

Physics of the microwave oven

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Abstract

This is the first of two articles about the physics of microwave ovens. This article deals with the generation of microwaves in the oven and includes the operation of the magnetrons, waveguides and standing waves in resonant cavities. It then considers the absorption of microwaves by foods, discussing the dielectric relaxation of water, penetration depths of electromagnetic waves in matter and, in considering the possible chemical changes during the microwave heating, multi-photon ionization or dissociation.

What are microwaves?

Microwaves are electromagnetic waves. Their frequencies (wavelengths) are in the range from 300 MHz ($\lambda = 1$ m) up to 300 GHz ($\lambda = 1$ mm). Regarding wavelengths as typical spatial dimensions, one realizes that microwaves do not have dimensions of μm , as might be expected from the misleading 'micro' in their name. Following international conventions, microwave ovens at home or in restaurants operate at frequencies of about 2.45 GHz, i.e. $\lambda = 12.23$ cm.

Physics of a microwave oven

Figure 1 depicts a typical microwave oven (many details can be found in [1–3]). Microwaves are generated in a magnetron which feeds via a waveguide into the cooking chamber. This cuboid chamber has metallic walls and so acts as a Faraday cage. The front door, made of glass, and the light bulb cavity are both covered by metal grids. The holes in the grids are small compared with the wavelength of the microwaves, hence the grids act just like metal plates.

Most microwaves cook the food on a rotating turntable in this chamber, but some designs include a rotating reflector, acting as a stirrer. Expensive models may include thermometers, additional

1. Microwave oven

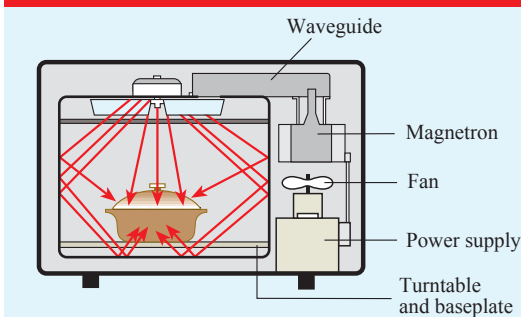


Figure 1. Schematic diagram of a typical microwave oven.

conventional cooking facilities such as grills, oven heaters and even refrigeration.

Interaction of microwaves with metals

Microwaves, incident on the metal walls of the oven, behave similarly to visible light hitting a silver mirror (e.g. [4]). The microwaves are absorbed very effectively, since the electric fields of the waves interact very strongly with the nearly free electrons of the metal. In a simple model, the electron behaviour is described as a damped forced oscillation. These accelerated electrons re-radiate electromagnetic waves at the same frequency and

in phase, hence the microwaves are perfectly reflected. Macroscopically, this behaviour is described by the complex dielectric constant $\varepsilon(\omega)$, which is the square of the complex refractive index ($\varepsilon_1 + i\varepsilon_2 = (n_1 + in_2)^2$).

The refractive index of many metals gives reflectivities close to 100% at low frequencies. The penetration depth of electromagnetic waves of wavelength λ is given by

$$\delta = \lambda/4\pi n_2. \quad (1)$$

For example, for microwaves with $\lambda = 12.2$ cm incident on aluminium, $\delta \approx 1.2 \mu\text{m}$.

These are similar to skin depths, i.e. the attenuation depths of alternating currents of frequency ω in metals. (The relation between skin depth and refractive index for small frequencies is discussed, e.g., by Feynman [5].)

Generating microwaves in magnetrons

The most powerful microwaves produced by solid state devices, such as used in cell phones, are far too weak for cooking. Instead electron beams in vacuum tubes under the combined effect of electric and magnetic fields are made to follow curved trajectories (the detailed mechanism for which is described below). Most microwave ovens use magnetrons. First invented in 1921 and strongly improved around 1940, magnetrons allow either continuous or pulsed microwave generation with powers up to megawatts and frequencies between 1 and 40 GHz. Efficiencies are around 80% and lifetimes about 5000 hours.

