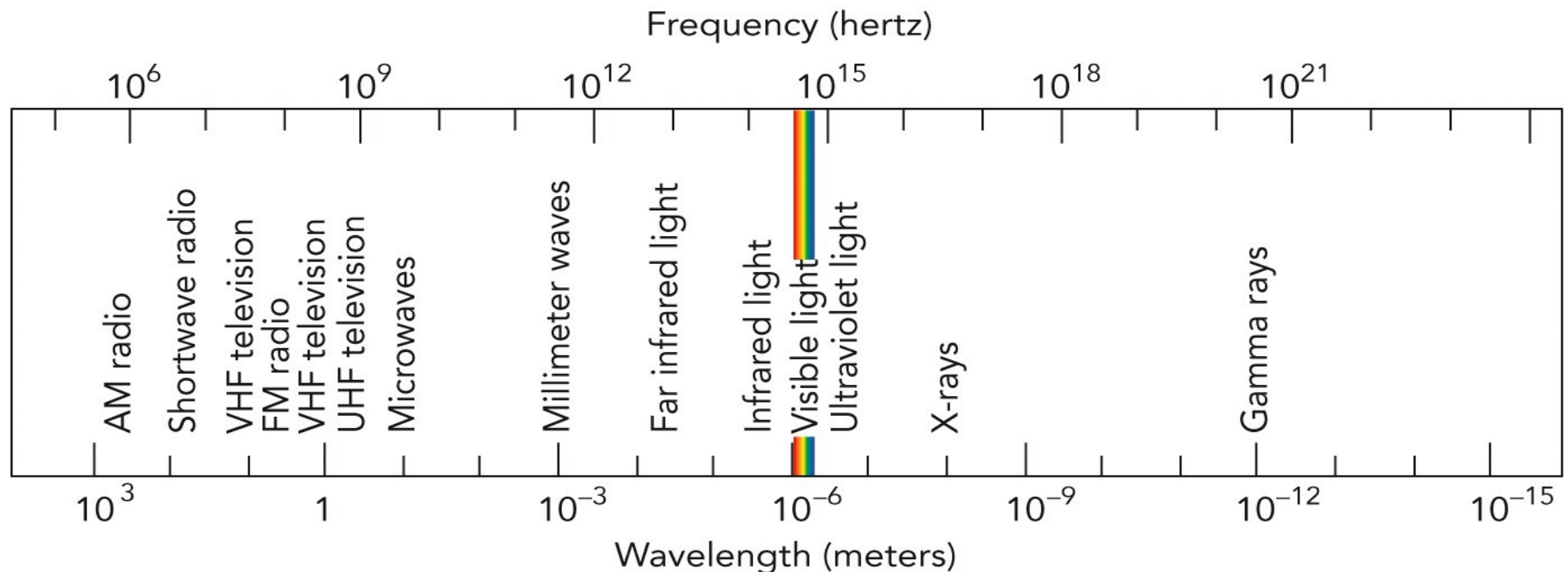
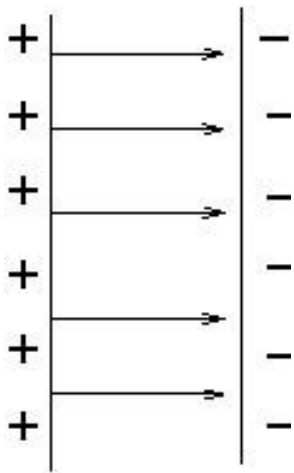


Electromagnetic waves

We previously saw that Maxwell's change to the equations of electricity and magnetism explained the wave nature of light and all electromagnetic waves. EM waves are transverse waves with electric and magnetic fields. The changing electric field creates a magnetic field and the changing magnetic field creates an electric field that propagates through free space at the **speed of light** ($c = 3 \times 10^8 \text{ m/s}$)



Energy in Electric Fields



We saw in the previous chapter that magnetic fields store energy. Electric fields also store energy. Consider two metal plates separated by a small distance. One plate has a positive charge and the other a equal magnitude negative charge. Such an arrangement is

called a capacitor. The capacitance is defined by:

$$q = CV$$

where q is the magnitude of the charge in Coulombs on the plates, V is the potential difference in volts between the plates and C is the capacitance in Farads (F) = Coulomb/Volt. A Farad is a very large unit. Normal capacitors are micro-Farads $\mu F = 10^{-6}F$ or even pico-Farads $pF = 10^{-12} F$.

