Principles of Microwave Radiation

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ABSTRACT

Microwaves, such as those used in cooking and processing food, are part of the broad spectrum of electromagnetic radiation which includes radio waves, microwaves, infrared radiation, visible light, ultra-violet radiation, x-rays and Gamma rays. Electromagnetic radiation has a dual nature, it is both wave-like and particle-like. An understanding of this dual nature of electromagnetic radiation is necessary for an understanding of the processes of emission, transmission and absorption of microwaves, which is in turn necessary for understanding the processes and phenomena which are important in the use of microwave radiation as a source of energy for heating and food processing. The properties of electromagnetic waves and the processes of emission, transmission and absorption are described and some effects in microwave-heating applications are discussed.

Establishment of electric and magnetic fields in empty space requires the expenditure of energy, much the same as stretching a spring requires an expenditure of energy. When the spring is stretched we say that the work done in stretching it is stored as elastic energy in the stretched spring. We can get the energy back by letting the spring relax to its original condition. Similarly, we say that the energy expended in establishing electric and magnetic fields is stored in those fields and we can get the energy back by letting the fields relax to nothing. Of course, if we want to use the stored energy for some purpose we may have to be quite ingenious as to how we couple the electric and magnetic fields to the material on which we want to do work. In a long spring, if we stretch some local region and release it, the strained region of the spring will travel in both directions from its original position. We can think of the energy stored in the stretched part of the spring as traveling along the spring. When the stretched region reaches the end of the spring, it can deposit its energy in the mounting at the end, if the mounting is what we call a “lossy” one. Similarly, energy deposited by a pebble striking the surface of a pond travels outward and is carried in waves to the shore where it is deposited. When energy is put into a region by establishment of an electric field, the field will start to decrease at the original location if the cause of the field is removed. This will cause a magnetic field to be formed, the change of which gives rise to generation of new electric fields in the surrounding space and a wave of the electric field will travel outward and carry energy with it.

It is most common to consider periodic electromagnetic waves. Periodic electromagnetic waves are generated by oscillating electric charges which cause oscillating electric fields. The changing electric fields also cause oscillating magnetic fields. The interplay of a changing electric field generating a magnetic field, the change of which gives rise to an oscillating field, allows the propagation of an electromagnetic field in free space. In 1864, James Clerk Maxwell set down the equations governing the electric and magnetic fields and their interactions. He noted that one of the solutions to his equations was a wave of oscillating electric and magnetic fields propagating at a fixed velocity in empty space.

Some time later, in 1886, Hendrich Hertz, for whom the frequency unit is named, developed oscillating electric circuits and generated electromagnetic waves. He measured the velocity of these waves and confirmed their transverse nature. The fact that light waves exhibited the same properties and traveled at the same speed helped with their identification as electromagnetic waves of very short wavelength.

For periodic electromagnetic waves, there is a definite relationship between the wave velocity (v), the frequency of oscillation (f) and the wavelength (λ) of the wave. The wavelength of the wave is equal to the wave velocity divided by the frequency, λ = v/f. The wave velocity of electromagnetic waves in empty space is 2.997 × 10^8 meters/second. The waves we will be interested in have wavelengths of 0.5 to 50 cm, which means that the frequencies of these microwaves lie between 3 × 10^10 Hz and 6 × 10^8 Hz. To generate electromagnetic waves of a given frequency, electric charges must be oscillated at that frequency. One can identify the kind of oscillating charged system which can give rise to a given wavelength electromagnetic wave because of the limits imposed by the frequency of oscillation. In Table 1, the relationship between frequency, wavelength and the kind of oscillating source necessary to generate the electromagnetic wave is shown for a large range of wavelengths.

The quantized nature of electromagnetic waves was established by Max Planck and was used by Einstein to explain the photoelectric effect and by Bohr in his theory of the hydrogen atom spectrum. One can describe the quantized nature of electromagnetic waves by saying that electromagnetic waves can only be absorbed or emitted in definite energy units, called photons; the energy content of a photon depends on the frequency or wavelength of the radiation. The energy of the photon is given as:

\[ E_{\text{photon}} = hf \]

where \( h = 6.625 \times 10^{-34} \) Joule - seconds (is called Planck’s constant) and \( f \) is the frequency of the radiation. The wavelength values of Table 1 are for
empty space only. When electromagnetic radiation travels through any material, it travels at a different velocity, and as a consequence the frequency remains the same but the wavelength of the wave changes. In general, the wavelength shortens since the velocity of an electromagnetic wave is less in a material than it is in empty space.

