Return to Electronic & Optical Materials

Learning about Electric Dipoles from a Kitchen Microwave Oven

H. Jain
Professor
Department of Materials Science and Engineering
Lehigh University, Bethlehem PA 18015

Key Words: Microwave heating, dipoles, dielectric loss, atom movement

Prerequisite Knowledge: Definitions and elementary knowledge of dielectric properties.

Objective: To develop an understanding of dipolar relaxation in dielectric materials using the heating of food in a kitchen microwave oven.

Equipment:

1. A kitchen microwave oven
2. A kitchen refrigerator
3. A microwave-safe ceramic mug
4. A thermocouple
5. A digital multimeter with a least count of 0.01 mV or better.
6. Food items having regions ofvariable water content e.g. Danish pastry with a cherry, jelly-filled donut etc.
7. Water and (optional) water-free ethanol.
8. A stop watch

Introduction:

Our common experience shows that the temperature of a material increases when it absorbs electromagnetic radiation. The passive solar heating of water and brewing of tea in a glass jar by sunlight are just two illustrations of this process. Is the food in a microwave oven heated by the same process? The answer is yes, to the extent that the food is heated by the absorption of electromagnetic radiation of microwave frequencies. At the same time we know that cold water kept in a thermally insulated opaque flask will not warm up by keeping it in the sun but will readily heat up in a microwave oven. So the exact mechanism of absorption of sunlight and microwaves by materials must be somewhat different. The present experiment is designed to demonstrate the fundamental aspects of microwave heating and in turn, to elucidate the dipolar dielectric loss phenomenon at the molecular level The emphasis is on the basic physics and the use of common inexpensive instrumentation and materials, rather than the accuracy of results. The students are also exposed to some of the issues dealing with the microwave processing of materials. Due to the familiarity with the experiment there is greater excitement for learning and, the students appear to remember the underlying principles more than from sophisticated experiments.

Background:

A very important feature of microwave cooking is that certain food items are more readily warmed up than others. For example, in a Danish pastry the cherry in the middle gets much hotter than rest of the pastry. A few deductive experiments show that the presence of water is the key for a food to be heated effectively. The science behind these observations is that the frequency (f_{mw}) of the microwave radiation (typically at 2.45 GHz) allows for energy absorption by water molecules rather than by most other ingredients of the food. In a water molecule the two hydrogen and one oxygen atoms are not arranged in a line i.e. the H-O-H angle is 104.5^o rather than 180^o. This nonlinear configuration together with the different electronegativity of H and O atoms creates an asymmetric charge distribution within the molecule, which can be described by a permanent electric dipole consisting of $-\delta$ and $+\delta$ partial charges as shown schematically below:

