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Chapter

Energy Transfer from Electromagnetic Fields to Materials

Graham Brodie

Abstract

Electromagnetic fields are complex phenomena, which transport energy and information across space. Information can be imposed onto electromagnetic waves by human ingenuity, through various forms of modulation; however, this chapter will focus on the acquisition of information as electromagnetic waves are generated by materials or pass through materials. The chapter will also consider how energy is transferred to materials by electromagnetic fields.

Keywords: electromagnetic propagation, dielectric properties, information acquisition, dielectric heating

1. Introduction

Electromagnetic fields are a complex phenomenon because they can propagate through vacuum without the need for a material medium, they simultaneously behave like waves and like particles [1, 2], and they are intrinsically linked to the behaviour of the space–time continuum [3]. It can be shown that magnetic fields appear through relativistic motion of electric fields, which is why electricity and magnetism are so closely linked [4]. It has even been suggested that electromagnetic phenomena may be a space–time phenomenon, with gravitation being the result of space–time curvature [3] and electro-magnetic behaviour being the result of space–time torsion [5].

James Clerk Maxwell developed a theory to explain electromagnetic waves. He summarised this relationship between electricity and magnetism into what are now referred to as "Maxwell's Equations." An EM wave is described in terms of its:

1. Frequency (f), which is given the unit of Hertz (Hz);

2. Wavelength (λ), which is the distance between successive crests or troughs in the wave (m); and

3. Speed (c), which is measured in metres per second.

These three properties are related by the equation:

$$c = \lambda f \tag{1}$$

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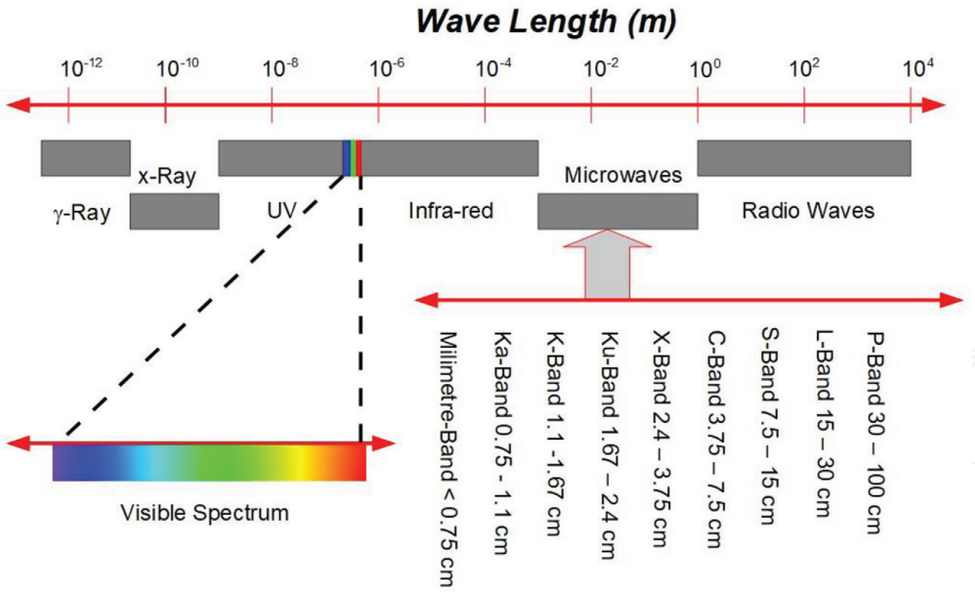


Figure 1.
Schematic of the electromagnetic spectrum.

The speed of the electromagnetic wave is determined by:

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \tag{2}$$

where ε is the electrical permittivity of the space in which wave exists and μ is the magnetic permeability of the space in which the wave exists.

Electromagnetic waves can be of any frequency; therefore, the full range of possible frequencies is referred to as the electromagnetic spectrum. The known electromagnetic spectrum extends from frequencies of around $f = 3 \times 10^3$ Hz ($\lambda = 100$ km) to $f = 3 \times 10^{26}$ Hz ($\lambda = 10^{-18}$ m), which covers everything from ultra-long radio waves to high-energy gamma rays [6]. A schematic of the electromagnetic spectrum is shown in **Figure 1**.

Electromagnetic waves can be harnessed to: transmit information; acquire information from a medium; or transmit energy. The first category of applications includes: terrestrial and satellite communication links; the global positioning system (GPS); mobile telephony; and so on [7]. The second category of applications includes: radar; radio-astronomy; microwave thermography; remote sensing and detection, and material property measurements [8]. The third category of applications is associated with electromagnetic heating and wireless power transmission.

This chapter will focus on the interactions of electromagnetic waves with materials and will therefore include acquiring information from a medium and transition of energy.