Energy in Electric Fields

Consider an uncharged capacitor. The work to move electrons from one plate (making it positive) to the other plate (making it negative) is just the charge moved times the average potential difference. The energy required to charge the capacitor is:

$$\text{Energy} = q \cdot \frac{1}{2}V$$

since the average potential is $\frac{1}{2}$ difference between the initial potential (0 V) and final potential (V). Since $q = CV$ then:

$$\text{Energy} = (CV) \frac{1}{2}V = \frac{1}{2} CV^2$$

This energy is stored in the electric field of the capacitor.

Energy in Electric Fields

The electric potential energy in a volume of space (in Joules) is:

$$\text{Energy} = \frac{E^2 V}{8\pi k}$$

Where V is the volume, E is the electric field (V/m) and k is Coulomb's constant. Coulomb's constant is often written as:

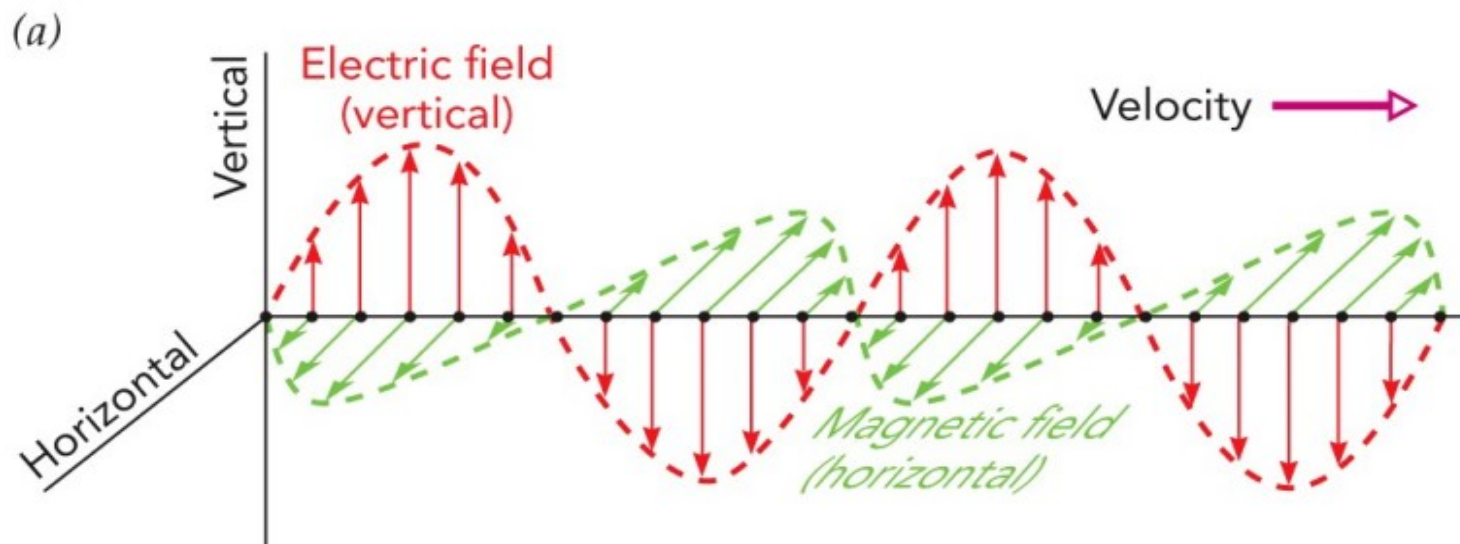
$$k = \frac{1}{4\pi\epsilon_0}$$

Where ϵ_0 is called the permittivity of free space. Using ϵ_0 , the electrical potential energy stored in a volume is then