The intensity of electromagnetic radiation is commonly expressed in one of two ways. The maximum value of the oscillating electric field strength, $E_{\text{max}}$, in volts per meter is given, or the energy flux, $I$, in watts per square meter (joules per square meter per second) is given. When dealing with microwave applications, the unit used is most often milliwatts per square centimeter. The intensity of radiation is proportional to the square of the maximum electric field intensity, which is called the amplitude to the wave. An easily remembered equality between these two ways of expressing the intensity of radiation is:

$$I = \frac{1}{2}c\varepsilon_0 E_{\text{max}}^2,$$

where $c$ is the velocity of electromagnetic waves in vacuum ($2,997 \times 10^8$ meters/sec), $\varepsilon_0$ is the permittivity of vacuum ($8.854 \times 10^{-12}$ Farads/meter) and $E_{\text{max}}$ is the maximum electric field strength, or amplitude, of the wave in volts per meter. A typical comparison is that a microwave with a electric field amplitude of 1 volt/centimeter has an intensity of 1.328 milliwatts/square centimeter.

**INTERFERENCE EFFECTS**

Microwaves, as all electromagnetic waves, are capable of interference effects. This occurs because the electric field intensity at a given point in space at one instant of time is the sum of the electric fields from each wave passing that point at that instant of time. Since electric fields can be in one direction or another, it is possible for the field at a point to be greater than that of any of the separate waves arriving at a point, or to cancel and cause a vanishing electric field at the point. Let us talk about a specific example. If a microwave source is set up and a beam of microwaves directed out into a large region, the measured intensity of this beam, that is the power per unit area of beam, will decrease continuously away from the source as the beam spreads. If one directs the beam perpendicularly towards a metallic sheet, then the beam will be reflected and in the region near the sheet, there are two waves of the same wavelength traveling in opposite directions, the direct wave from the source and the reflected wave from the sheet. The field of the reflected wave at the metal sheet is just opposite that of the incident wave and these two fields cancel at the metal sheet and each point an integral number of half wavelengths from this metal sheet. In between these positions, the electrical field oscillates with twice the amplitude it would have if only one or the other wave was present separately. Such a combination of two oppositely traveling waves is called a standing wave.

The wavelength of a wave can be determined by measuring the distance between nodes, the points at which no oscillating electric field exists because of cancellation between the oppositely traveling waves. The wavelength is twice the distance between nodes. We encounter examples of wave interference frequently; acoustically dead spots in rooms for certain frequencies, interpenetrating water waves and the fading in and out of the television program as a plane flies by. In this latter case, the direct and reflected waves cancel when path from the source to the receiver by reflection from the plane is some odd number of half wave lengths different from the direct path. Interference phenomena are also observed for light, which is also electromagnetic radiation. In fact, light exhibits reflection, refraction and polarization effects, and these same effects can be observed for microwave radiation.

**REFLECTION, REFRACTION AND POLARIZATION**

A good conductor, such as a sheet of metal, is a reflector of microwaves because the electrons in the metal, in the presence of the electric field of the wave, move in such a way as to reduce the electric field in the metal to zero. The response of the electric charges in the metal causes a reflected wave to come back from the surface of the metal, which cancels the field of the incident wave at the surface. At any place where there is an interface between materials with different electrical properties, a partial reflection will occur. For example, light is partially reflected at a glass to air interface, and similarly microwaves will be partially reflected at an air to roast or fat to muscle interface in a microwave oven.

The law of reflection holds for reflection of microwaves from a plane interface, that is the angle of the reflected beam to the normal to the surface is equal to the angle of the incident beam to the normal and the incident beam, reflected beam and surface normal are the same plane.

