On the Microwave-Water Energy Transfer

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Abstract

The well known analogy between quantum mechanics and optics is being used here to describe the interaction between microwave and water. As an application of this analogy we found a complex quantum potential associated to water relative to microwave photons.

Keywords: *water, microwave, quantum potential, compost*

Introduction

Interaction between microwave and water is the subject for a large number practical applications, from simple food heating, food preparing, and sterilization of different water containing products or, of products immersed in a water environment, to applications in medicine, biology and chemistry [7, 8].

In addition to most of this applications, the water is not pure, but as a mixture of a variable number of mineral and/or organic constituents. This results in the increase of the difficulties of analyzing the microwave propagation, through such complex environments.

The purpose of this paper is to set the conditions to be met for microwave sterilization of compost in conditions of maximum efficiency - minimum time of exposure to microwave radiation and minimum radiation power; and particulary, to find calculation techniques that involve the smallest number of parameters, without affecting the quality of the analysis performed on the microwave absorption in complex environments such as compost.

For this purpose we used the calculation methods of quantum mechanics, which have a strong mathematical support that allows reducing the number of electromagnetic wave parameters from six: three electric fields and three magnetic fields – to two: energy and momentum of the photons [10]. At this stage of our research we have summarized the investigative methods, to simple water, while in the next steps we will expand them to complex compost.

Particular structure of water molecule consisting of two OH covalent polar bonds of aproximative 0,096 nm lenghth, arranged at an angle of $104,5^0$ with the tendency of the four oxygen electron pairs to arange themselves in the corners of a simmetric tetrahedron – the corners thereof – resulting in a polar molecule in the shape of "V" [2].

The molecule polarity is generated by the combination of negative charged oxygen atom placed on top of the molecule and the two positive charged hydrogen atoms.

A determining role in the interaction between water molecule and an extern electromagnetic field is being held by the significantly different weight of the consisting atoms of water molecule: $m_H \cong \frac{1}{16} m_O$ (M(**H**) = 1.0079 g/mol si M(**O**) = 15.9994 g/mol).

It should be noted, that in contrast to water vapors, in liquid state, water molecule is set in connection to dipoles fields' more exactly oxygen atom of a molecule is linked with two atoms of hydrogen from other water molecules. The result is that the absorption frequencies of water in vapor state are different from absorption frequencies for water in liquid or solid state.

Predominant movements of water molecules consist from stretch vibration along OH bonds, and from oscillations of the OH bonds in the plane of the molecule, with periodical changing of $104,5^0$ angle between them. The water molecules also present rotational movements along the axis of a rectangular frame centered on the oxygen molecule. As a result of the fact that the oxygen atom is placed in frame core of the rotating system, and that the low mass hydrogen atoms are at the periphery, the whole water molecule appears to have a very low rotation moment of inertia. This leads, in the vapor case, to a large number of freedom degrees, so that the combined vibration-rotational spectra present thousands of absorption lines. Finally, it should be noted that for liquid water, the electromagnetic absorption spectra occurs in the area of microwave range 0.3 – 300 GHz up to visible electromagnetic spectrum 400 - 700 THz.

In the presence of an external electromagnetic field the water molecule dipole is constantly trying to shift along the field lines. Accordingly to its own dipole oscillation frequency, water molecule can oscillate in phase with the electromagnetic field, in advance or retarded from it. This shift depends on the mobility of the electronic cloud dipole. As the water molecule gets from gaseous to liquid and to solid state the mobility is being reduced - the links with neighboring molecules are proliferating - and the resonant frequencies are decreasing. While gaseous, water molecule can absorb electromagnetic radiation in the visible and infrared spectrum, in the liquid phase the resonance frequencies are in microwave range while, for ice the resonance frequencies are in long radio waves range. These involve large differentiation of describing models for interaction potential between water dipole and electromagnetic field. In the case of microwave water heating is used the so called TIP4P –FQ potential [4-9]. We have to mention that water heated for the purpose of sterilization of vegetables comes in intimate contact with plant components whose molecules in turn may resonate on microwave frequencies.