A cylindrical cathode is at the axis, several millimetres from a hollow circular anode (figure 2). Inside the anode there are a number of cavities designed to resonate at 2.45 GHz. A voltage of several kV is applied between the electrodes and a magnetic field is applied parallel to the axis such that electric and magnetic fields are perpendicular to each other.

Electrons ejected by the cathode accelerate radially at first, but because of the magnetic field they start to follow cycloidal paths. If the magnetic field is strong enough, the electrons cannot reach the anode but form a rotating space charge. The resonant cavities of the anode interact with the electrons by either accelerating or decelerating them. Finally this leads to electron bunches which move around the cathode at microwave

2. The magnetron

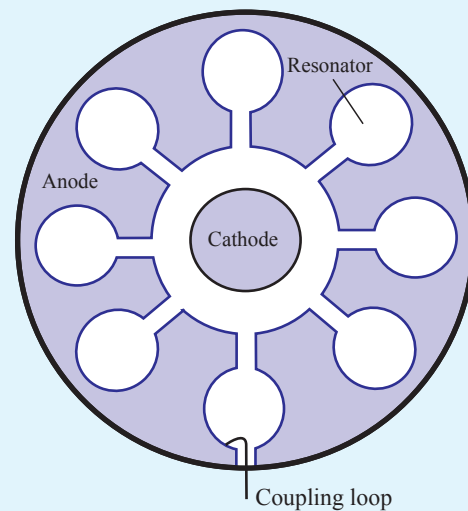


Figure 2. Schematic diagram of a magnetron.

frequencies, which in turn leads to self-sustaining oscillations of the resonant cavities. Part of the microwave power is extracted by a coupling loop (for more details, see [1–3]).

The magnetrons in domestic microwave ovens emit microwaves at 2.45 GHz (repeatable, each time the magnetron is switched on, to ± 10 MHz) with bandwidths of only a few MHz [6].

Connecting the magnetron with the cooking chamber: the waveguide

Waveguides carry the microwaves from the magnetron to the cooking chamber. They are usually metal tubes of rectangular cross section. The effect of the boundary conditions of the tubes leads to electric and magnetic field distributions which, in each of the two directions perpendicular to the axis, resemble standing waves [1, 5]. These are quite similar to standing waves on the ‘one-dimensional’ string of a guitar. Consequently, there is a maximum wavelength, λ_{max} , which can be transported by the waveguide. For a given direction perpendicular to the axis, the inner tube size is then just $\lambda_{\text{max}}/2$. Therefore, a waveguide filled with air which operates at 2.45 GHz ($\lambda = 12.2$ cm) must have at least one inner dimension larger than 6.1 cm. Usually, the waveguide has a smaller size in a perpendicular direction. Filling

Standing waves in microwave ovens

The solution of the three-dimensional wave equation with boundary conditions (see e.g. [1]) gives standing waves in the three dimensions x , y and z , which altogether obey the equation

$$\frac{1}{\lambda^2} = \frac{1}{\lambda_x^2} + \frac{1}{\lambda_y^2} + \frac{1}{\lambda_z^2}. \quad (2)$$

The wavelengths λ_x , λ_y and λ_z are determined by the linear dimensions L_x , L_y and L_z of the chamber:

$$L_x = l \frac{\lambda_x}{2} \quad L_y = m \frac{\lambda_y}{2} \quad L_z = n \frac{\lambda_z}{2} \quad (3)$$

where l , m , n are natural numbers. The solutions for given (l, m, n) are denoted as modes of the resonator. Obviously equation (2) allows more than one possibility to satisfy the same given value of λ . In commercial microwave ovens, the dimensions L_x , L_y and L_z scatter appreciably; e.g., a survey of about 20 different ovens gave values of $L_x = 28\text{--}35$ cm, $L_y = 27\text{--}33$ cm and $L_z = 17\text{--}21$ cm. In the following an example with $L_x = 29$ cm, $L_y = 29$ cm and $L_z = 19$ cm will be discussed. Equations (2) and (3) allow a number of resonator frequencies which lie close to the emitted magnetron frequency. Table 1 demonstrates that there are six possible solutions in the wavelength range between 12 cm and 12.5 cm.