2. Some background theory

When electromagnetic waves encounter materials, the wave will be partially reflected, attenuated, delayed compared with a wave travelling through free space [9–11], and repolarised. Surface interactions, such as reflection, refraction, transmission and repolarisation reveal important information about the material and its immediate environment. For example, **Figure 2** shows how reflection from the surface of a pond and transmission of light from in the pond water reveal

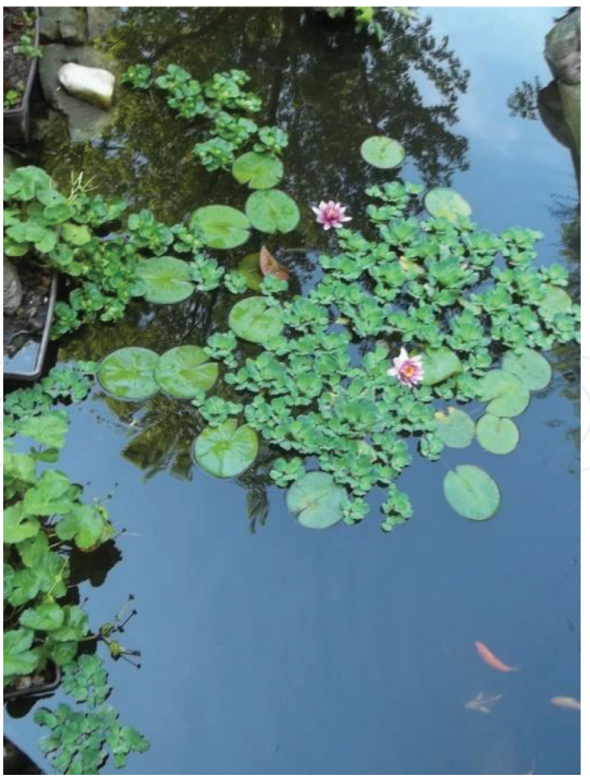


Figure 2.
The combination of surface reflection and transmission through the water in this pond reveal the fish in the water and the trees in the immediate environment of the pond, hence visible light can acquire and transfer this information through space.

information about what is in and around the pond. All interactions between electromagnetic waves and materials are governed by the dielectric properties of the material and how these properties alter the electrical and magnetic properties of the space occupied by the material.

2.1 Dielectric properties of materials

All materials alter the space, which they occupy. Because materials are composed of various charged particles, these alterations include changes to the electrical and magnetic behaviour of space. These properties are described by the electrical permittivity and magnetic permeability of the space, which the electromagnetic fields encounter.

Magnetic permeability is the measure of the ability of a material to support the formation of a magnetic field within itself. The magnetic permeability of space is: $\mu_o = 4\pi \times 10^{-7}$ (H/m). Except in the case of ferromagnetic materials, the magnetic permeability of many materials is equivalent to that of free space. The magnetic permeability of ferromagnetic materials varies greatly with field strength.

Space itself has dielectric properties [12] with an electrical permittivity of approximately $\varepsilon_o = 8.8541878 \times 10^{-12}$ or $\varepsilon_o \approx \frac{1}{36\pi} \times 10^{-9}$ F m^{-1}. Electrical permittivity describes the amount of charge needed to generate one unit of electric flux in a medium. All materials increase the electrical permittivity of the space they occupy, compared with free space (vacuum); therefore, some materials can support higher electric flux than free space. These materials are referred to as dielectric materials.

Debye [13] studied the behaviour of solutions with polar molecules and consequently refined the complex dielectric constant, which includes the conductivity of the material. His final equation became:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} - j\frac{\sigma}{\omega\varepsilon_o} \tag{3}$$

where ε is the dielectric constant at very high frequencies; ε_s is the dielectric constant at very low frequencies; ω is the angular frequency (rad s^{-1}); τ is the relaxation time of the dipoles (s); σ is the conductivity of the material (Siemens m^{-1}); j is the complex operator (i.e. $j = \sqrt{-1}$), and ε_o is the dielectric permittivity of free space.

Manipulating Eq. (3) to separate it into real and imaginary components yields:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2} - j\left\{\frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} + \frac{\sigma}{\omega\varepsilon_o}\right\} = \varepsilon' - j\varepsilon'' \tag{4}$$

The relaxation time τ is a measure of the time required for polar molecules to rotate in response to a changed external electric field, and hence determines the frequency range in which dipole movement occurs. This response time depends on the temperature and physical state of the material.

The dielectric constant ε' affects the wave impedance of the space occupied by the dielectric material [14] and causes reflections at the inter-facial boundary between materials due to changes in the wave impedance of the space occupied by the material. These changes in wave impedance also cause a change in the wavelength of the electromagnetic fields inside the dielectric material, compared with the wavelength in air or vacuum [15]. This change in wavelength affects the propagation velocity of the wave within the material.

The dielectric loss ε'' represents the resistive nature of the material [16], which reduces the amplitude of the electromagnetic field and generates heat inside the material.

It is common practice to express the dielectric properties of a material in terms of the relative dielectric constants κ' and κ", which are defined as: $\varepsilon' = \kappa'\varepsilon_o$ and $\varepsilon'' = \kappa''\varepsilon_o$. The general form of the dielectric properties of polar materials resembles the normalised example shown in **Figure 3**.

The dielectric properties of most materials are directly associated with its molecular structure. Debye's basic relationship assumes that the molecules in a material are homogeneous in structure and can be described as "polar". Since few materials can be described in this way, many other equations have been developed to describe frequency-dependent dielectric behaviour.