Refraction occurs for microwaves as well as for other electromagnetic radiation. If a beam of microwaves strikes an interface between two regions of different electrical properties at other than normal incidence, the direction of travel of the wave will change. This is the same effect as the bending of a light beam when it passes...
from air to water. The same law governs the direction of the incident and refracted beams in the case of microwaves as in the case of visible light. Lenses and optical instruments are designed on the basis of the laws of reflection and refraction, thus it is obvious that microwave lenses and focusing mirrors can be constructed. You see these devices in use on the top of microwave communication towers.

Another property of microwaves is polarization. Polarization of a wave is best visualized by imagining waves on a rope. If a wave on a horizontal rope causes the rope to oscillate vertically we say that the wave is polarized vertically, if the rope oscillates horizontally perpendicular to the length of the rope we say the wave is polarized horizontally. Only transverse waves, that is waves for which the wave motion is perpendicular to the direction of wave travel, can exhibit polarization. Sound waves, for example, cannot be polarized. They are longitudinal waves, waves in which the wave motion is back and forth along the direction of propagation of the wave.

Electromagnetic waves can show polarization, thus they are transverse waves. The wave is a wave of electric and magnetic fields which are directed perpendicular to the direction of propagation of the wave. There are two directions perpendicular to the direction of travel of the wave, thus there are two directions for plane polarization. An actual wave may have both plane polarizations present at the same time, and, depending on the relative phase between them, the resultant electromagnetic wave may be plane-polarized or elliptically-polarized. Interfering waves of different polarizations can never totally cancel so they will not show complete destructive interference.

Polarization of electromagnetic waves is determined by the direction of motion of the oscillating charges which serve as a source of the waves. Microwaves are usually generated by moving electrons back and forth at high frequency in a wire antenna or on the inner surface of a wave guide. There is a direction associated with the motion of the electrons and the radiated waves are usually plane-polarized.

**SOURCES OF ELECTROMAGNETIC RADIATION**

The sources of electromagnetic radiation are ultimately oscillating electric charges. As we have remarked earlier, these can vary from the acceleration of the protons in a nucleus in the case of gamma rays, to the motions of inner shell electrons giving rise to x-rays, to the motions of the charged nuclei and electrons in vibrating and rotating molecules which are the origins of infrared and some microwave radiation and finally to the acceleration of electrons in electronic circuits which are the sources of microwaves and radio waves. For electronic circuits, the efficiency of conversion of electrical energy into electromagnetic radiation is high. These circuits are capable of relatively easy control so that this will be the best source of microwaves for heating applications.

The only frequencies which are approved by the Federal Communication Commission for industrial, medical and scientific uses in the United States and the wavelength of these microwaves are given in Table 2.

**TABLE 2. Frequency and wavelength of microwaves approved for industrial, medical and scientific use.**

<table>
<thead>
<tr>
<th>Frequency band (MHz)</th>
<th>Central wavelength (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>915 ± 25</td>
<td>32.8</td>
</tr>
<tr>
<td>2450 ± 50</td>
<td>12.2</td>
</tr>
<tr>
<td>5800 ± 75</td>
<td>5.2</td>
</tr>
<tr>
<td>22125 ± 125</td>
<td>1.4</td>
</tr>
</tbody>
</table>

To understand the sources of microwave radiation, we can first look at a radio frequency oscillator which consists of a capacitor and inductor. The capacitor consists of two conducting plates with an insulator between them. If electric charge is moved from one plate to the other an electric field is set up between the plates, a voltage will exist between the plates and work will have been done in the process. We can consider the energy to be stored in the capacitor. If we connect the two plates with a wire a current will flow, the charge will be neutralized and the electrical potential difference (voltage) and the stored energy will go to zero. An inductor consists of a wire coil with or without a core. If current is passed through such an inductor, a magnetic field is set up. Work is done in establishing the current in the coil, and if the driving source of the current and power is removed the magnetic field starts to collapse. This collapsing magnetic field induces an electrical potential (voltage) in the coil which tends to keep the current flowing in the same direction as before. A combination of an inductor and a capacitor forms an electrical circuit which is capable of oscillating charges back and forth over a large range of frequencies, from zero up to about 1 MHz, depending on the values of the capacitance and inductance.