The quality factor Q [1, 7] is a measure of the energy losses and, hence, also the frequency width $\Delta\omega$ of the modes. Q gives the ratio of the energy stored in the resonator and the energy loss per cycle:

$$Q = \omega E / (dE/dt). \quad (4)$$

For $Q \gg 1$ this may be written as

$$Q \approx \omega / \Delta\omega. \quad (5)$$

The energy losses are due to four factors. First, microwaves may exit through the housing of the microwave oven. Safety regulations ensure that this contribution is negligibly small. Second, losses occur due to absorption in the walls, third due to absorption in the food within in the cooking chamber (the desired mechanism), and fourth, there is the chance that microwaves are coupled back into the magnetron. The latter mechanism may play a role if the oven is used empty, and it should be avoided in order to ensure a long lifetime of the magnetron. The overall quality factor can be calculated from

$$1/Q = 1/Q_1 + 1/Q_2 + \dots \quad (6)$$

If the oven is used empty, wall losses are most important. They can be estimated from the penetration depth δ [1, 7]:

$$Q_{\text{empty}} \approx V/S\delta \quad (7)$$

where V is the volume and S the inner surface area of the chamber. Typically, with air-filled volumes of about $29 \times 29 \times 19$ cm³ and $\delta \approx 1$ μ m one finds Q -values of the order of 10^4 . For frequencies of 2.45 GHz, this leads to frequency widths of only 0.25 MHz, i.e. the resonance modes are very narrow compared with the magnetron frequency width. Figure 3 depicts schematically a frequency spectrum of the modes of a cooking chamber. If some water containing food is placed in the chamber, i.e. a dielectric is inserted, the additional losses—being much larger than the wall losses—lead to a shift of the resonances to lower frequencies as well as an appreciable broadening of the modes. Due to the shifts and broadening, described by a quality factor that may well be of the order of 10^2 , more than one resonator mode may be excited. The larger the oven and the more losses are present, the more modes may be excited simultaneously. These multimode cavities have a more homogeneous field distribution, which is desirable for many applications, including cooking.

3. How Q varies

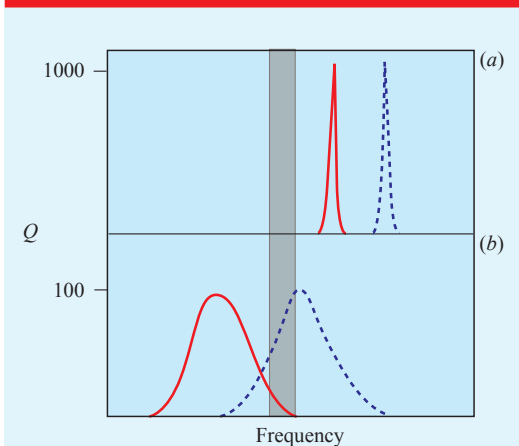


Figure 3. Schematic diagram showing how Q varies with frequency for two different modes of resonance in a microwave oven (not to scale): (a) with oven empty, (b) with food. The shaded band shows the frequency of the magnetron. If drawn to scale the widths of the modes in (b) would be about 100 times those in (a).

Table 1. All modes of a microwave oven of dimensions $29\text{ cm} \times 29\text{ cm} \times 19\text{ cm}$, which lead to a wavelength in the interval $12.0\text{ cm} < \lambda_0 < 12.5\text{ cm}$. Four modes are quite close to the magnetron wavelength of 12.25 cm .

λ_0 (cm)	l	m	n
12.103	1	1	3
12.274	2	4	1
12.274	4	2	1
12.277	2	3	2
12.277	3	2	2
12.375	0	1	3

the waveguide with a dielectric shifts the cut-off frequency and wavelength. Because only one inner dimension is greater than the cut-off length the microwaves leaving the waveguide are polarized. As the waves are reflected in the cooking chamber the degree of polarization decreases.

The cooking chamber: why do microwave ovens use a rotating turntable?