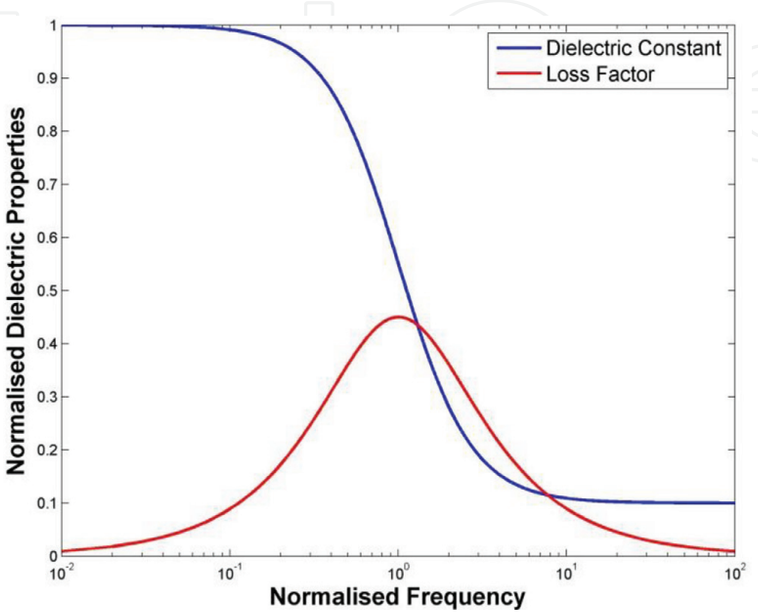


Figure 3.
Normalised dielectric properties of a polar material.

In many cases, the material may be regarded as a composite or mixture and will exhibit multiple relaxation times. If this is the case then the complex dielectric constant may be represented by a variation of Debye's original equation [17]:

$$\kappa = \kappa_\infty + a\left(\frac{\kappa_s - \kappa_1}{1 + j\omega\tau_1}\right) + b\left(\frac{\kappa_1 - \kappa_2}{1 + j\omega\tau_2}\right) + .. - j\frac{\sigma}{\omega\varepsilon_o} \tag{5}$$

where κ_1 and κ_2 are intermediate values of the dielectric constant between the various relaxation periods of τ_1 and τ_2, and a and b are constants related to how much of each component is present in the total material.

2.2 Temperature dependence of the dielectric properties

As temperature increases, the electrical dipole relaxation time associated with the material usually decreases, and the loss-factor peak will shift to higher frequencies (**Figure 4**). For many materials, this means that at dispersion frequencies the dielectric constant will increase while the loss factor may either increase or decrease depending on whether the operating frequency is higher or lower than the relaxation frequency [18]. For example, **Table 1** demonstrated how the dielectric properties of some food stuffs, in the microwave band, vary with temperature.

Some food stuffs in **Table 1** follow the predicted trend of increasing dielectric constant as temperature increases; however, it is apparent that the dielectric constant of other entries in **Table 1** decline with increasing temperature rather than increasing with temperature. This is linked to their water content, because the dielectric constant of water at a fixed frequency decreases with increasing temperature (**Figure 4**). **Figure 5** shows how the dielectric properties of water vary with temperature, over a wider range of frequencies.

2.2.1 Density dependence of dielectric properties

Because a dielectric material's influence over electromagnetic waves depends on the amount of the material present in the space occupied by the material, it follows that the density of the material must influence the bulk dielectric properties of

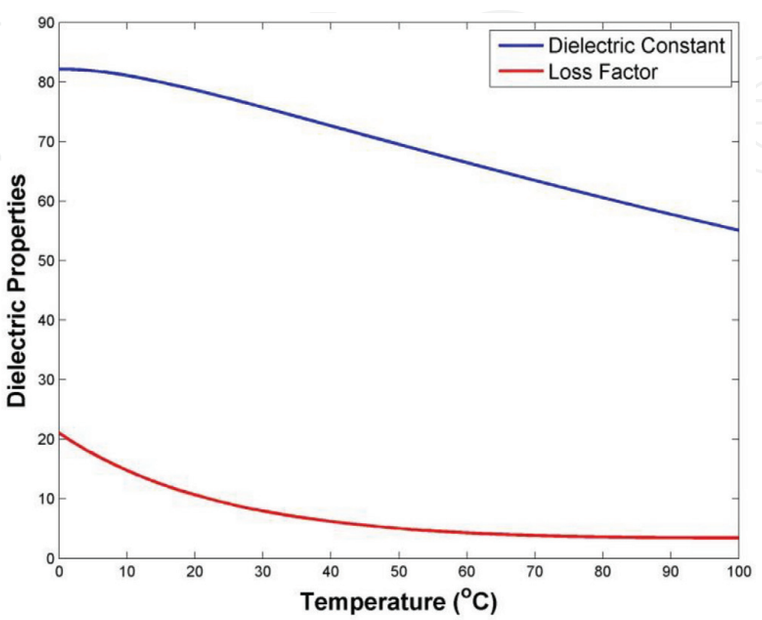


Figure 4.
Dielectric properties of pure water as a function of temperature at 2.45 GHz.