$$\text{Energy} = \frac{1}{2}\epsilon_0 E^2 V$$

Electromagnetic Waves

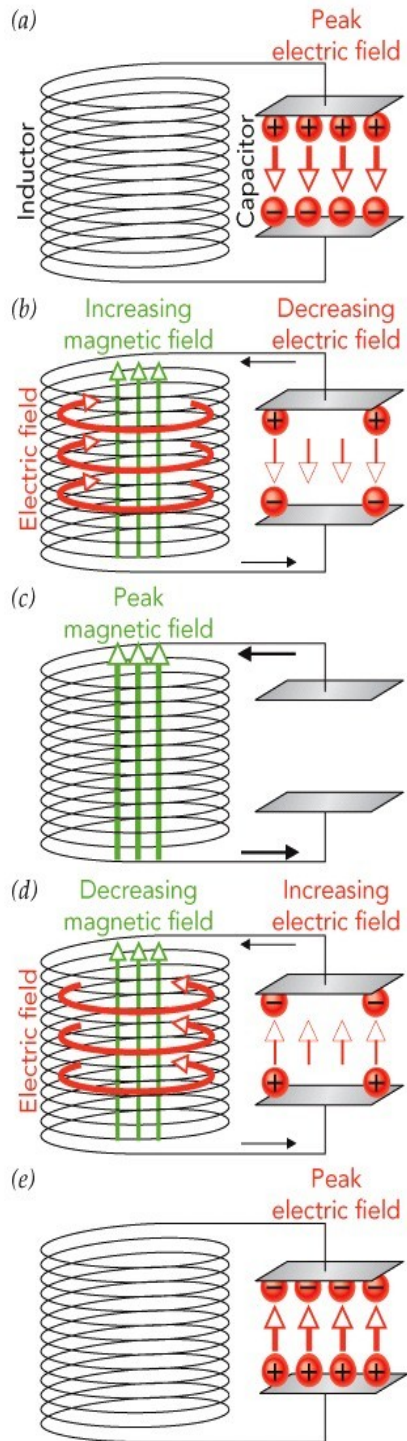
As we briefly discussed Maxwell and the nature of EM waves. It is a wave so $v = c = \lambda f$ as for any wave. The speed any EM wave in vacuum is $c = 3. \times 10^8 \text{ m/s}$. The amplitude of the wave is the amplitude of the electric field in V/m or magnetic field in Tesla. Because of Maxwell's observation, the wave propagates by changing perpendicular electric and magnetic fields. The EM wave is 'polarized' if all the electric fields are aligned in the same direction.