In Fig. 1, the oscillation of a capacitor-inductor circuit is shown. In sketch (a) we start with the capacitor charged and no current. There is an electric field (E) in the

**Figure 1. Schematic diagram of the phase of electrical oscillations in a capacitor-inductor radio frequency oscillator.**
capacitor and consequently a voltage across it. This situation cannot exist unchanged so a current begins to flow through the coil, reducing the charge on the capacitor. The current through the coil sets up a magnetic field (B) through the coil as shown in sketch (b). This continues until the charge on the capacitor is zero and the magnetic field in the coil is at a maximum. Under this condition the current cannot simply stop because the magnetic field will start to decrease and will cause a voltage to be induced in the coil which will keep the current flowing in the same direction as we see in sketch (c). The capacitor starts charging up in the opposite direction as a result of the current flow, as in sketch (d). This continues until the magnetic field is reduced to zero, and the capacitor has its maximum electric charge in the opposite direction as in (c). The current flow now reverses and the current oscillates back and forth. This oscillating current can be the source of electromagnetic waves, more commonly the potential difference across the coil and capacitor used to drive a current in some radiating element such as an antenna. The energy that is lost to the radiation of electromagnetic waves must be replaced if the oscillations are to continue. The energy to replace that lost by radiation is obtained by using an amplifier to drive a current through a feed-back coil adjacent to the coil in the oscillating circuit. The current in the feed-back coil is arranged to increase the magnetic field in the inductance coil at its peak, and thus put additional energy into the oscillating circuit. This is just like keeping someone going in a swing by pushing a little at the top of the swing each time.

The kind of circuit we have just described works well up to a maximum frequency of a few megahertz; at higher frequencies it becomes impossible to make macroscopic capacitors and inductors with small enough values to serve as oscillating circuit elements. The oscillating at a frequency of 2450 ± 25 MHz as a source of cavities in good conductors. The inductance of such a circuit is provided by the magnetic fields established when current flows in the surface of the cavity; the capacitance is provided by the electric field from one area of the cavity to another. The values of these capacitances and inductances can be made very small and thus the resonant frequency of oscillation is quite high, in the range of 100 MHz to 30,000 MHz. These resonant cavity circuits are contained in tubes called magnetrons, klystrons or traveling wave tubes. These tubes contain not only the resonant cavities but also are arranged to accelerate electrons and bring them by the resonant cavities at just such a time as to put more energy in the current oscillations in the walls. The energy output of these tubes is brought out by either directly connecting the resonant cavity to a wave-guide which will direct the waves away or by inducing a current in a pick up loop of a conductor in the tube cavity, the other end of which serves as an antenna to induce waves in the wave guide. Most home microwave ovens use a magnetron oscillating at a frequency of 2450 ± 25 MHz as a source of microwaves. The radiation is coupled into the oven through a very short piece of wave guide.

**PROCESS OF HEATING**

We are all familiar with the usual processes by which food is heated in ovens for cooking or other processing. The outside of the food is heated by convection of heated oven air. The hot walls, heating elements, resistance rods or burners radiate infrared waves which are absorbed and heat a very thin layer at the surface of the food. The interior of the food is then heated by conduction from the heated surface. The thermal conductivity of foods is not high; thus it takes quite long for the interior of food heated in this way to reach cooking temperatures. When food is heated by microwaves, the energy is deposited well within the food and thus the time for the food to reach cooking temperature is reduced. It is necessary to understand the mechanisms by which the energy of microwaves is converted to thermal energy to understand some of the effects encountered in microwave applications.

In general, the first step in conversion of microwave energy into thermal energy is absorption of the microwaves by some microscopic absorbing system and then the degradation of the energy into thermal vibrations of the molecules of the absorbing matter. Microwaves can be transmitted through many materials without being absorbed. This is because microwaves, as all electromagnetic radiations, are only emitted or absorbed in fixed quantities we call photons. As we have previously stated, the amount of energy carried by a photon is directly proportional to the frequency of the radiation, thus the amount of energy carried by a microwave photon is quite small.