The Experiment

The Analyzing Method

There are many methods to determine the dielectric constant of medium using microwaves. A complete analysis of a dielectric, presumes to evaluate the loss tangent, i.e. to establish the real and the imaginary component of permittivity, the second being responsible for the dielectric loss and dielectric heating.

To verify the method we confrunted the theoretical predictions for microwave absorption in water with the experimental results as described below.

The technique used by us consists in measurement of the so-called S parameters of the dielectric sample. "S" symbol comes from the term "scattering" introduced for the first time in 1965 [5]. The studied dielectric, water in our case, was introduced into a microwave resonator. The resonance frequency of the resonater was modified by the presence of the water [11]. The S parameter measurements were performed successively with emptied, cleaned resonator

and with it filled with water. The difference between the two cases allowed evaluation of the dielectric parameters with minimum error.

Electrical Parameters of Water

To analyze the behavior of water in relation to an electromagnetic signal, one needs to analyze its electrical characteristics. The predominant field of electromagnetic wave, which interacts with water, is its electric field:

$$\vec{E} = \vec{E_0} e^{i(\vec{k}\vec{r} - \omega t)}. \tag{1}$$

The water as a whole, is a group of polar molecules with a permanent dipolar moment $\vec{p_i}$. For the ith molecule the dipole located in an external electric field is exerting a force

$$\vec{F_i} = \nabla(\vec{p_i} \cdot \vec{E}). \tag{2}$$

The force is directed along $\frac{\partial \vec{E}}{\partial l}$ vector where l is the length of the dipole, trying to rotate the the dipole with the maximum electric field. The potential energy of dipole in the external electric field is

$$w_i = -\vec{p_i} \cdot \vec{E}. \tag{3}$$

Polarization vector $\vec{P}$ is the vector sum of all the dipoles associated to water molecules from a unit volume

$$\vec{P} = \lim_{V \to 0} \left(\frac{1}{V} \sum_{i=1}^{n} \vec{p_i} \right), \tag{4}$$

where n is the number of water molecules in volume V. Polarization vector $\vec{P}$ will try to follow the external electric field variations. Usually water polarization vector $\vec{P}$ is not able to follow the electric field $\vec{E}$ and a time delay appears as a phase shift angle φ:

$$\vec{P} = \vec{P_0} e^{i(\vec{k}\vec{r} - \omega t - \varphi)}. \tag{5}$$

Mechanical work done by these dipoles under the action of the external electric field is found in the heat transferred to water.

The water dipole moving equates with the occurrence of an electric current of intensity $I = \frac{1}{l} \left| \frac{d\vec{P}}{dt} \right|$ and an electrical voltage $= \vec{E} \cdot \vec{l}$. Taking into account that both units are harmonic functions and that between them exists a shift φ, the interaction of the dipole with the external field results in the energy transferred to water as heat:

$$Q = \frac{1}{2} P_0 E_0 \omega t \sin \varphi. \tag{6}$$

Note that a nonzero shift φ between electric field and polarization is essential in heating process. In absence of this shift, the phenomenon of water-heating is not possible.

The typical physical quantities of a dielectric are the electric induction $\vec{D} = \varepsilon_0\vec{E} + \vec{P}$, relative electric permittivity ε, with $\vec{D} = \varepsilon\varepsilon_0\vec{E}$ and dielectric susceptibility χ with $\vec{P} = \chi\,\varepsilon_0\vec{E}$.