Food product	Moisture content	Fat content	Temperature					
			50		75		100	
			ε'	ε"	ε'	ε"	ε'	ε"
Peanut butter	—	48.5	3.1	4.1	3.2	4.5	3.5	5.0
Ground beef	50.7	31.9	39.0	10.4	32.2	11.5	31.7	12.6
Ham	69.1	4.7	66.6	47.0	87.4	57.0	101.0	60.0
Concentrated orange juice	57.6	—	54.1	15.7	53.5	15.2	52.0	15.7
Mashed potatoes	81.3	0.9	60.6	17.4	56.3	16.5	52.9	15.8
Peas, cooked	778.6	—	60.8	12.6	50.5	9.7	46.6	9.1

Table 1.
Dielectric properties of some common foods at 2.8 GHz as a function of temperature (source: [19]).

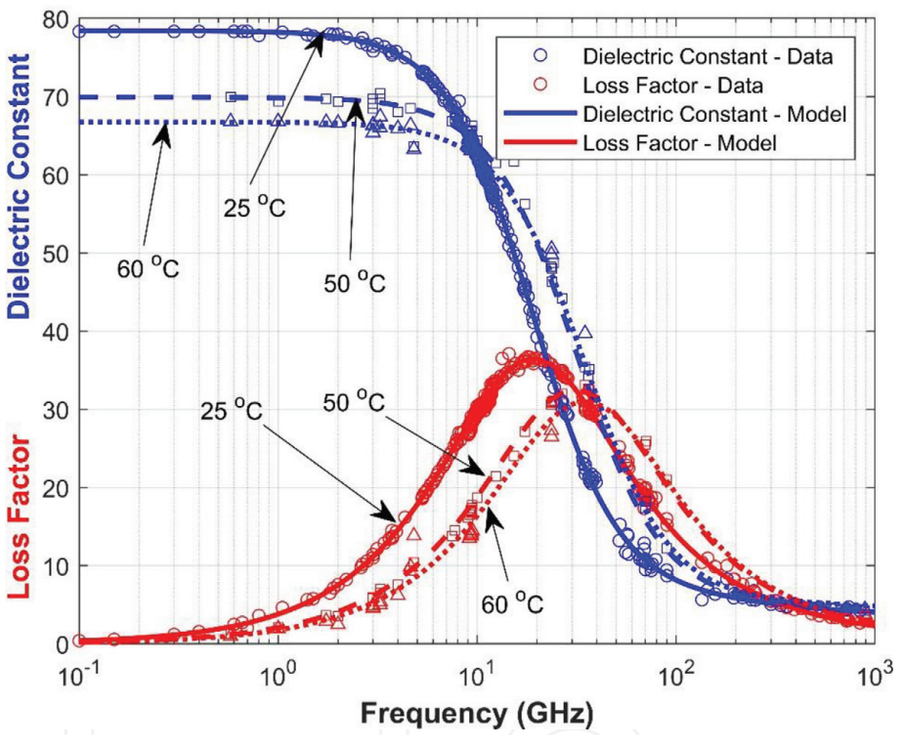


Figure 5.
Dielectric properties of pure water as a function of frequency and temperature (data sources: [20]; model for dielectric properties based on: [21]).

materials. This is especially true of particulate materials, such as soil, grains or flours [18].

As an example, the dielectric properties of oven dry wood, with the electric field oriented perpendicular to the wood grain, are described by [22]:

$$\kappa' = \kappa_\infty + \frac{(\kappa_o - \kappa_\infty)\left[1 + \omega\tau^{(1-\alpha)}\, Cos\left(\pi\frac{1-\alpha}{2}\right)\right]}{\left[1 + \omega\tau^{2(1-\alpha)} + 2\omega\tau^{(1-\alpha)}\, Cos\left(\pi\frac{1-\alpha}{2}\right)\right]} \tag{6}$$

and

$$\kappa'' = \frac{(\kappa_o - \kappa_\infty)\left[1 + \omega\tau^{(1-\alpha)}\, Cos\left(\pi\frac{1-\alpha}{2}\right)\right]}{2\left[1 + \omega\tau^{2(1-\alpha)} + 2\omega\tau^{(1-\alpha)}\, Cos\left(\pi\frac{1-\alpha}{2}\right)\right]} \tag{7}$$

Table 2 shows the values of κ_o and κ as a function of wood density.

2.3 Wave propagation

If a material is homogeneous in terms of its electromagnetic properties, it is apparent that an incident electromagnetic wave would be partly reflected at the material boundary and partly transmitted. The transmitted energy would be dissipated due to any losses within the medium. If a plane wave is propagating through space in the x-direction, it can be described by:

$$E(x,t) = E_o e^{j(kx-\omega t)} \tag{8}$$

where, in general, the wavenumber (k) can be described by:

$$k = k_o(\beta + j\alpha) \tag{9}$$

where k_o is the wavenumber of free space:

$$k_o = \frac{2\pi f}{c} \tag{10}$$

Van Remmen, et al. [23] show that the components of the wavenumber are given by:

$$\beta = \sqrt{\kappa' \frac{\sqrt{1+\left(\frac{\kappa''}{\kappa'}\right)^2}+1}{2}} \tag{11}$$

and:

$$\alpha = \sqrt{\kappa' \frac{\sqrt{1+\left(\frac{\kappa''}{\kappa'}\right)^2}-1}{2}} \tag{12}$$

The term α is associated with wave attenuation with distance travelled through a medium. For free space (or air) α = 0 at most frequencies.