All material systems, nuclei, atoms and molecules small or large, have only certain allowed energy states. The lowest of these energy states permitted by nature is called the ground state. This is the state that most materials are in when not heated. For a molecule to absorb a photon, the energy of the photon must exactly match the energy difference between the present state of the molecule and some other allowed energy state. A further requirement is that the presence of the photon influences the molecule. This is usually described by saying that the molecule and radiation field must be coupled together. In general, the radiation field couples to molecular systems through the force that the electric field of the radiation exerts on charged parts of the molecular system. Magnetic effects would be important if the systems involved were ferromagnetic. The systems of interest here are not ferromagnetic and all magnetic effects will be ignored. For example the ends of the diatomic molecule, hydrogen chloride (H+Cl-), have opposite charges. While the HCl molecule is not one which would be involved in microwave cooking, it provides a simple example of absorption by a polarized molecule. In Fig. 2, the electrical field intensity at different points of an electromagnetic wave is shown schematically. As the wave travels by a molecule, the molecule will
experience an electric field oscillating up and down. If the electrical field of an electromagnetic wave oscillates along the length of the bond between the hydrogen and chlorine atoms, as the wave goes by, this tends to push and pull the atoms along the bond and thus to set up a vibration along the bond, as is shown in Fig. 2b. If the electrical field of the electromagnetic wave exerts forces perpendicular to the bond length, then there will be a torque exerted on the molecule which will tend to set it into rotation, as is illustrated in Fig. 2c. Energy will be transferred to the molecule, provided the frequency of the photon is one of the values for which the energy of the photon matches one of the energy differences in the allowed vibrational or rational energies of the HCl molecule.

The above considerations make it clear that the passage of an electromagnetic wave will tend to do work on a polar molecule such as HCl. Water (H2O) is another polar molecule, and the presence of water in condensed phases, either intercellular or absorbed water, accounts for much of the primary absorption of microwaves in biological materials. If the H2O molecules through which electromagnetic waves pass are well separated, as in the gaseous state, then there will be a relatively small number of allowed energy differences, and thus only photons of certain definite frequencies will be absorbed. Microwaves of other frequencies will be transmitted without energy loss. In fact, the presence of many kinds of molecules can be determined by the set or spectrum of electromagnetic radiations they absorb. One can only transfer microwave energy to such a set of isolated molecules if the frequency of the source is one of those which will be absorbed. This makes it difficult to heat a vapor with a fixed frequency microwave source.

If one has a liquid made up of H2O molecules, the molecules are much closer together and then the hydrogen bonding between molecules will cause the allowed energy states of the collection of H2O molecules to cover larger bands of microwave frequencies and become nearly continuous. Under these circumstances almost any frequency microwave will match with some allowed transition energy, and can interact with the charges involved in hydrogen bonding and be absorbed.

We have seen how polar molecules interact with a radiation field and absorb energy. What will cause absorption of microwaves in non-polar materials? In the molecules of non-polar materials, the electrical charges are symmetrically distributed. If an electric field is applied to such a material, the positive charges experience a force in the direction of the field and the negative charges experience a force opposite to the field direction. This will lead to a displacement of these charges from their original symmetrical arrangement and the molecule will become polarized. This induced polarization then allows the electrical field of the electromagnetic wave to interact with the molecule. This provides the mechanism of energy transfer from an electromagnetic field to molecules of oils and fatty tissue in a microwave oven.

Some organic molecules have polar and non-polar regions, thus they can interact with a radiation field by both permanent and induced polarization of the molecule. When plane electromagnetic waves travel through a homogeneous absorbing medium, energy is removed from the wave. The rate of energy deposition in a given region is directly proportional to the intensity of the wave in that region, and a constant, a, called the absorption coefficient, which represents the microscopic loss processes in the material. If one has a standing electromagnetic wave in a material, the energy deposition per unit volume is proportional to the square of the amplitude of the electrical field of the standing wave and the absorption coefficient of the material. Once the primary absorption of microwave energy occurs, it becomes energy of hindered rotation and vibration of the absorbing collective molecular system. If this energy were to be reradiated, the temperature of the material would remain essentially unchanged. For the energy to appear as heat, it must be transferred into the vibration of each molecule against its surroundings rather than remain as internal vibration in the absorbing molecules. This redistribution of energy takes place through the forces that the internal motions of one molecule exert on its neighbors. Some people refer to this effect as a "molecular friction" effect. Once the energy has been degraded into thermal energy, the entropy of the system has increased and the reverse process will not occur in an isolated system, thus the energy is captured from the electromagnetic field and prevented from being reradiated as electromagnetic waves.