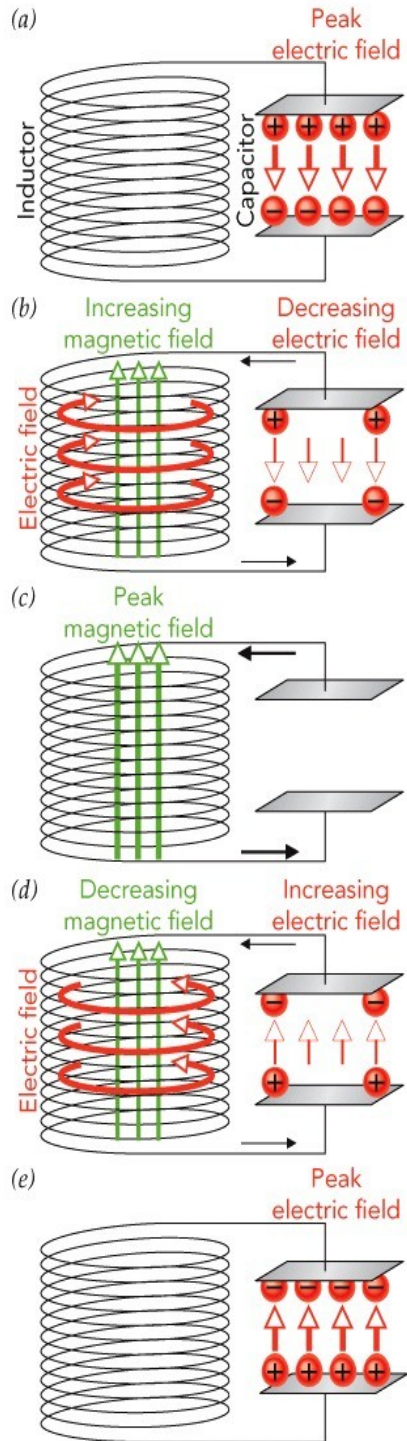
Tank Circuit

How do you make an EM wave? When a charged particle is accelerated, it radiates EM waves. Could it be done with a generator?

A **tank circuit** (capacitor and inductor in parallel) produces a sinusoidal wave which can be amplified to produce an EM wave on an antenna. Consider a charged capacitor connected to an inductor. As the capacitor discharges through the inductor a current flows and creates a magnetic field around the inductor. When the capacitor is discharged the current stops. The magnetic field collapses and induces a current to flow which charges the capacitor but in the opposite direction.



Tank Circuit



After the inductor has charged the capacitor in the opposite direction and the induced current stops, the capacitor discharges into the inductor creating a magnetic field in the opposite direction as the first magnetic field. When the capacitor is completely discharged the magnetic field collapses and induces a current which charges the the capacitor in its original state. The process repeats over and over and is only limited by the resistance in the circuit (which turns the electrical and magnetic energy into heat from ohmic heating).

The circuit is called a tank circuit because the currents 'sloshes' back and forth like water in a tank. Another name for this type of circuit is an 'LC' circuit.

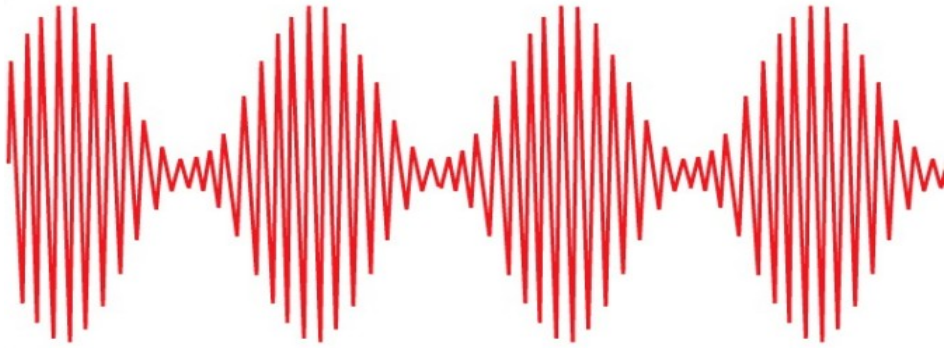
Antennas transmitters and Receivers

If you use an amplifier to make a larger current from a tank circuit, the oscillating current can be send to an antenna to make a transmitter of EM waves. An antenna is normally just a piece of wire with a length that is appropriate for the wavelength of the EM wave.

If you attach an antenna to a tank circuit with the appropriate LC values, the tank circuit will resonate with the antenna. Amplify the tank circuit and you have a receiver of of EM waves.

The optimum length for the antenna is $\lambda/4$ of the EM wave. This applies to both transmitting and receiving. The length of $\lambda/4$ allows the antenna to experience (see) the largest electric field of the wave (see the maximum potential difference).