In the case of water heating as a result of interaction with an electromagnetic wave, we have to consider the dielectric with loss. In this case the dielectric has a complex permittivity

$$\varepsilon = \varepsilon_1 + i\varepsilon_2\,, \tag{7}$$

where ε_2 is the imaginary part of permittivity, responsible for the electromagnetic energy loss in water, and the real part ε_1 which refers to the electromagnetic energy stored in the dielectric. In [1] an expression for complex water permittivity is indicated:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_l - \varepsilon_i}{1 + i\omega\tau_1} + \frac{\varepsilon_i - \varepsilon_\infty}{1 + i\omega\tau_2}. \tag{8}$$

ε_l is the relative permittivity at low frequencies, ε_∞ is the relative permittivity at high frequencies (optical permittivity), ε_i is the intermediate relative permittivity, and τ_1 and τ_2 are relaxation times $\tau_1 > \tau_2$. The first relaxation time τ_1 is about 18ps and decreases strongly with temperature [6], τ_2 is much smaller of about 0.2ps [6] and has a low temperature dependence.

Quantum Model for Water - Electromagnetic Field Interaction

Maxwell equations for transparent dielectric media can be written as:

$$\nabla \cdot \left(\sqrt{\varepsilon}\vec{E}\right) = 0, \qquad \nabla \times \left(\sqrt{\varepsilon}\vec{E}\right) = -\frac{\sqrt{\varepsilon\mu}}{c}\frac{\partial}{\partial t}\left(\sqrt{\mu}\vec{H}\right), \tag{9}$$

$$\nabla \cdot \left(\sqrt{\mu}\vec{H}\right) = 0\,, \qquad \nabla \times \left(\sqrt{\varepsilon}\vec{E}\right) = +\frac{\sqrt{\varepsilon\mu}}{c}\frac{\partial}{\partial t}\left(\sqrt{\varepsilon}\vec{E}\right). \tag{10}$$

We wrote the matrix form for the wave function associated to a photon [3],

$$\vec{\Psi} \rightarrow |C|\frac{1}{\sqrt{8\pi}}\begin{bmatrix} \sqrt{\varepsilon}E_x + \sqrt{\mu}H_x \\ \sqrt{\varepsilon}E_y + \sqrt{\mu}H_y \\ \sqrt{\varepsilon}E_z + \sqrt{\mu}H_z \end{bmatrix} \equiv \begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix}. \tag{11}$$

With this, Maxwell equations can be written in a more concise form

$$\nabla \times \vec{\Psi} = \frac{i}{v}\frac{\partial\vec{\Psi}}{\partial t}, \quad \nabla \cdot \vec{\Psi} = 0, \quad \text{with } v = \frac{c}{\sqrt{\epsilon\mu}}. \tag{12}$$

In the first of these equations the total energy operator $\hat{E}$ can be recognised:

$$\hat{E} = -\frac{\hbar}{i}\frac{\partial}{\partial t}, \tag{13}$$

$$\hat{E}\Psi = \hat{H}\Psi, \tag{14}$$

and using spin 1 algebra

$$\vec{S} \times \vec{S} = i\vec{S}, \quad \vec{S}^{+} = \vec{S}, \tag{15}$$

$$\vec{S} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{bmatrix} \vec{i}_1 + \begin{bmatrix} 0 & 0 & i \\ 0 & 0 & 0 \\ -i & 0 & 0 \end{bmatrix} \vec{i}_2 + \begin{bmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \vec{i}_3, \tag{16}$$

we can write

$$\hat{H} = v(\vec{S} \cdot \vec{p}). \tag{17}$$

This is the photon wave equation for an infinite medium characterized by parameters (ε, μ), with relative refraction index

$$n = \sqrt{\epsilon \mu}. \tag{18}$$

Some simple algebraic transformations led us to the equation [10]

$$\left(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \Psi - \left(\frac{\omega}{c} \right)^2 (1 - n^2) \Psi = 0. \tag{19}$$

And finaly, we found out the dielectric potential in connection to an electromagnetic wave as

$$U = i\hbar\omega\sqrt{n^2 - 1}. \tag{20}$$

As showed in [10] the electric pemittivity is a complex number which means that potential U will have real and imaginary parts:

$$U = Re\ U + i\ Im\ U. \tag{21}$$

The Equipment

Measurements were made with a vector network analyzer "VectorStar Broadband NPV - ME7828A" whose working frequency covers frequency domain analyzed, the first 3-10 GHz and the second 50 - 115 GHz. Calibration was done with the calibration device provided by the manufacturer "36585 Series Precision AutoCal". We also used for mechanical calibration the kits model 3655E-1 and 3655V-1, provided by manufacturer as well.