For a wave that is perpendicularly incident onto the surface of a material, the reflection coefficient, which is the ratio of the reflected wave amplitude to the incident wave amplitude, is given by:

$$\Gamma = \frac{(\beta_1+\beta_2)(\beta_1-\beta_2)+(\alpha_1+\alpha_2)(\alpha_1-\alpha_2)}{(\beta_1+\beta_2)^2+(\alpha_1+\alpha_2)^2} + j\frac{(\beta_1+\beta_2)(\alpha_1-\alpha_2)-(\beta_1-\beta_2)(\alpha_1+\alpha_2)}{(\beta_1+\beta_2)^2+(\alpha_1+\alpha_2)^2} \tag{13}$$

Wood density (g cm^{-3})	κ_o	κ_∞	Wood density (g cm^{-3})	κ_o	κ_∞
0.13	1.4	1.16	1.0	4.0	2.3
0.2	1.6	1.2	1.2	4.8	2.5
0.4	2.0	1.4	1.4	6.0	2.8
0.6	2.5	1.65	1.53	6.8	2.9
0.8	3.2	2.03			

Table 2.
Values of κ_s and κ for oven dried wood of various densities when the electric field is perpendicular to the wood grain (based on data from: [22]).

where the subscripts refer to medium 1 and medium 2 across the medium interface. The transmission coefficient, which is the ratio of the transmitted wave amplitude to the incident wave amplitude, is given by:

$$\tau = 2\left\{\frac{{\beta_1}^2 + \beta_1\beta_2 + \alpha_1\alpha_2 + {\alpha_1}^2}{(\beta_1+\beta_2)^2 + (\alpha_1+\alpha_2)^2} + j\frac{\beta_2\alpha_1 - \beta_1\alpha_2}{(\beta_1+\beta_2)^2 + (\alpha_1+\alpha_2)^2}\right\} \tag{14}$$

Therefore, the wave, which propagates across a boundary from one medium (or vacuum) to another, is described by:

$$E(x,t) = E_o\tau \bullet e^{j(k_o\beta x - \omega t)} \bullet e^{-k_o\alpha x} \tag{15}$$

3. Transmission through a material

If the electromagnetic wave passes through a material, the wave emerging on the other side will be described by:

$$E(x,t) = E_o\tau_{1,2} \bullet \tau_{2,1} \bullet e^{j(k_o\beta_1 x + k_o\beta_2 L - \omega t)} \bullet e^{-k_o\alpha_2 L} \tag{16}$$

where $\tau_{1,2}$ and $\tau_{2,1}$ are the transmission coefficients of the two material interfaces and L is the thickness of the material through which the wave passes. Therefore, the wave is delayed, phase shifted (because of the complex value of the transmission coefficient) and attenuated by the material, in comparison to a similar wave propagating though free space. This is illustrated in **Figure 6**.

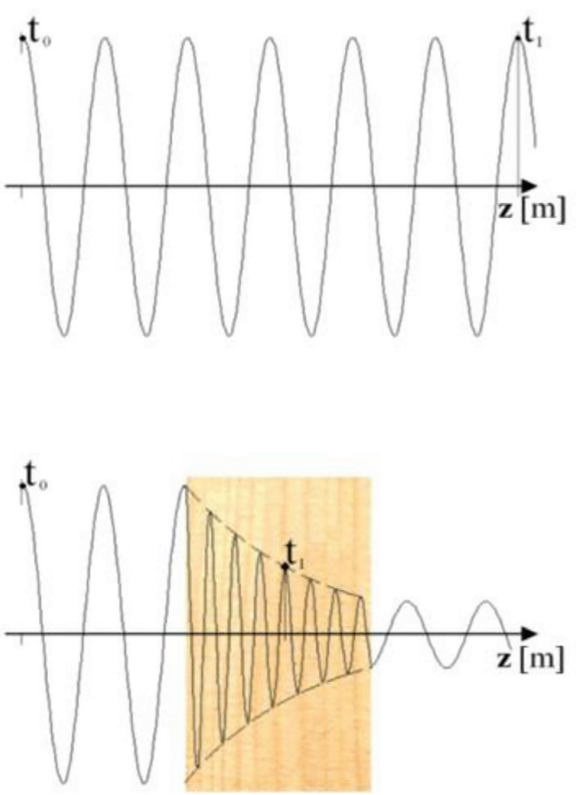


Figure 6.
Schematic of some changes in an electromagnetic wave associated with transmission through a material.