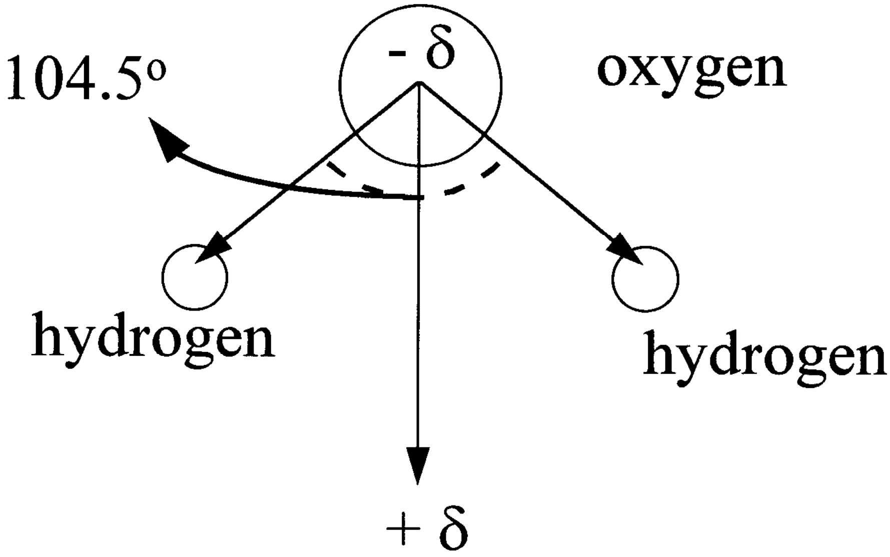


Fig. 1. Schematic of water molecule

In the absence of any external field the dipoles in water are randomly oriented due to thermal agitation. However, a dc electric field would attempt to align the dipoles along its direction as much as permitted by the randomizing effect of temperature. At the beginning when the field (E) is turned on, the dipole assembly relaxes to the new equilibrium configuration as determined by E and temperature T. For the simple case where the dipoles do not interact with each other, the approach to equilibrium follows an exponential time dependence which can be described by a characteristic relaxation time, τ. Perhaps it is easier to visualize the converse process viz. relaxing of the dipoles from partial alignment to random orientation after the dc field is turned off In this case, the decay of polarization is given by:

$$P(t) = P_0 \exp(-t/\tau) \qquad (1)$$

where P_0 is the equilibrium value of polarization in the presence of dc field and P(t) is its value t sec after the field is turned off. When the same assembly of dipoles is placed in an ac electric field, the dipoles tend to follow its time dependent variation, but usually there is a time lag between the maximum of the field and the polarization produced by the alignment of the dipoles. This “phase lag” between the cause (electric field) and its effect (polarization) produces a loss of energy in the system which is proportional to the imaginary part of the dielectric constant (also known as loss factor) [1],

$$\varepsilon'' = (\varepsilon_s - \varepsilon_\infty)\omega\tau/(1+\omega^2\tau^2) \qquad (2)$$

where ε_s and ε_∞ are the static (dc) and high frequency dielectric constants, ω (=$2\pi f$) is the angular frequency of electric field and τ is the relaxation time for the dipoles. The electrical energy loss in the system is dissipated as heat and thus raises the sample temperature.

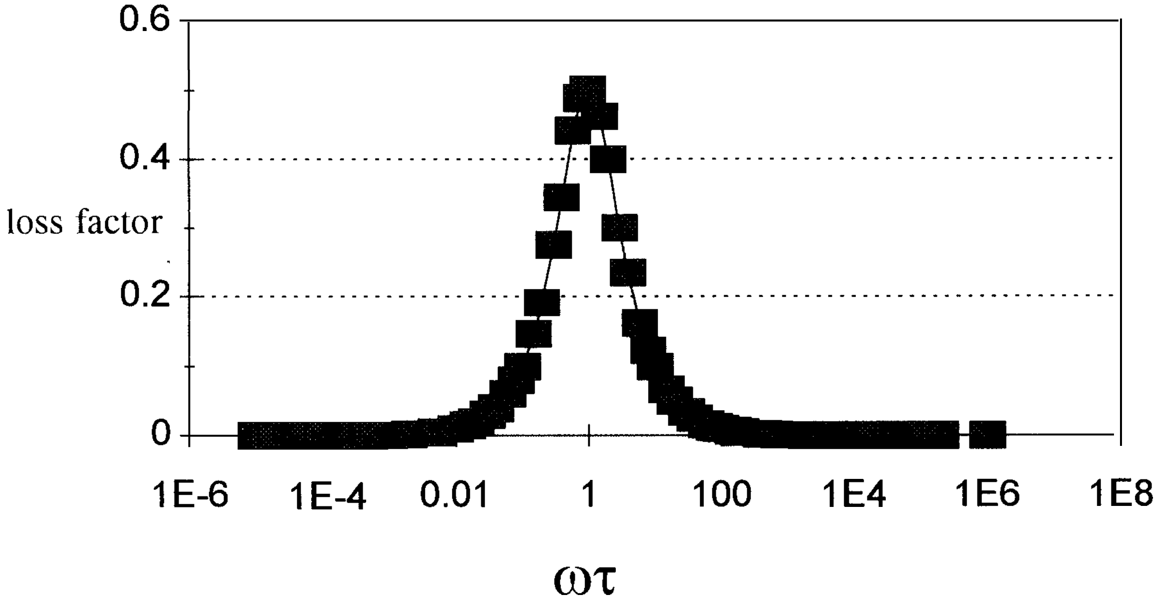


Fig. 2. Loss factor (ε'') as a function of ωτ. The vertical scale is normalized by (ε_s - ε_∞).

