Chapter

Introductory Chapter: Causal Models of Electrical Permittivity and Magnetic Permeability

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1. Fundamental concepts

The electricity and magnetism theory was formulated by a series of experimental physical laws, such as the Gauss's law of electrostatics, Ampere's law, Biot and Sabart's law, and Faraday's law, with the concepts of charges and electric currents that were used up to the middle of the 1800s. Since James C. Maxwell's *Treatise on Electricity and Magnetism*, with his contribution in the year 1873 [1], it was essential to formulate electromagnetic theory. This electromagnetic theory considers the addition of the displacement current to the conduction current to obtain the total current, which was a fundamental contribution to consider all the physical laws including the law of conservation of charge. Maxwell's equations are generally expressed differentially and are used considering the constitutive relationships, which are the relationships between the vectors of the electric and magnetic fields, which when applying the boarder conditions and the initial conditions, allow obtaining the solutions. These solutions are usually the electric and magnetic fields, since with these vector fields, the electric current, the electric potentials, the power, and other physical parameters of technological utility can be obtained. An issue that has been important in solving the cases that are found experimentally has been the electric and magnetic potentials, which allow the fields to be obtained many times in a simplified form. In electromagnetic theory, the so-called simple media are commonly used, whose characteristics are homogeneous, isotropic, and linear [2]. Here the properties of the media such as the electrical permittivity and the magnetic permeability of the constitutive relationships can be represented as complex numbers, where the electrical and magnetic losses are considered in the imaginary part. For cases of ferrous magnetic materials, for example, with losses, it is necessary to consider nonlinear behavior, although it will not be of interest in our study. Furthermore, the usual treatment of electromagnetic theory is done from the macroscopic point of view, although materials with electric or magnetic dipole moments are considered, because the treatment of quantum electromagnetism is already a specific topic.

2. Electromagnetic model of a material

Consider a material medium with an excitation of one electromagnetic wave, whose electric and magnetic fields vary over the time, it is considered that the input variables will be the electric or magnetic fields and the output variables will be the vectors of electric flux density and magnetic, respectively. The material can be considered as a system, with a specific transfer function, and this system is usually considered causal in physics, and from the point of view of the study of signals, it is called linear and time independence (LTI) [3]. These causal systems are important, because the Kramers-Kronig relations can be applied, which relate the real and imaginary part of the electrical permittivity and the magnetic permeability. The theoretical model of electrical permittivity and magnetic permeability of each media can be tested by mean of the Kramers-Kronig relations and Hilbert transform [3, 4]:

$$\varepsilon'(\omega) - 1 = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\varepsilon"(x)}{x - \omega} dx \tag{1}$$

$$\varepsilon"(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\varepsilon'(x) - 1}{x - \omega} dx \tag{2}$$

where P is the Cauchy principal value.

The fundamental assumption is known as the causality condition. The most primitive and intuitive one can be formulated as follows: the effect cannot precede the cause [5]. The numerical techniques now can allow the computation of Hilbert transform in order to test the electric permittivity model of the material.

3. Electromagnetic wave propagation

The interaction of electromagnetic waves with matter is an interesting topic to study several applications. Maxwell's equations allow to solve propagation problems in different media together with the boarder solutions that allow to obtain solutions in each application. In electromagnetic theory it is the development of the wave equation or D'Alembert's equation that is in the time domain, and as a function of frequency, we work with the Helmholtz equation, which, in the case of monochromatic sources, provides the two wave solutions, the wave vector and the propagation constant that allow to study the propagation in the different media, which are usually studied as perfect dielectrics or dielectrics without losses, perfect conductors, and dielectrics with losses. This last case of dielectric with losses is the one that has application to the topics of electromagnetic engineering, optoelectronic engineering, RF engineering, and communications engineering. The frequency of electromagnetic waves in technological applications is ranging from low-frequency waves, radio frequencies, microwaves, optical frequencies, infrared, ultraviolet, and even higher to high-energy frequencies. The energy associated with the electromagnetic wave is proportional to the propagation frequency using the Plank constant. The electromagnetic waves that affect an interface from the air to the dielectric medium that usually has losses will be reflected energy and transmitted to the medium under study, dissipating heat in the medium, and it will attenuate the amplitude of the electromagnetic wave that propagates and causes the dispersion effect. This means that the propagating signal will have different propagation speeds for different frequencies, causing a distortion of the propagating signal as it moves through the dispersive medium. Knowledge of the electrical and magnetic properties, which are intrinsic properties of matter, such as the response of materials to be used in the electronic industry, are essential for the design and construction of electrical and electronic devices. The materials in the transmission lines, waveguides, and fiber optics where an electromagnetic wave propagates in the infrared band have materials that have losses and dispersion that must be considered. In the case of an alternating current flowing in the soil, it will also be necessary to consider the electrical properties of the soil as the electrical conductivity for the various applications in electrical engineering. The application of heat to a junction of two metals or two semiconductors produces a potential difference at the ends; this phenomenon is called the Seebeck effect, which in metals the potential differences obtained are very small. For this reason, new composite materials that can obtain a higher Seebeck coefficient are investigated. In metals the Seebeck coefficient is generally of the order of $1\mu V/C$; it increases greatly in cases where a metal is measured with a semiconductor, for example. Currently, a technological application of this effect is thermocouples, which are used to measure temperature.

4. Organization of the book

In chapter I of the book, the physical sense of the phenomenon of dispersion of electromagnetic waves is discussed; the group speed is obtained. Then from the Lorentz force, the plasma model and the dispersion in the plasma, and in a conductive medium, are discussed. Dispersion topics that are of greatest technological interest are discussed, such as modal, chromatic, and intramodal dispersion. Chapter II studies electromagnetic propagation through the soil, where historically it was used for telegraphic transmissions, in the transmission of surface waves in the AM bands; the knowledge of the electrical properties of soil are applied to the study of agriculture and archeology, which have become very relevant these days. In this chapter the different methods of measuring the electrical properties of the soil are discussed. A widely used technique is time domain reflectometry, which studies the response of the reflected pulses in the time domain to obtain the electrical properties of the soil. Another way to obtain the electrical properties of the soil is by measuring the impedance in the frequency domain of a transmission line known and built for this purpose. In this chapter the own experimental results obtained by the author are presented. In chapter III the electrical conductivity in direct current in molten salts ("Electrical Conductivity of Molten Salts") is studied from a microscopic point of view using the Langevin equation, which implies a time-dependent memory function $\gamma(t)$ in relation to the friction forces acting on the constituent ions under the electric field. The properties of the ionic liquid transport phenomenon are important for industry and technological applications. Ionic liquids are divided into two main groups: molten salts and electrolytic solutions. Chapter IV deals with the interaction of electromagnetic waves with the biological tissues of human beings and the skin of animals. Electromagnetic waves can come from the sun, and frequencies range from very low frequencies to gamma ray frequencies. As it is well-known, the atmosphere filters the highest energy frequencies such as gamma rays, X rays, or ultraviolet rays. This work deals with and studies the transmission, reflection, and reflection coefficients in the skin of humans and animals of electromagnetic waves. In chapter V, we work with the Seebeck effect, which is about two metals or semiconductors to which different temperatures are applied, and a potential difference is produced. The reverse effect is called Peltier and consists of applying a potential difference to the conductors/semiconductors, and heating or cooling occurs at the junction. These thermoelectric properties have technological applications that are being used such as thermocouple temperature sensing and Peltier effect cooling systems. Here we present new thermoelectric materials tested as tellurium telluride chalcogenide nano-materials.

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