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Spatio-spectral analyses of electromagnetic wave energy absorption and heating effect

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ABSTRACT

This study presents a theoretical analysis method to calculate electromagnetic (EM) wave power absorption spectrum of materials by using attenuation coefficients. The heating effect of EM waves is modeled to analyze spectral distribution of temperature rises inside material body as a result of EM wave power absorption. These analyses are very useful for the investigation of electromagnetic wave-material interaction on the bases of electro-physical material parameters (permittivity, permeability and conductivity). An illustrative analysis of spatio-spectral distribution of EM wave energy absorption and resulting heating effect were conducted for muscle tissues and the results are discussed.

1. Introduction

Many technologies utilizing transmission properties of EM waves were developed the last century. These developments involves in many fields such as communication [1], medical technologies [2–4], heating processes [5–8], energy conversion [9]. Increasing demand in daily use of RF and microwave technologies in consumer electronics such as cellular phones, wireless communication raises questions and doubts about the negative effects of EM waves on public health [10–14]. Today, research studies on the effects of EM radiation on biological tissues are getting more and more important. Besides, use of EM waves for the propose of medical treatment has become one of substantial research topics of medical physics [2,4]. RF and microwave heating of foods is another beneficial application of EM waves [8].

Recent researches on interaction of EM waves with microstructured or composite materials promise novel developments for future world. Particularly, progress in metamaterials science [1,15–17] has been yielded novel applications such as photonic crystal perfect lens [18], waveguides [19]. Investigation and characterization of EM energy absorption properties of materials is very important on the way of practical implementation of large-scale microfabricated optoelectronic systems. Wave isolation features, heating of substrates and energy consumption of microfabricated systems are strongly depended of EM energy absorption properties of materials.

The penetration depth, attenuation of waves and temperature rise due to power absorption from EM wave varies from material to material, and choosing effective materials meeting application specifications is a necessity for technology development. Specifically, obtaining EM wave attenuation coefficient spectrum of materials is very beneficial for identifying penetration depth, energy absorption properties, isolation and heating features of the materials that are desired to utilize in EM technology development. This study is devoted to derive basic formulations to obtain attenuation coefficient spectrum depending on measurable electro-physical parameters of materials and suggests a spatio-spectral EM wave energy absorption and heating model. This model is based on energy conservation law postulating that energy difference between incoming and outgoing waves is absorbed by energy conservative systems. In this aspect, the spatial distribution of absorbed EM wave energy can be characterized by attenuation of EM waves while penetrating into the material.

The characterization of material properties associated with EM wave transmission is very substantial for the development of computer-aided EM technology development tools such as finite difference time domain (FDTD) wave simulation methods. FDTD based numerical simulations were effectively used to investigate transient properties of EM wave propagation [2–4,20,21]. However, there is still a need for analytical formulations to calculate spatio-spectral power absorption and heating properties of materials defined by measurable electro-physical material parameters: effective permittivity, permeability and conductance parameters.

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In the literature, Gorobets et al. presented an analytical solution for EM wave energy absorption throughout layers with smoothly varying dielectric parameters [22]. They considered absorbed energy at a cross-section of the material with non-uniform dielectric parameters as the remaining energy from reflected energy and transmitted energy from the material cross-section. In a recent work, Moritz successfully used EM wave penetration model based on exponential decay (Beer–Lambert Law) to obtain radial distribution of temperature in a thin lens due to absorption of light and heat conduction [7]. In our study, power dissipation due to the exponential decay of EM wave energy is assumed to turn into heat and increase the temperature of conservative materials with isotropic attenuation coefficient.

EM interaction with matters is depended on EM wave frequency. Because electro-physical and structural properties alter spectral response of matters. For instance, state of dipoles, free charge and atomic and molecular structure of substances affect EM wave propagation and absorption properties. Complexity of materials, as in biological materials, seriously complicates theoretical analyses, modeling efforts of the EM propagation and absorption mechanisms inside the material structures. The movement of bulk collection of charges is possible, which can be characterized by conductivity parameters. These charge motions resulting from EM interaction may cause the instant electric currents inside the materials or new EM radiations. A portion of EM wave energy spends for charges motions. Besides, vibration of molecular dipoles and atoms due to the varying fields of EM wave causes energy absorption and hence the heating of materials. In many recent works, EM energy absorption analyses were conducted by using specific absorption rate (SAR) on the bases of the conductivity of medium [2,11,21]. However, EM energy absorption of complex material depends on not only motion of free charges (space charges) and ions but also rotation of molecular dipole structures. Rotation and vibration states of molecules lead to an energy absorption mechanism so called dielectric heating, which is particularly effective in the microwave spectral region and infrared region. At lower frequencies, ion-drags due to EM waves are also a main factor in generation of thermal energy. Unless it radiates, all absorbed EM energy by means of these mechanisms turns into heat in the conservative system, and finally this results in a rise in body temperature of materials. Body temperature of materials is a measure of the average vibration energy of atoms and molecules composing the material. All these complicated and uncertain microscopic physical mechanisms involving in the EM waves-material interactions finds characterization in electro-physical parameters; permittivity, permeability and conductivity.