Eq. 2 is better known as a Debye equation and is plotted in Fig. 2. ε'' and hence the sample heating is maximum at a special frequency, ω_{max}, given by the condition

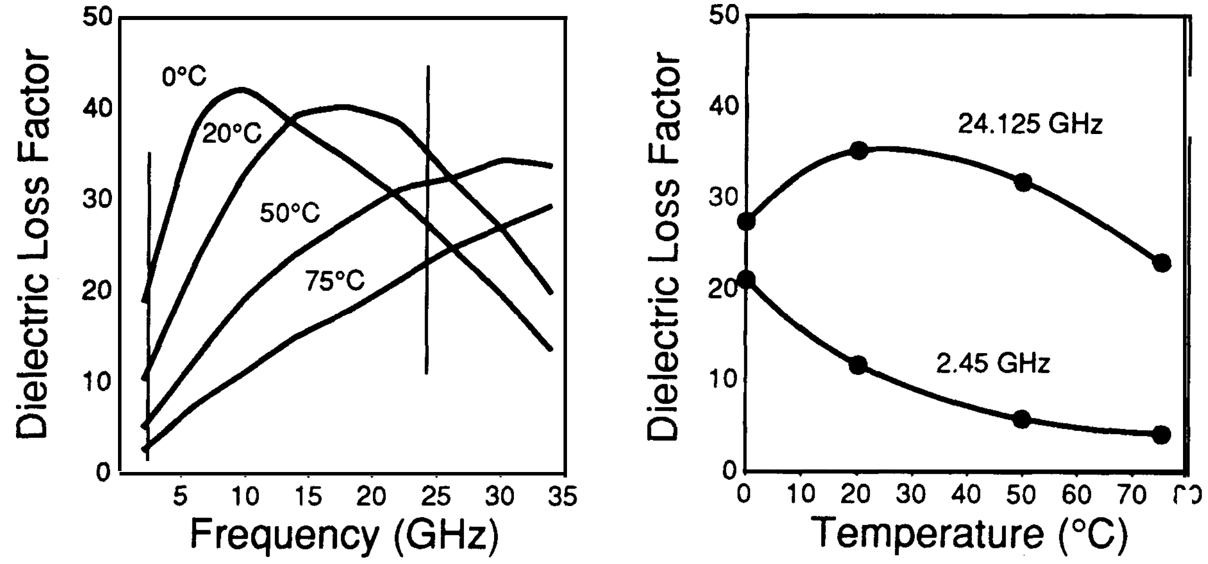
$$\omega_{max}\tau = 1 \qquad (3)$$

Thus if an assembly of dipoles is subjected to an ac electric field of electromagnetic radiation, the sample will absorb energy and heat up by the dipolar loss mechanism. Clearly this dielectric heating effect is a strong function of ω, showing a maximum when the frequency of the radiation is ω_{max}. For $\omega \gg \omega_{max}$ or $\omega \ll \omega_{max}$ dielectric heating will be negligible. Of course, if the system does not contain dipoles, no such heating will occur. Can you name two materials which do not contain permanent dipoles?