The processes just described are frequently called dielectric heating. There is an additional mechanism for conversion of electromagnetic energy into thermal...
This effect is rather striking in the case of a good conductor. Good conductors of electricity are not free to travel perpendicular to the slits; the conductor will behave as a solid conductor and reflect the wave. The charges in the holes are much smaller than the wavelength of the wave, and the electron will not reradiate all of the energy that it has received from the electromagnetic field. This means very good conductors of electricity are poor absorbers of electromagnetic radiation; they are instead good reflectors of electromagnetic radiation. This phenomenon is used in constraining the electromagnetic waves in waveguides and in microwave ovens. The door of a microwave oven is a good conductor, usually aluminum, with a regular pattern of small holes in it so that one can see into the oven. One might wonder if the microwaves could not escape from the oven through these holes. The results of both calculations and measurements is that if the holes are both much smaller than the wavelength of the radiation then the electromagnetic fields extend through the holes only a distance comparable to that of the hole diameter and that no waves are passed through. This effect is rather striking in the case of a good conductor with slits cut in it which are narrow compared to the wavelength of some particular microwave radiation. If the microwave is polarized, say its electric field oscillates in the vertical direction, and if the conductor is placed with the slits perpendicular to the electric field, or horizontal, the wave will travel through because the charges in the conductor are not free to travel perpendicular to the slits and the slitted conductor acts on a non-conductor. If the slits are vertical, the electrons in the conductor are free to respond to the electromagnetic field and the slitted conductor will behave as a solid conductor and reflect the waves. Such a slitted conductor can be used to analyze the polarization of microwaves.

CONTROLLING LEAKAGE

As we have noted, the reflection of microwaves from a good conductor is used to confine microwaves in an oven cavity. The door closure provides a possibility for some microwave leakage since the length of the opening is longer than the wavelength. There are two ways by which this leakage is minimized generally. One way is by electrically connecting the door to the oven interior, using a conducting strip with fingers that contact both the door and the interior of the oven. This technique works quite well as long as the mechanical alignment of the door is maintained so that the contacts have very low electrical resistance. If the door becomes bent or misadjusted, some microwave leakage may occur. A second method is to use a lossy flexible gasket at the distance from the interior of the oven where the current flow in the gasket due to leakage is maximized. This maximizes the absorption of the leakage from the oven interior and is less sensitive to some door misalignment than the electrical contacts described previously.

ATOMIC BASIS FOR HEATING

One needs to understand the existence of allowed energy states of material systems and the quantization of the electromagnetic field to discuss the absorption and thermalization of microwave energy on an atomic scale; however, for many purposes the classical viewpoint of Maxwell is quite adequate. In this classical approach, the properties of the atoms and their interactions are expressed in terms of measured constants for a given material under its physical conditions of pressure and temperature. These empirical constants express the strength of the interaction between the radiation field and the matter as well as the ability of the material to thermalize the absorbed energy, or its "lossiness." For visible radiation, the constants usually given are the index of refraction (n) and the absorption coefficient (a), both of which generally depend on the frequency of the radiation. For microwaves, it is more common to give either the real (K) and imaginary (K') parts of the dielectric constant or the real part of dielectric constant (K) and the resistivity (p) of the material. These constants have been determined experimentally for a wide variety of materials over a large frequency range (1,3,4).