4. Non-invasive detection of internal structures of objects

Wave attenuation, reflections from the material surface, and internal scattering from embedded objects or cavities in the material causes "shadows" on the opposite side of the material from the electromagnetic source. An X-ray image (**Figure 7**) is a good example of how shadows associated with propagation delay and wave attenuation can be used to interpret the internal structures of objects. Effectively the combination of attenuation and phase delay, which are directly linked to the dielectric properties of the material, provide information about the material through which the electromagnetic wave travels.

Wave penetration into any material can be defined by the penetration depth (d), when the ratio of the wave amplitude to initial amplitude is $\frac{1}{e} = 0.3679$:

$$d = \frac{1}{k_o \alpha} \tag{17}$$

The penetration depth of an electromagnetic wave is inversely proportional to the wave frequency and the attenuation factor of the material. If the penetration



Figure 7.
Example of an X-ray image.

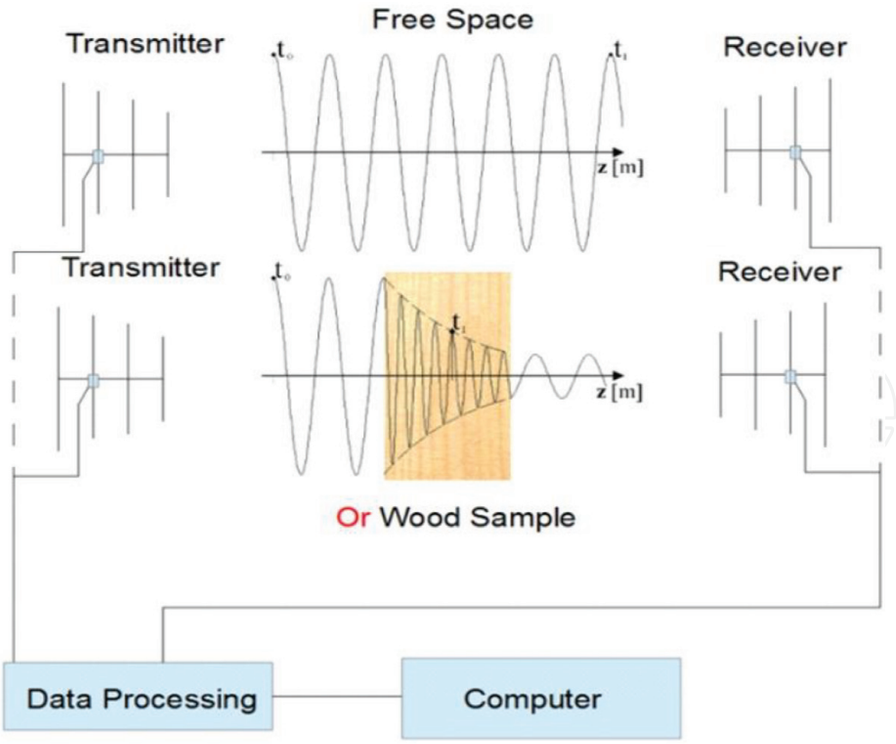


Figure 8.
Schematic of a 'look through' microwave system for assessing the properties of materials.

depth of a material is far greater than the thickness of the material at a given frequency, the material appears to be 'transparent' to the electromagnetic wave. If the penetration depth of a material is far smaller than the thickness of the material at a given frequency, the material appears to be 'opaque'. If the penetration depth of the material is similar to the thickness of the material at a given frequency, the material may be regarded as 'translucent'.

Although X-rays have been used to investigate the internal features of objects, other frequencies of the electromagnetic spectrum can also be used [24]. For example, microwaves can be used to assess the internal structure of materials, by 'looking through' the objects, as illustrated in **Figure 8**. Such microwave systems have been used to assess moisture content of materials [25–28], detection of decay is timber [29–31], detection of insects in bulk materials such as grains and wood [32–34], assessment of wooden structures of cultural significance [24], and 'see through walls' Wi-Fi imaging [35, 36].

5. Energy transfer

Electromagnetic waves can transfer energy from one object to another through open space. Generally, the amount of energy transferred depends on: the intensity of the electromagnetic fields; the frequency of the fields' oscillations; and the dielectric properties of the material. The power dissipated per unit volume in a non-magnetic, uniform materials, exposed to electromagnetic fields can be expressed as [37]:

$$P(x) = 55.63 \times 10^{-12} \bullet f \bullet (\tau \bullet E)^2 \bullet \kappa'' \bullet e^{-2k_o \alpha x} \tag{18}$$

where f is the frequency, κ" is the dielectric loss factor of the heated material, k_o is the wavenumber of free space, α is the attenuation factor, and x is the distance

below the surface of the material. Therefore, more power is dissipated in a material at higher frequencies; however, the wave attenuation factor is higher at higher frequencies and therefore the penetration of the heating into the surface of the material is lower at higher frequencies.

5.1 Dielectric heating

Dielectric heating usually takes place in the radio frequency, microwave or millimetre wave bands of the electromagnetic spectrum. Before World War II, there is little evidence of work on dielectric heating; however, Kassner [38] mentions industrial applications of microwave energy in two of his patents on spark-gap microwave generators [38–40]. Unfortunately early studies in radio frequency heating concluded that microwave heating of food stuffs would be most unlikely because the calculated electric field strength required to heat biological materials would approach the breakdown voltage of air [41].