AM Radio

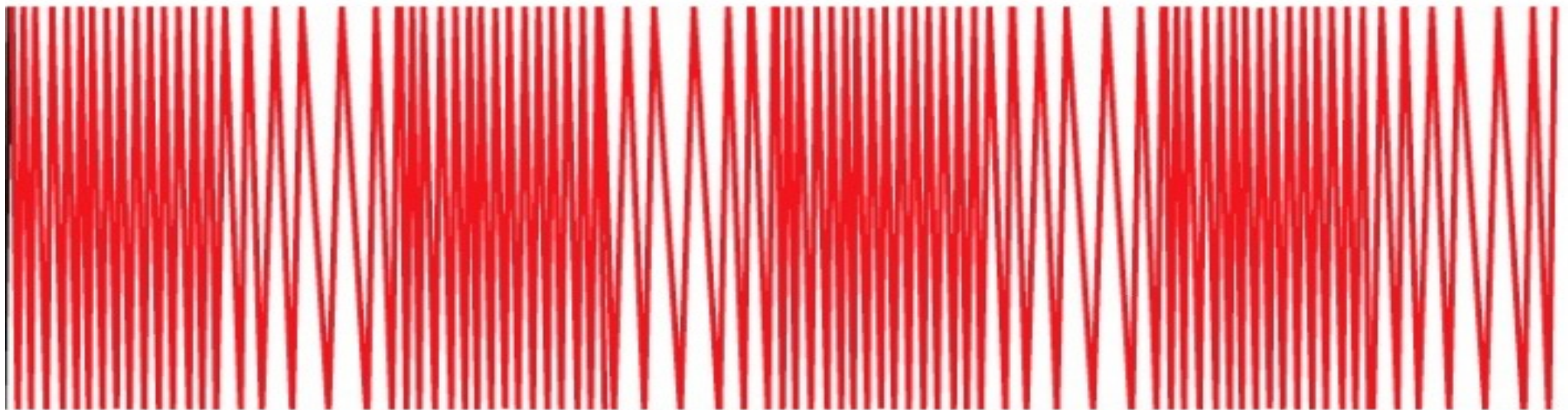


Just transmitting and receiving the EM waves does not send any information. You could use Morse code ('wireless') but something more is needed to

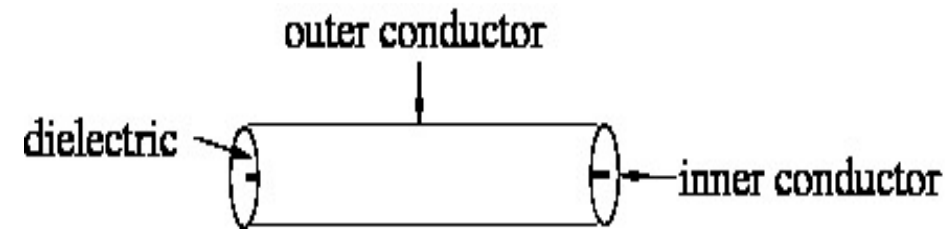
something more is needed to transmit speech or music. One method is call 'AM' or **amplitude modulation**. The amplitude of the wave's EM fields can be varied to contain the desired information e.g., speech. AM radio uses a 'carrier' frequency of **550 kHz to 1.6 MHz**. Depending on power and conditions, it can be received over hundreds of miles. Using interference effects ('beat frequencies) the information (speech or music) can be extracted, amplified and sent to a speaker. However, the **bandwidth of the signal is only 5 kHz** which is fine for speech but too limited for music. AM is more subject to 'static' interference and lose of lower intensity detail at large distances.

FM Radio

Another way to transmit a radio signal is frequency modulation or FM. In FM radio the signal is transmitted by varying the frequency of the wave within the assigned bandwidth. FM radio uses frequencies between 88 MHz and 108 MHz in the US. The receiver measures the radio wave's frequency and uses the measured frequency to recreate the audio signal. The audio signal has a 'bandwidth' of 200 kHz which allows for stereo (two channels) high quality sound. FM is not subject to interference (static) as much as AM. The limitation is FM requires more powerful transmitters and does not transmit over long distances (greater than 100 miles).