Once the microwaves have been coupled into the cooking chamber, they are effectively reflected by the metallic walls. The waves resonate in the cavity and form standing waves. The analysis of these standing waves is simplified by the fact that

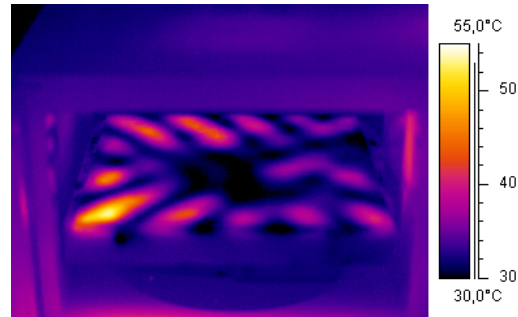


Figure 4. Visualization of the horizontal mode structure in a microwave oven using infrared thermal imaging. A glass plate with a thin water film was placed at a height of 8 cm and heated for 15 s with a microwave power of 800 W without using the turntable (for more details on the experiment, see [10]).

the wavelength of the microwaves is roughly the same as the linear dimensions of the chamber.

An ideal microwave oven cooks all food evenly but the nodes and antinodes of the standing waves can cause the food to burn in some places but to remain cool in others. The homogeneity of the field distribution may be estimated theoretically from the number of modes that may be excited within a narrow frequency range close to the magnetron frequency (see below) or studied experimentally [8].

Figure 4 shows the intensity distribution within an oven of $29 \times 29 \times 19\text{ cm}^3$ at a height of about 8 cm . A horizontal glass plate covered with a thin film of water was placed in a microwave (without its rotating turntable) on full power (800 W) for about 15 s . The false colour image was obtained with a thermal infrared camera [9]. With only a small amount of water present, the image shows the microwave intensity distribution in a nearly empty chamber. There is a pronounced horizontal mode structure, which would lead to uneven heating of food. This is the reason for having a rotating turntable: the rotation will move the food in and out of the hot spots. Some ovens have a mode stirrer, i.e. a rotating reflector at the top to get a more homogeneous field distribution, and there are investigations into how geometrical changes of the wall structure may improve the situation. More details on experiments on horizontal and vertical modes and also on changes of the mode structure upon filling of the cooking chamber with food will be discussed in the following article [10].