A discovery that microwave energy could heat food by Spencer [42] lead to a series of patents for microwave cooking equipment [43–45]. Radiofrequencies and microwaves interact with all organic materials. The strength of this interaction depends on the dielectric properties of the materials. These dielectric properties are strongly influenced by the amount of water in the material. Absorption of radio-frequency or microwave energy by these dielectric materials generates heat in the material.

The major advantages of dielectric heating are its short start-up, precise control and volumetric heating [46]; however dielectric heating suffers from: uneven temperature distributions [10, 23]; unstable temperatures [47–50]; and rapid moisture movement [51]. The advantage of radio frequency and microwave heating is its volumetric interaction with the heated material as the electromagnetic energy is absorbed by the material and manifested as heat [52]. This means that the heating behaviour is not restricted by the thermal diffusivity of the heated material.

In industry, dielectric heating is used for drying [46, 53–55], oil extraction from tar sands, cross-linking of polymers, metal casting [46], medical applications [56], pest control [32], enhancing seed germination [57], and solvent free chemistry [58].

The temperature response of the material, other than on the surface, is limited by the coefficient of simultaneous heat and moisture movement [51]. If for any reason the local diffusion rate is much less than the electromagnetic power dissipation rate, the local temperature will increase rapidly. With increasing temperature, the properties of the material change. If such changes lead to the acceleration of electromagnetic power dissipation at this local point, the temperature will increase more rapidly. The result of such a positive feedback is the formation of a hot spot, which is a local thermal runaway [59].

Thermal runaway, which manifests itself as a sudden temperature rise due to small increases in the applied electromagnetic power, is very widely documented [48, 60]. It has also been reported after some time of steady heating at fixed power levels and is usually attributed to temperature dependent dielectric and thermal properties of the material [48, 60].

5.2 Hot body radiation energy transfer

Any object that is above zero degrees Kelvin will radiate energy in the form of electromagnetic photons. The German physicist, Max Planck (1858–1947), deduced that the radiation spectral density (ρ) given off from a hot object depended on the wavelength of interest and the temperature of the object. This spectral density can be described by:

$$\rho = \frac{2hc^2}{\lambda^5\left\{e^{\frac{hc}{\lambda kT}} - 1\right\}} \tag{19}$$

where h is Planck's constant (6.6256×10^{-34} J s), c is the speed of light, λ is the electromagnetic wavelength of interest, k is Boltzmann's constant (1.38054×10^{-23} J K^{-1}), and T is the temperature in Kelvin. A typical set of spectral distributions for different temperatures is shown in **Figure 9**.

The wavelength at which peak radiation intensity occurs can be found by differentiating Planck's equation and setting the derivative equal to zero. Therefore, the wavelength of peak radiation is determined by:

$$\lambda_p \approx \frac{hc}{5kT} \tag{20}$$

where λ_p is the peak radiation wavelength (m). At room temperature, or above, the wavelength of peak radiation will be in the micrometre range (~10 μm), which is in the long-wavelength infrared band (**Table 3**). The penetration of electromagnetic energy into materials is limited by the wavelength and the dielectric properties of the material [61], as pointed out in Eq. (17). The penetration depth of any radiation from objects at room temperature, or above, will be in the nanometre

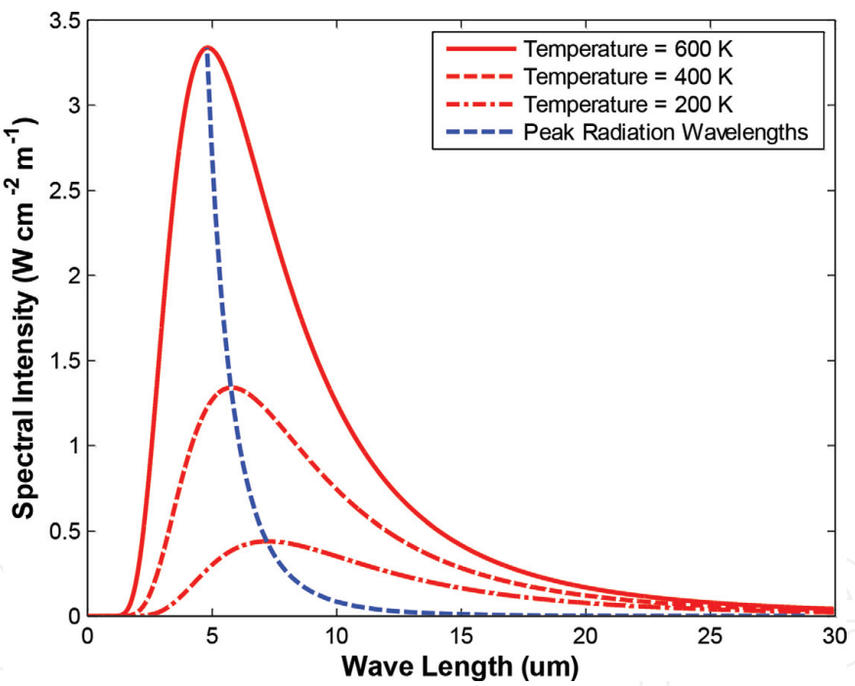


Figure 9.
Radiative spectral density at different temperatures as a function of temperature and wavelength.