It was estimated that the measurement error made in this way did not exceed 3% on all areas of analyzed frequencies.

Experimental Results and Comments

Water permittivity was determined on two areas of frequency, 3-10 GHZ and 50-115 GHz. In Figure 1 are represented the real and imaginary parts of experimental permittivity. The theoretical values from relationship (8) are represented by continuous curve. Experimental values are represented by dots, fitted by the dashed line. On abscise is marked the electromagnetic test signal frequency expressed in Hz, on a logarithmic scale.

In Figure 2 we represent the water associated quantum potential, his absolute value in Figure 2a, and its phase in Figure 2b. The fitted experimental values are represented by the dotted curve. Continuous curve represents the theoretical dependence of the module and phase of the quantum potential according to Eq. (20).

Complex electric permittivity of water, Eq. (7) and (8) causes a complex size for the water associated quantum potential relative to the microwave photons, Eq. (20) through the Eq. (18). Finally it we obtain the quantum potential with his real and imaginary components.
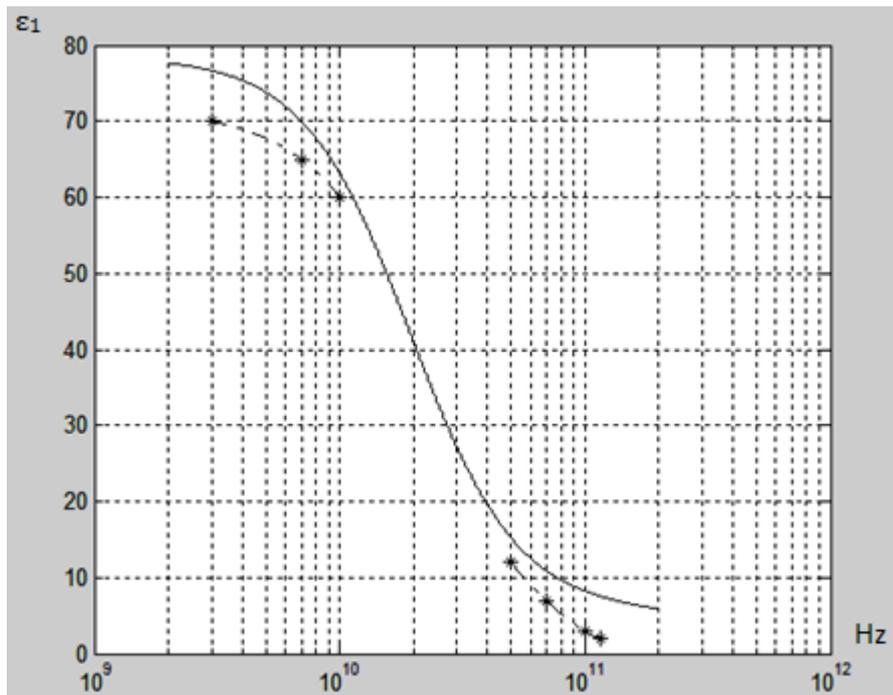
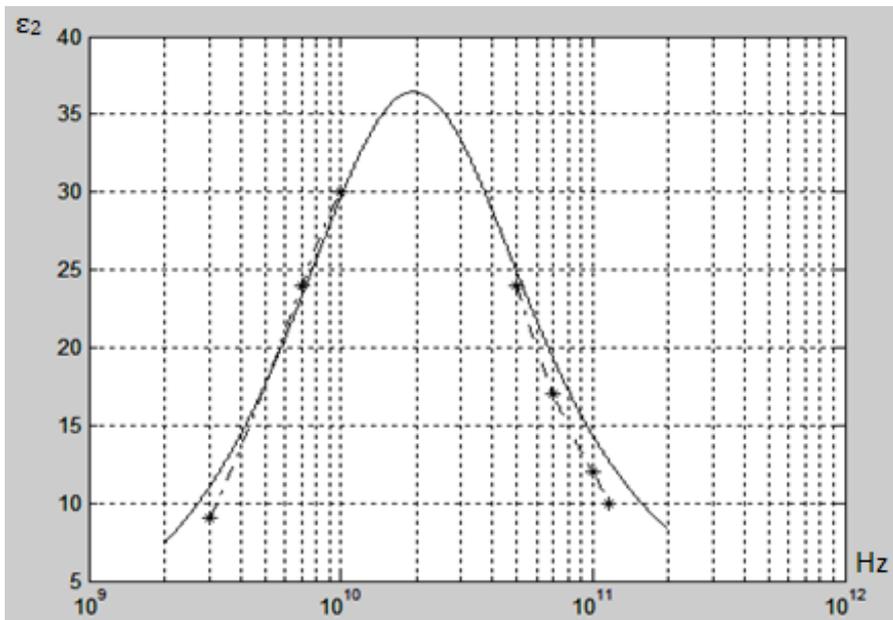**Fig. 1a**. The real part of water permittivity function of test frequency