5. Dielectric constant and temperature

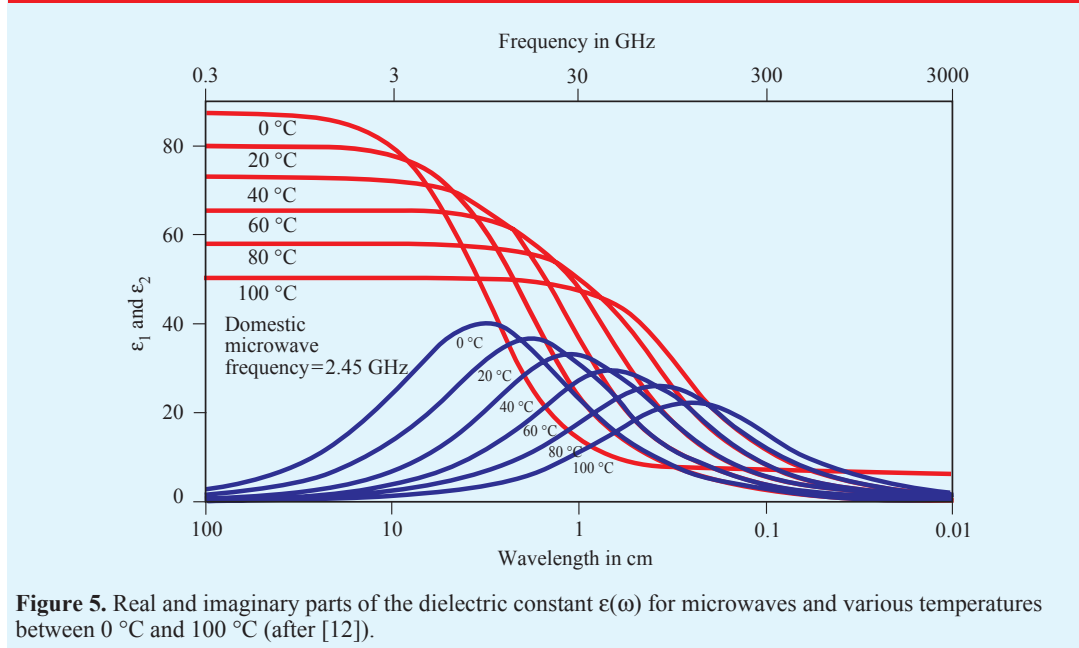


Figure 5. Real and imaginary parts of the dielectric constant $\epsilon(\omega)$ for microwaves and various temperatures between 0 °C and 100 °C (after [12]).

Heating of food in a microwave oven

Absorption of microwaves by water

Electromagnetic waves may be absorbed by matter in many different ways depending on their wavelength and the state of the matter (gas, liquid, solid). Free atoms and molecules usually absorb ultraviolet (UV) by excitation of electrons whereas in the infrared, excitation of molecular vibrations and/or rotations dominates. Free and undisturbed rotations cannot occur in liquid water due to the interactions with neighbouring molecules but solids and liquids may absorb microwaves due to the polarization induced by the external oscillating electric field. In a microwave oven, the electrically dipolar water molecules absorb most of the microwave energy.

In low frequency electric fields the dipoles easily follow the changes in the field and their orientation changes in phase with the field. At higher frequencies the inertia of the molecules and their interactions with neighbours make changing orientation more difficult and the dipoles lag behind the field. Finally, at very high frequencies (1–10 THz) the molecules can no longer respond to the electric field. At the GHz frequency of a microwave oven the phase lag of the dipoles behind the electric field absorbs power from the field. This is known as dielectric loss due to dipole relaxation.

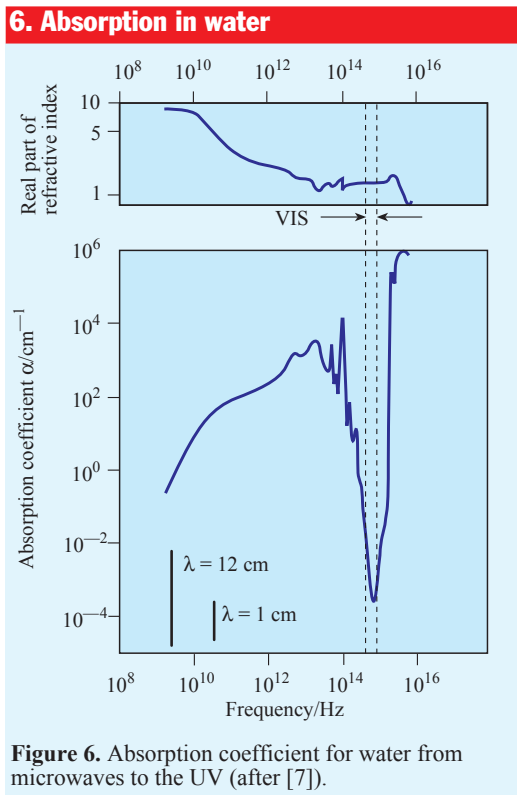
Quantitatively, the average microwave power absorbed by a dielectric may be written as [1, 11]

$$P = \omega \epsilon_0 \epsilon_2 E_{\text{eff}}^2 V \quad (8)$$

where V is the volume of the dielectric and E_{eff} the square of the average electric field within this volume. ϵ_2 is the imaginary part of the dielectric constant $\epsilon = \epsilon_1 + i\epsilon_2$. For pure liquid water, the changes of $\epsilon_1(\omega)$ and $\epsilon_2(\omega)$ are displayed schematically in figure 5 for various temperatures. These curves are considered to be typical for most kinds of food containing water.