The dipolar dielectric heating can be also varied at a fixed frequency if τ is changed. In this regard note that although τ is a material property, it can be conveniently varied by changing the temperature. Often the reorientation of the dipoles involves movement of atoms and therefore τ follows an Arrhenius temperature dependence given by

$$\tau = \tau_0 \exp(Q/kT) \qquad (4)$$

where τ_0 is the pre-exponential factor, Q is the activation energy for dipole reorientation, k is the Boltzmann constant and T is absolute temperature. Thus τ decreases exponentially with increasing T. For the present case Q will be the energy barrier for the reorientation of a water molecule by necessary molecular movement. By inserting Eq. 4 into Eq. 2 it becomes clear that for a fixed frequency (say, $\omega_{mw} = 2\pi f_{mw}$)a plot of ε'' vs. 1/T will have the same shape as Fig. 2. That is, the dielectric heating will be maximum at a temperature (say T_{max}) which gives $\tau = 1/\omega_{mw}$. For $T>T_{max}$ or $T<T_{max}$, the dielectric heating will be less effective. Fig. 3 shows experimental results of ε'' measurements on water at various temperatures and frequencies [2]. The general features of the ε'' plots in this figure are consistent with the theory summarized above. However, the width of the ε'' peak is wider than predicted by the simple theory and its shape is skewed. Such minor deviation from theoretical predictions indicates the complicated nature of dipolar relaxation in water, which, while interesting, is beyond the scope of this report [3].



(a)

(b)

Fig. 3. (a) Frequency dependence of ε'' for water at different temperatures. (b) The data of (a) replotted to show the temperature dependence of ε'' for water at 2.45 GHz and 24.125 GHz. Figure taken with author's permission from ref. [2].

A kitchen microwave oven is designed to produce electromagnetic radiation at a fixed frequency of f_{mw} = 2.45 GHZ which is close to f_{max} for water molecules. According to Fig. 3 (b) the dielectric loss factor at this frequency decreases with temperature. Therefore, ifheating of food in a kitchen microwave oven is indeed by the dipolar heating of water, one would predict a gradually less efficient heating with increasing temperature. Obviously the heating characteristics of a food depend on its constituents and their dielectric loss factor at the temperature of interest. If the food does not contain any dipoles or if ω_{max} for the dipoles is very different from the microwave frequency (2.45 GHz), the heating will not occur. The following experiments demonstrate these predictions and thus elucidate the mechanism of food warming by a microwave kitchen oven and, in general, the dipolar dielectric loss.

Procedure:

Experiment A. First convince yourselfthat indeed water is responsible for most of the heating of food in a kitchen microwave oven. Take the jelly filled donut and warm it in the oven. Observe the variation of temperature within the donut. Repeat the experiment with other food items of your choice.

Experiment B. The specific objective of experiment B is to establish whether or not the heating of, water by a kitchen microwave oven is a function of water temperature itself Does the heating decrease with a rise in temperature as suggested by the theory above?

The experiment consists of monitoring the heating of about 200 ml of water in a microwave-safe mug using a kitchen microwave oven. To extend the span of available temperature range, cool the water in a refrigerator before starting the experiment. Ideally one would like to conduct an ***in situ*** measurement of temperature of the liquid, but this can not be done easily as a common temperature probe itself is heated by the microwave radiation. Therefore, the following sequence of measurements is suggested: (at time t=0 sec) start to heat the liquid for **15** sec in the microwave oven, take it out and stir for **15** to 20 sec with a thermocouple whose output is continuously monitored with a multimeter. Next, leave the thermocouple in the center of the cup for **10** seconds. Record the output of the thermocouple at t=45 sec. Place the cup back in the oven and start heating again at t=60 sec. Repeat the one minute cycle of heating and measurement until the liquid starts boiling. Record the data in the first three columns of the following table. Convert the thermocouple output into temperature using appropriate conversion tables.