Fig. 1b. The imaginary part of water permittivity function of test frequency
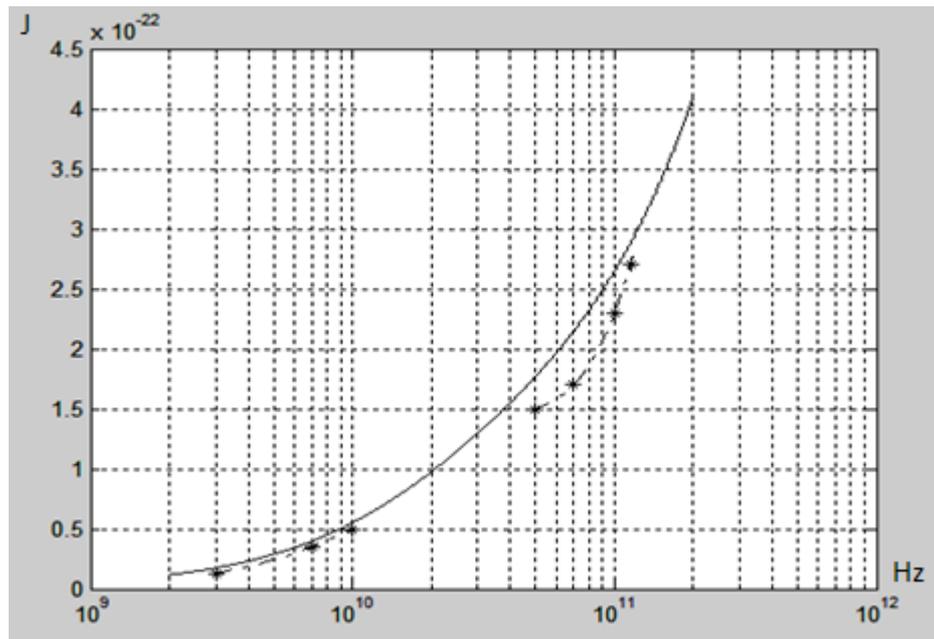
Fig. 2a. The absolute value of water quantum potential in Joule,
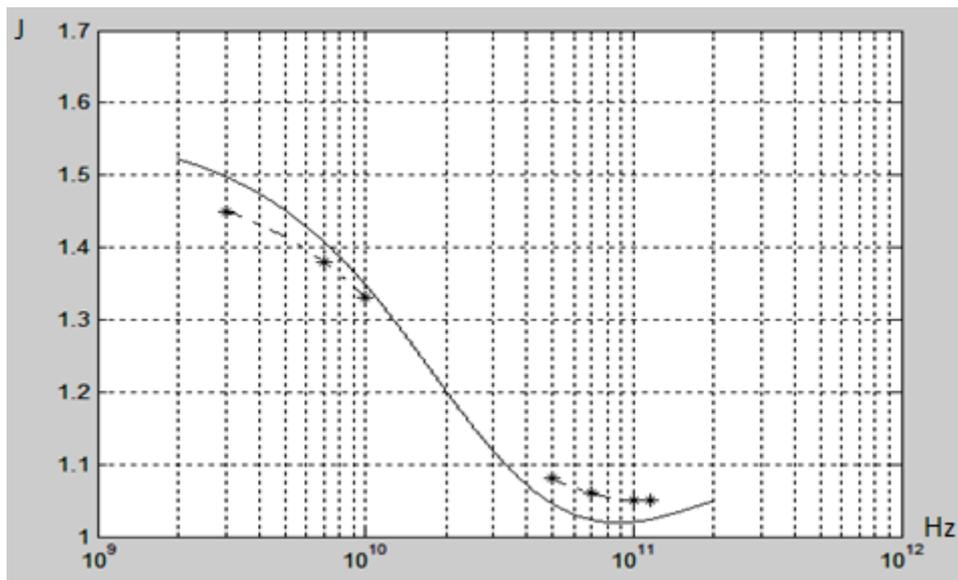as function of electromagnetic test frequency in Hz