At first glance it is clear that ϵ_1 and ϵ_2 both strongly depend on temperature. For fixed temperature, say 20 °C, ϵ_1 starts from the static value of about 80, then decreases in the GHz range and finally reaches a value of about 1.78 at optical frequencies (which would give the well known refractive index of water in the visible $n \approx 1.33$). At the same time, ϵ_2 shows a pronounced maximum around 20 GHz. For increasing temperature, both functions drop in size and shift to higher frequencies. Therefore the temperature rise of a piece of food depends on its starting temperature (see [10])!

Since food is usually heated from about room temperature to, say, 100 °C, figure 5 suggests that



choosing a frequency between 10 and 100 GHz will produce optimum power absorption according to equation (8). As a matter of fact, a different physical criterion decides which frequency to choose.

Penetration depths of microwaves in water: explanation of the frequency used

Using $\varepsilon = n^2$ one may calculate the imaginary part of the refractive index and from this the absorption coefficient α , which is related to the penetration depth δ of the electromagnetic waves (equation (1)) by $\alpha = 1/\delta$.

Figure 6 gives a crude overview in the form of a double logarithmic plot of the absorption coefficient of water from the microwave region (0.1 GHz) to the UV region (10^{16} Hz). Obviously water shows a very pronounced increase of the absorption coefficient with frequencies extending into the IR region. This may even lead to $\alpha > 10^3 \text{ cm}^{-1}$, which corresponds to penetration depths δ of less than $10 \mu\text{m}$. Between the vibrational excitations in the IR and the electronic excitations in the UV, there is the well known minimum of

$\alpha \leq 10^{-3} \text{ cm}^{-1}$ in the visible, which leads to δ well above 10 m for clear water, i.e. the high transmission of water experienced every day.

Figure 6 also explains why microwave ovens use a frequency of about 2.45 GHz rather than 20 to 1000 GHz, as may have been guessed from figure 5. With increasing frequency, α increases rapidly, i.e. the penetration depth $\delta = 1/\alpha$ decreases rapidly. The food in microwave ovens has typical dimensions of the order of cm, and hence the penetration depth should be in this range. With a frequency of 20 GHz, the penetration depth would be much smaller, i.e. the energy would be absorbed in a thin surface layer of the food (toasting the food) while the interior would remain cold. The lower frequency chosen results in absorption of the microwaves everywhere in the food. Therefore the surface will only get a brown crust if additional grilling facilities are available.

Frequently asked questions

Does the rate of heating depend on the type of food?

The above discussion applies to pure water, and undoubtedly the main factor determining the rate of heating in a food is its water content. However, the salt added to many foods may allow an additional heating mechanism. In solution, the charged Na^+ and Cl^- ions (with or without surrounding ion clouds) also react with the alternating electric field. This leads to tiny movements of the ions, which may induce collisions with neighbours, thereby producing heat. This behaviour can be seen from the curves of $\varepsilon_2(\omega)$ (see e.g. [12]). It may therefore be possible to heat salty food more quickly than pure water (see figure 7 and [13]).

Can ice be melted in a microwave oven?

All microwave ovens come with a defrost facility. However, it takes much longer to get ice to raise its temperature by 1°C than it does for a similar amount of liquid water. In ice the molecules of H_2O are held in a crystal lattice in fixed positions. The dipoles cannot follow an external field as easily as they can in liquid water, therefore there is less heating effect. Hence ε_2 for ice at 2.45 GHz is three to four orders of magnitude below that of liquid water (see [14]). As a consequence, the