This study presents a theoretical model for the analysis of spatio-spectral distribution of EM wave power losses according to the exponential decay formulation (Beer–Lambert Law like) while propagating through a dispersive material. The attenuation coefficient of the material was expressed with respect to measurable electro-physical parameters of mediums (effective permittivity, effective permeability and effective conductance) and the EM wave frequency ($w = 2\pi f$). In this model, a decrease in energy of propagating EM waves in the material is assumed to be completely absorbed by dispersive materials exhibiting isotropic electro-physical parameters and the spatio-spectral energy absorption distribution and the spatio-spectral heating distribution are expressed analytically. The paper presents an illustrative analysis on muscle tissues characterized by permittivity, permeability and conductivity.

2. Methodology

Basic assumptions of the proposed energy absorption model are as follows:

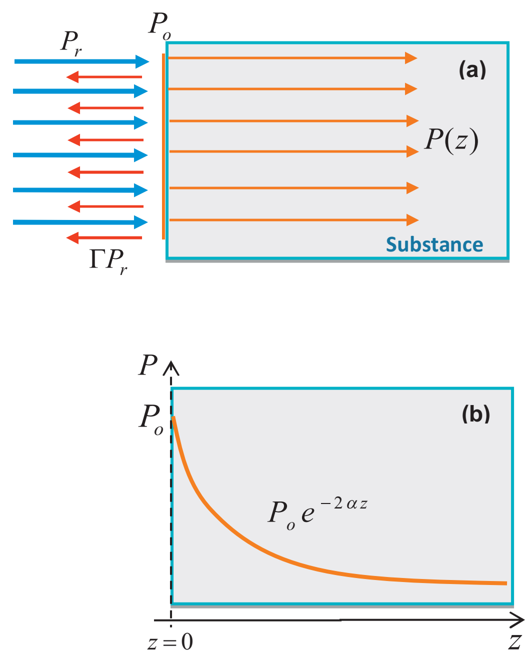

Fig. 1. (a) Ray-trace illustration of collimated EM waves propagating trough the substance; (b) an illustration for exponential decay of EM power in materials.

(i) Effective permittivity (ε), effective permeability (μ) and effective conductivity (σ) of materials are assumed to be invariant in time and space.

(ii) The whole energy lost by EM wave in materials is assumed to turns into heat in a conservative system.

The energy conveyed by electromagnetic wave are characterized by pointing vectors representing the directional energy flux density as [23]

$$\langle \vec{S} \rangle = \frac{1}{2} Re(\vec{E}_c \times \vec{H}_c^*) \tag{1}$$

The fields vectors in the complex form are expressed as,

$$\vec{E}_c = E_o \ \exp(-\alpha z) \ \exp(j(-\beta z + \psi) \times \vec{x}_0 \tag{2a}$$

$$\vec{H}_c^* = \left(\frac{1}{|Z_o|} \right) (E_o \ \exp(-\alpha z) \ \exp(j(\beta z - \psi) \times \vec{y}_0 \tag{2b}$$

where the parameter Ψ is phase difference between the field components $\vec{E}_c$ and $\vec{H}_c^*$. If the relation of $\vec{x}_0 \times \vec{y}_0 = \vec{z}_0$ is considered for the equal phases of $\vec{E}_c$ and $\vec{H}_c^*$, the average power is obtained as,

$$P = 0.5 \left(\frac{E_0^2}{|Z_0|} \right) \exp(-2\alpha z) = P_0 \ \exp(-2\alpha z) \tag{3}$$

$$P_0 = \frac{1}{2} \frac{E_0^2}{|Z_0|} \tag{4}$$

where, $P_0 = P(z = 0^+)$ and $E_0 = E(z = 0^+)$ represent the average power and the electric field of EM waves penetrating into matter at the surface of material. The parameter Z_0 denotes characteristic impedance of materials. When incident EM wave comes from outside of the materials as in Fig. 1(a), EM wave penetrating into materials from the surface can be written with respect to the average power of incident waves (P_r) and the refraction coefficient (Γ) as $P_0 = P_r - \Gamma P_r$. Here, the refracted power from the surface $P(z = 0^-)$ is expressed by the term ΓP_r. Eq. (3) refers that energy conveyed by the electromagnetic waves exponentially decay depending on