Division name	Abbreviation	Wavelength (μm)	Temperature (K)
Near infrared	NIR	0.75–1.4	3964–2070
Short-wavelength Infrared	SWIR	1.4–3.0	2070–966
Mid-wavelength Infrared	MWIR	3.0–8.0	966–362
Long-wavelength Infrared	LWIR	8.0–15.0	362–193
Far infrared	FIR	15.0–1000	193–3

Table 3.
A commonly used sub-division scheme for the infrared part of the electromagnetic spectrum.

range; therefore, this form of radiative energy transfer must be regarded as a surface phenomenon, where further energy transfer from the surface into the material occurs via internal conduction and convection.

The total radiated power can be determined by integrating Planck's equation across all wavelengths for a temperature to yield the Stefan-Boltzmann equation. The power transferred from an object at one temperature to another object at a lower temperature is given by [62]:

$$q = \varepsilon\sigma A\left(T_A^4 - T_{\mathrm{p}}^4\right) \tag{21}$$

where q is the radiation power transferred (W); ε is the surface emissivity of the radiator material; σ is the Stefan-Boltzmann constant ($5.6704 \times 10^{-8}\,\mathrm{J\,s^{-1}\,m^{-2}\,K^{-4}}$); A is the surface area of the heated object (m^2); T_A is the temperature of the infrared source (K); and T_p is the temperature of the material being heated (K). In the case of a normal object the power transfer is reduced by a factor ε, which depends on the properties of the object's surface. This factor is referred to as the emissivity of the surface.

5.3 Thermal imaging

Brightness temperature is the temperature that a black body, in thermal equilibrium with its surroundings, would need to have in order to duplicate the observed electromagnetic wave intensity, at a known wavelength. The brightness temperature of a body can be determined by rearranging Planck's equation to find T_b for a given spectral density value, at a wavelength λ:

$$T_b = \frac{\mathrm{hc}^2}{\lambda k \bullet \ln\left(\frac{2\mathrm{hc}}{\rho\lambda^5} + 1\right)} \tag{22}$$

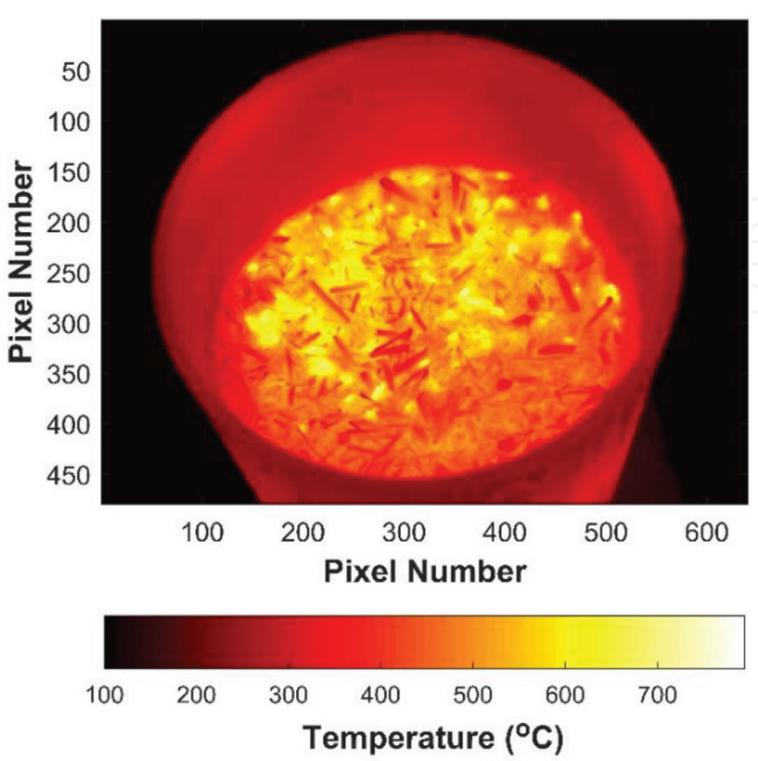


Figure 10.
Thermal image of a microwave heated sample of biosolids.

The real surface temperature of an object can be determined by dividing the brightness temperature by the surface emissivity of the object being assessed. Since the emissivity is a value between 0 and 1, the real temperature will be greater than or equal to the brightness temperature. This is effectively how remote thermal sensors and thermal imaging systems operate (**Figure 10**).

6. Conclusion

Space-time behaves like a dielectric, allowing electromagnetic waves to propagate through it. The inclusion of material objects in space alters the fundamental dielectric properties of space-time in such a way that electromagnetic energy is reflected from the surface of material objects, transmitted through material objects and absorbed by material objects. These interactions, along with other changes in the electromagnetic wave propagation, allow: information about the space occupied by the material object to be non-invasively acquired; or facilitates the transfer of energy from the electromagnetic wave to the material object. In a practical sense, these interactions between electromagnetic waves and material objects can facilitate remote sensing and energy transfer over very long distances.

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