7. Dielectric constant of food

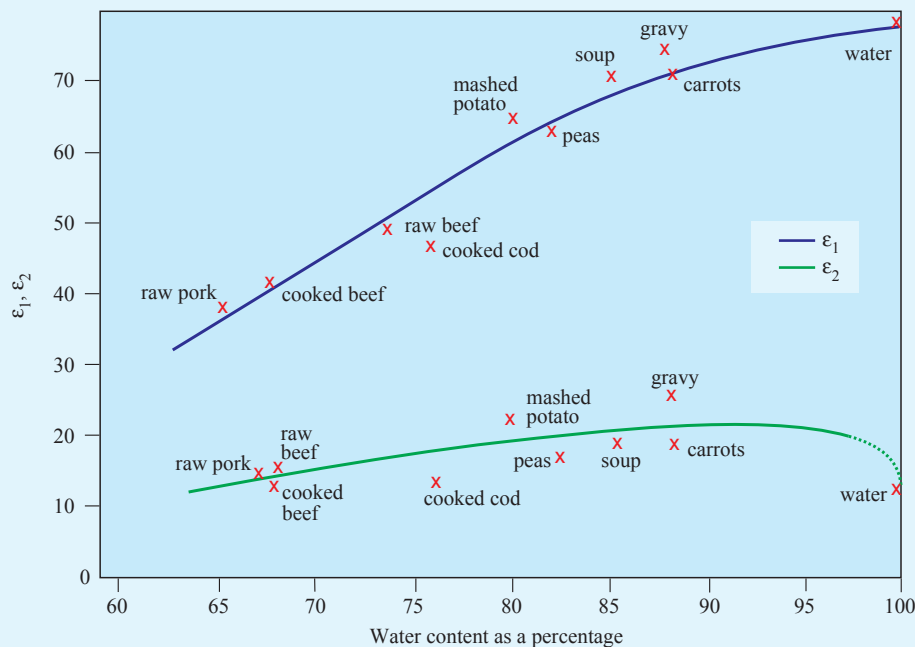


Figure 7. Dielectric constants of various kinds of food (after [13]).

penetration depth is much larger and less energy is absorbed.

It is still much quicker to defrost food in a microwave than to leave it in air at room temperature. The oven is periodically turned on for short periods and then off for longer time intervals. If by chance, some ice has melted at some spot, the liquid water will be heated in the 'on-phase'. During the 'off-phase', the contact of this heated water with the surrounding ice melts more ice such that in the next 'on-phase', more water will be heated and so on.

Can microwaves get out of the oven?

There are very strict regulations governing how much radiation is allowed to be emitted from microwave ovens: they could be a health risk and they could interfere with other electronic apparatus. Because a microwave oven is a Faraday cage little radiation is expected to escape. The most crucial part is the door, which is equipped with additional so-called $\lambda/4$ radiation traps [1]. In every country there are official institutions, in Germany for example it is the Bundesamt für Strahlenschutz (BfS) [15], which check the safety

of electrical appliances. The radiation level close to the surface of most ovens amounts to about 1% of the allowed limit of 5 mW cm^{-2} . As you get further from the oven the intensity rapidly decreases, such that the usual radiation dose is well below 1/1000 of the maximum permitted value.

Since a small amount of radiation does escape from the oven, it is also possible for microwaves to enter the closed oven. This may be demonstrated by putting a cell phone into the oven (turned off!) and calling it [10].

Most ovens have an 'off' button which simultaneously shuts off the magnetron and opens the door. Can any lingering radiation escape when this happens? How long will the microwaves remain in the cooking chamber after the magnetron is turned off? Using equation (4) one may easily estimate the decay times of the fields, which depend on the quality factor of the chamber:

$$E(t) = E(0) \exp(-\omega t/Q). \quad (9)$$

For an empty oven ($Q = 10^4$) the field has decayed to less than 1/1000 after a time of about $4.5 \mu\text{s}$; if there is food in the oven, reducing Q to about 10^2 , the time changes to only 45 ns. Obviously, nobody can open an oven door that fast.

Is it possible that microwaves can change the food chemically?

People often assume that microwaved food is unhealthy. Could it be chemically different to conventionally heated food? For this to happen, the microwaves would need to create chemical radicals involving energies of the order of an electron-volt. Microwave photons have energies of the order of 10^{-5} eV. Simple estimates easily show [8] that the number of microwave photons within a commercial oven is orders of magnitude too small to establish multiphoton dissociation or ionization. One may therefore conclude that the food cannot be altered chemically while heated in a microwave oven.

Are microwave ovens only used for heating food?

Microwave ovens are used in many other industrial fields, e.g. pasteurization of vegetables, drying of paper or textiles, thermal treatment of pharmaceutical products and vulcanization of rubber and elastomers (see [1, 2]).

Acknowledgments

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