Cable and Bandwidth



The amount of information that can be transmitted depends on bandwidth. A coaxial cable can

transmit a large amount of information. A coaxial cable is an outer conductor with another conductor down the center. The two are held apart by an dielectric (air, plastic etc.). Normally an outer plastic insulator protects the entire cable. An EM wave propagates in the region between the two conductors. The EM wave is contained inside the cable between the two conductors. Coaxial cables are a type of waveguide. A typical coaxial cable can have 1 GHz of bandwidth. One cable can carry many TV signals. Two wires separated by a fixed distance ('twisted pair') can also act as a waveguide. Twisted pairs are used in Ethernet cables. 'Cat 5' (Cat 6) twisted pair cable can carry up to 350 MHz (1 GHz) of bandwidth. Coaxial cable is being replaced by 'fiber optic' which use visible or infrared light. Fiber optic cables have huge bandwidth.

Microwave Ovens and Magnetrons

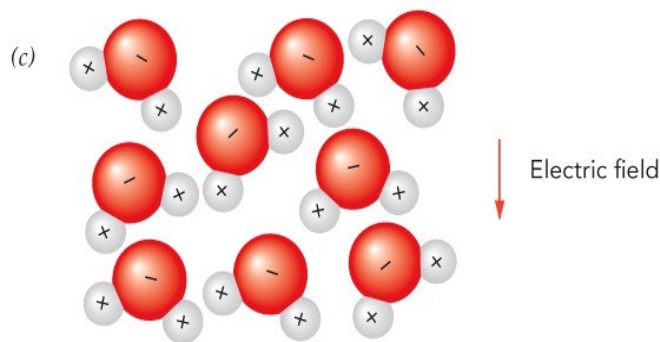
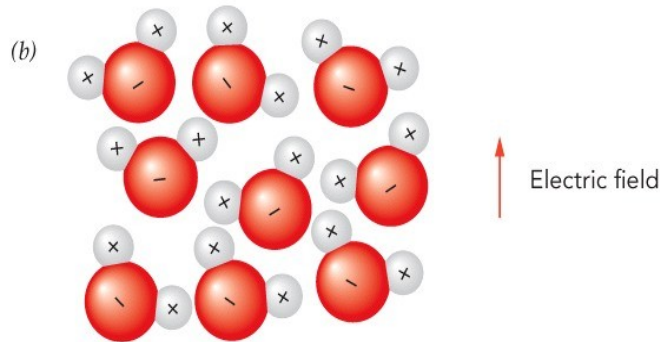
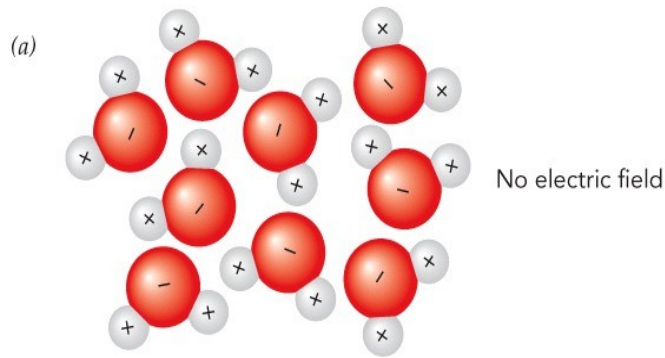
Microwave ovens use EM radiation to heat and cook food. The oven is just a metal box with dimensions that set up standing waves. Microwave radiation is sent into the metal box from a magnetron. It is called a microwave since the EM waves have a wavelength of a few centimeters. (Note: microwaves are not ionizing. They are like TV signals). You can see inside through the door of a microwave oven because there is a metal grid with holes that are much smaller than the EM waves. The grid reflects the EM waves just like the other parts of the metal box.

A typical microwave oven uses a frequency of 2.45 GHz. Since $\lambda = c/f$. The wavelength is

$$\lambda = (3 \times 10^8 \text{ m/s}) / (2.45 \times 10^9 \text{ s}^{-1}) = 0.122 \text{ m}$$

or about 12 cm.

