enhanced. Nanomagnets and micromagnets could require for their study an enhancement of the fields they experience inside a resonant cavity. This could be achieved by introducing an extra conductor (wire) in the cavity in order to expose its free electrons to the microwave electric field in the cavity. Induced currents in the conductor, of the same frequency of the microwaves, would produce an extra magnetic field H^+ in some small regions, γ, very close to the extra wires, w^+. Placing a micron- or nano-sized sample, η, in region γ of increased field $H_{incr} = H_0 + H_{int} + H^+$ could produce an amplified ferromagnetic resonance absorption, since now $\hbar\omega = g\beta H_0$ is fulfilled as before, but more microwave effective power is absorbed by a micro- or nano-magnetic material with a not so large total magnetic moment, M, placed at the γ region. This was proven experimentally by R. Rodbell in 1952 [39, 40] more than half a century ago; we consider it a classic of deep understanding of electrodynamics in cavities and a good example of how to use them in novel ways. Present-day microwave experiments of these kinds can be performed on ferromagnetic resonance equipment that looks like the one shown in **Figure 13**.

One interesting result obtained by Rodbell is that the microwave magnetic field strength near the surface of a conducting rod may be easily made to exceed the maximum magnetic field strength existing in the unperturbed cavity at the same

Figure 17.
The intensity of the ferromagnetic resonance measured for a sample of MnFe$_2$O powder as it depends upon position of the sample in a rectangular TE$_{011}$ X-band microwave cavity. The incident power is 50 mW. (a) FMR with the ferrite alone, (b) ferrite near a cooper wire, (c) ferrite powder glued to the copper wire. The FMR absorption increase amplification is more than 1000X.

incident power level. This would appear to be a useful means of effectively coupling microwave energy into a magnetic specimen. The experiment described by Rodbell is the measurement of the relative intensity of the microwave magnetic resonance absorption of an $MnFe_2O_2$ powder specimen (manganese ferrite) as it depends upon position within a rectangular (TE) microwave cavity at ≈ 9 kMc/s, **Figure 17**. The powder specimen is cemented onto the outside surface of a quartz capillary tube that is 3 mm long and of 0.25 mmo.d. The capillary is attached to a quartz post so that it can be positioned along the central "E" plane of the cavity with the capillary axis along the microwave **E** field. The total resonance absorption here is composed of contributions from many, essentially isolated, randomly oriented particles of the ferrite powder; the line width of the composite absorption is about 1000 Oe. The resonance absorption is used here as an indication of the square of the microwave magnetic field strength averaged over the sample. This is the variation expected for a magnetic resonance absorption that is driven by the usual microwave magnetic field strength for this cavity geometry. The experiment is now repeated after introducing into the capillary tube a bare copper wire that is 3 mm long and of 0.025 mmdiam. The cavity coupling and incident microwave power are constants of the experiment. The small variation of the cavity Q with dc magnetic field is used as a measure of the magnetic resonance absorption in the standard way.

The results indicate that the electric field "drives" the absorption; that is, the microwave electric field is locally perturbed and gives rise to a locally large magnetic field. Further confirmation is found in curve (c) of **Figure 17** which displays the result of an experiment in which a copper wire of the same size as in (b) is coated directly (no intervening quartz capillary) with approximately the same amount of the ferrite ($MnFe_2O_4$) powder. The increased absorption, here relative to (b), is interpreted to be the result of the larger microwave magnetic field that occurs closer to the perturbing conductor.

8. Conclusions

An overview of the universality of the microwaves in the universe and in the modern technology world was given. Maxwell's equations are placed in the center of the electrodynamics universe and in particular in all the technological applications that were mentioned: microwaves in open spaces as in radar, Wi-Fi, guided microwaves, and microwaves in closed resonant cavities with very good conducting walls. Solutions of Maxwell's equations are given in tables, and the phenomena of reflection, refraction, and absorption are shown to be universal. The Snell and Fresnel reflection and refraction equations are given. The fundamental physics of propagation is given, and the main features of electromagnetism in resonant cavities were described. Real waveguides and cavities and microwave equipment were presented, and general ideas of their use for research were also given. Few applications of absorption measurements under ferromagnetic resonance and nonresonant conditions for ferrites, amorphous microwires, and conductors with magnetism were given.

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