There is a definite relationship between these constants. For materials in which magnetic effects are negligible, the imaginary part of the relative dielectric constant, K", is related to the resistivity, p, of the material, the frequency of the radiation, f, and the dielectric constant of a vacuum, ε₀, as follows:

\[ K'' = \frac{1}{2\pi fp\varepsilon_0} \]

The absorption constant, a, is related to the frequency of the radiation, f, and the real and imaginary parts of the dielectric constant by the expression:

\[ a = \frac{2\pi}{c} \sqrt{\frac{K}{c}} \left[ \left( K' \right)^2 \left( \frac{1}{2} - 1 \right) \right] \]

where c is the velocity of electromagnetic radiation in empty space. This expression relates the absorption and the imaginary part of the dielectric constant, the loss part, which is in turn related to the resistivity of the material. This is another way of describing the absorption or absorption of energy within the material. If one is interested in the relative absorbing properties of different materials, it is the absorption constants for the materials which should be compared. If only the real and imaginary parts of the dielectric constant are known, one can readily compute the absorption coefficient from the preceding equations.

The velocity of travel of electromagnetic waves in biological material such as we have been describing is given by the real part of the index of refraction, n. This constant is related to the frequency of the radiation, f, and the real and imaginary parts of the dielectric constant.
constant by the equation,

\[ n_r = \frac{c}{v} = \sqrt{\frac{K'}{2}} \left[ 1 + \left( \frac{K''}{K'} \right)^{2/2} + 1 \right]^{1/2}, \]

where \( v \) is the wave propagation velocity in the material. One of the consequences of the change of velocity in a material from that in vacuum is that the wavelength in the material is changed and is generally shorter than it is for the same frequency of radiation in air or a vacuum,

\[ \lambda_{\text{material}} = \frac{\lambda_{\text{vacuum}}}{n_r} \]

The wavelength of microwaves in a material is of importance because the spacing of interference effects in the material depends on this wavelength.

It is possible, for materials for which the real part of the dielectric constant \( K' \), and the resistivity, \( \rho \), are known at the frequencies of interest, to solve Maxwell's equations for the electromagnetic field in matter. The solution can be in closed analytical form for simple cases and or be obtained numerically for cases with complicated geometry. These solutions will give the intensity of the oscillating electric field due to the electromagnetic waves at any point in the material, and the rate of conversion of electromagnetic energy into thermal energy at each calculated point from the intensity of the radiation and the absorption coefficient of the material. The preceding equations relating to the absorption coefficient and real index of refraction to the resistivity of a material and the real and imaginary parts dielectric constant were obtained from the analytical solution to Maxwell's equations for plane waves in a homogeneous absorbing material. Such calculations have been carried out for plane electromagnetic waves incident perpendicular to the surface of material having the electrical properties of a thin layer of skin, a layer of fat and a very thick layer of muscle or simply a layer of fat and a layer of muscle. The calculations were carried out, using transmission line computational methods. The calculations were made to estimate the biological dosage, that is, the energy deposited per unit volume per unit time in the tissue for a given intensity of microwave radiation incident on the layers of tissue (2).

It is instructive to look at the results of such calculations. A typical result is shown in Fig. 3a. (a) The greatest rate of energy deposition occurs in the skin layer because the intensity of the beam is greater there and the absorption coefficient is moderately high. (b) The rate of energy deposition is low in the fat because the absorption coefficient for fat is relatively small. The variation of the energy deposition rate with distance in the fat layer is an interference effect between the incoming radiation and that reflected at the fat-muscle interface. (c) The rate of energy deposition in the muscle layer is higher than in the fat layer near the fat-muscle interface. The rate of energy deposition in the muscle layer shows the exponential decrease expected when electromagnetic waves travel through a homogeneous absorbing material. Similar comments can be made concerning the two layer absorption shown in Fig. 3b. From looking at Fig. 3b, one can see that the energy deposition will not be uniform in an oven load such as a roast. This is accounted for in microwave cookery by letting the food stand for a time after the power has been removed from the oven. During this time the heat from the hotter regions is transferred by conduction to the cooler regions and the cooking is completed.

In a microwave oven, the food is not exposed to a simple plane wave of electromagnetic energy traveling in one direction. The waves are radiated into the oven from a wave guide and are then reflected from the walls and can set up interference patterns because of the shape of the oven, this effect is indicated in Fig. 4a. The effect of these interference patterns, which are sometimes described as standing wave patterns, can be averaged out by moving the oven load around to different parts of the oven as is shown in Fig. 4b. This problem can also be attacked by changing the reflection directions of the