Fig. 2b. The phase of water quantum potential in radian,
as function of electromagnetic test frequency in Hz

The existence of a real and a imaginary component of electric water permittivity and its associated quantum potential, that is responsible for the electromagnetic energy losses in the dielectric, i.e. the losses in water responsible for its heating.

Both in Figure 1 and Figure 2 it is a noticeable deviation from the theory, in connection to salts dissolved in not sufficiently purified water. They are reponsible for the occurrence of electrical charge carriers, absent is pure water, which alters the behaviour of water molecules dipole in the presence of microwave electromagnetic field. More specifically, part of the microwave photon energy is consumed for moving ions arising through the dissolution of salts, between water

molecules, which is a rubbing motion. Consequently, salt dissolved in water produces an increased absorption of electromagnetic energy and thus a faster heating.

We mention that the water used in the experiment came from the city water network.

Conclusions

This paper is an application of computer techniques in quantum mechanics , which avoids the use of Maxwell equations in the case of microwave propagation and absorption in water. Actually, the new approach reduces the number of variables, six in the case of Maxwell equations, corresponding to electric and magnetic fields to two, corresponding to microwave photons energy and momentum. Computing effort is thus proportionally reduced.

A detailed analysis of real and imaginary components of water quantum potential relative to microwave photons as indicated in [1] is the subject to special review.

The results of this work will be used in a next paper to analyze microwave absorption in water – materials mix order to establish the mechanisms that occur in the process of sterilization through microwave heating. In order to use this technique, we will apply the methods previously verified in the calculation of electric permittivity and magnetic permeability as they are presented in [11 and 12].

Experimental verifications carried out on samples of water confirm the accuracy of the model adopted in the case of quantum interactions between microwave photons and water.

We intend to exploit these results in a more complex analysis, regarding the process of drying and sterilization of compost, in order to improve the involved operations. Also we will try to extend these results to the case of large amounts of other products / materials which require a drying and sterilization in a short time frame.

Finally we will generate nomograms allowing the setting of exposure time and power levels of microwave radiation on different types of materials, with different degrees of moisture.

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Transferul de energie de la microunde la apă

Rezumat

Binecunoscuta analogie dintre mecanica cuantică şi optică este utilizată pentru descrierea interacţiei dintre microunde şi apă. Ca aplicaţie se găseşte un potenţial cuantic complex asociat apei, relativ la fotonii de microunde.