Heating cycle: i =1, 2....	Time (min, sec)	Thermocouple output (mV)	Observed Temp. T (°C)	Corrected Temp. T' (°C)	$\Delta T = T'_{i+1} - T'_i$ (°C)

A correction to T is needed because the temperature of water decreases during the 45 sec period after stopping the microwave oven. The cooling of the liquid during measurements depends on the temperature itself according to Newton's law of cooling. The water near the boiling temperature will cool much more rapidly than, for example, water close to the room temperature. To get an estimate of the correction to T allow the heated water to cool down on its own and continue to record the multimeter output every 30 sec until the water temperature reaches the room temperature within a few degree Celsius. (Note: If the starting water is below the room temperature, a correction may be needed for its normal warming by the environment.) Use this information to correct the temperature recorded during the cycles of microwave heating. Enter the corrected temperature T' in the table and obtain AT. Next, plot the variation of temperature increase (AT) in each heating cycle as a function of sample temperature. From the plot determine whether the microwave heating of water becomes more efficient, less efficient or is unaffected by the sample temperature. Compare your findings with the theoretical predictions. Comment on any discrepancies.

Experiment C. To increase the usefulness of the results of Experiment B for real kitchen applications, consider the microwave heating of alcohol. Using the following data from Böttcher [4], predict the differences between **the microwave heating characteristics of the food containing primarily (a) water for which** $\tau_{max} = 1 \times 10^{-11}$ **sec at 19 °C or (b) alcohol (ethanol) for which** $\tau_{max} = 13 \times 10^{-11}$ sec at 20°C. Repeat experiment B with water-free alcohol. Compare the results of the two experiments, test your predictions and explain the differences.

Experiment D. Having understood the origin of microwave heating of water, what would you predict for the heating of ice? Take a piece of ice from the freezer, wrap it in a paper towel to keep it dry. Note that any water even on the surface w-ill foil the experiment. Heat the ice in the microwave oven for a minute. Has the ice melted? If not, why not? What do the results tell about dipole relaxation in the solid state vis-a-vis in the liquid state.

Note to the Instructor

1. To ensure that a ceramic mug is microwave safe, heat it dry in the oven for l-2 minutes. If it is not heated or remains lukewarm to touch it may be acceptable for the experiment. Avoid using a ceramic mug which is excessively heated because of the water trapped in the ceramic itself
2. Try covering the mug with an insulating plastic lid to minimize heat loss. However, if the cover complicates the temperature measurement, do not use it. In any case, it is important that the conditions for water cooling for temperature correction are the same as during the heating cycles.
3. Making the measurement in milivolts is important, as it emphasizes that the thermoelectric effect is responsible for causing the observed signal. This could lead into a classroom discussion of the thermoelectric effect or could be the basis for an expanded lab report.
4. The instructor may wish to make reference to industrial applications of microwave heating e.g. in the curing of thermosetting coatings and adhesives, microwave processing and remediation of hazardous waste, high temperature processing of ceramic materials etc.

References:

1. Von Hippel, A.R, Dielectrics and Waves, Wiley, New York (1954).
2. Blackham, D., David, F. and Engelder, D., ‘High frequency dielectric materials measurements”, RF and Microwave Measurement Symposium and Exhibition, Hewlett Packard Lit. No. 5952-2385E, pp. 62-74 (1991).
3. Schwan, H.P. , Sheppard, RJ. and Grant, E.H., J. Chem Phys. 64 (1976) 2257. Also references therein.
4. Böttcher, C. J.F., Theory of Electric Polarization, Elsevier, Amsterdam (1952).

Professor Himanshu Jain received the degree of Doctor of Engineering Science in Materials Science from Columbia University in 1979. Before joining the faculty of Lehigh University he conducted research at Argonne and Brookhaven National Laboratories for several years on various glasses and the problems of corrosion under nuclear repository conditions. He has developed and taught both graduate and undergraduate courses in materials science specializing in glasses and ceramics. His current research interests include: point defects, electrical relaxation, conductivity and dielectric properties of amorphous and crystalline ceramics. Surface conduction. Effect of radiation on transport properties. Mechanisms of diffusion and nuclear spin relaxation in glasses. Structure of glass. Radiation enhanced processing of ceramics and cation diffusion in perovskite structure. Dr. Jain is an editor of 3 books and, author of 2 U.S. patents and over 100 research articles on glasses, ceramics, etc.