Microwave Ovens and Magnetrons



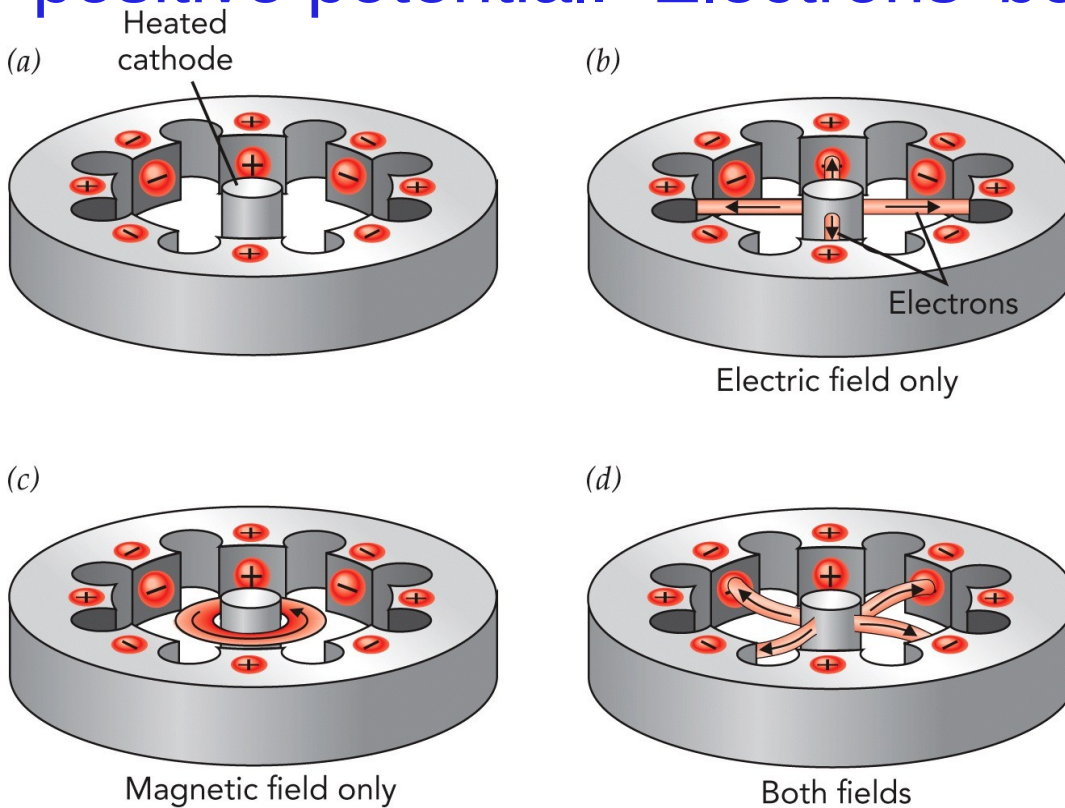
Microwaves heat the water in food. Water is a electric dipole. The two hydrogen make a positive charge on one side and the oxygen made the negative on the other side. When a microwave electric field moves by the water molecule it first aligns the molecules one way and then the other. The causes the molecule to rotate. The rotating molecules bump into one another with causes the water in the food to heat up. The 2.45 GHz frequency is the resonant frequency for the water molecule. The resonance frequency is determined by the rotational inertia of the water molecule.

Magnetrons

The **magnetron** was invented by the UK in 1940 during WWII. The magnetron was extremely important to the development of radar.

In the center of the **magnetron** is a heated filament. The region between the filament and an outer ring is evacuated. The filament is at a low (negative potential) and the outer ring at a positive potential. Electrons 'boil' off of the 'cathode' and

travel to the positive 'anode'. In the evacuated region is a magnetic field which causes the electrons to travel in a curved path. The dimensions of the circular cutout of the ring are such that the electron generate very high frequency EM waves in the circular cutouts.



Magnetrons

The dimensions of the circular cutouts resonate at a particular frequency (2.45 GHz for a microwave oven magnetron).

Inside of each cutout is a $\lambda/4$ antenna (wire) which transmits the EM wave out of the cavity. Each cutout cavity is then combined and transmitted by a coaxial cable (or waveguide) to be the metal box of the microwave.