Chapter

Introductory Chapter: Electromagnetism

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1. Introduction

There are four fundamental forces in nature, namely:

(i) The strong nuclear force is the strongest among the four forces. The strong force is known to bind subatomic particles (such as protons and neutrons) to form nucleus.

(ii) The electromagnetic force which is in the order of 10^{-2} that of the strong force [1]. The electromagnetic force governs the interactions among electrically charged particles.

(iii) The weak nuclear force which is in the order of 10^{-14} of the strong force [1]. The weak force acts in each individual nucleons (i.e., collections of protons and neutrons) and is responsible for the radioactive decay when neutrons decay to protons and electrons.

(iv) The gravitational force which is the weakest among all forces. The gravitational force attracts any object with mass.

A field is a spatial distribution of quantity, which may or may not be a function of time [2]. To put it in simple terms, an electromagnetic field is basically the field produced as a consequence of positively and/or negatively charged particles, be at rest or in motion, and exerted forces among each other. The electromagnetic field consists of both the electric field and the magnetic field. During static condition, both electric and magnetic fields exist independently. When only an electric field is present and is constant in time, the field is known as an electrostatic field; similarly, when only a constant magnetic field is present, it is known as a magnetostatic field. When the fields change over time (i.e., in time-varying condition), however, both fields have to be concurrently present. This is to say that a time-varying electric field induces a time-varying magnetic field and vice versa [1], resulting in both fields being coupled together.

Due to its particle-wave duality nature, an electromagnetic field can be viewed as a continuous field which propagates in a wavelike manner, while at the same time, it can also be seen as quantized particles called photons. When the wave of the electromagnetic field propagates in an isotropic homogeneous medium, the electric and magnetic field components are mutually transverse to the direction of the energy transfer, as depicted in **Figure 1**. The radiation is therefore known as a transverse electromagnetic or TEM wave.

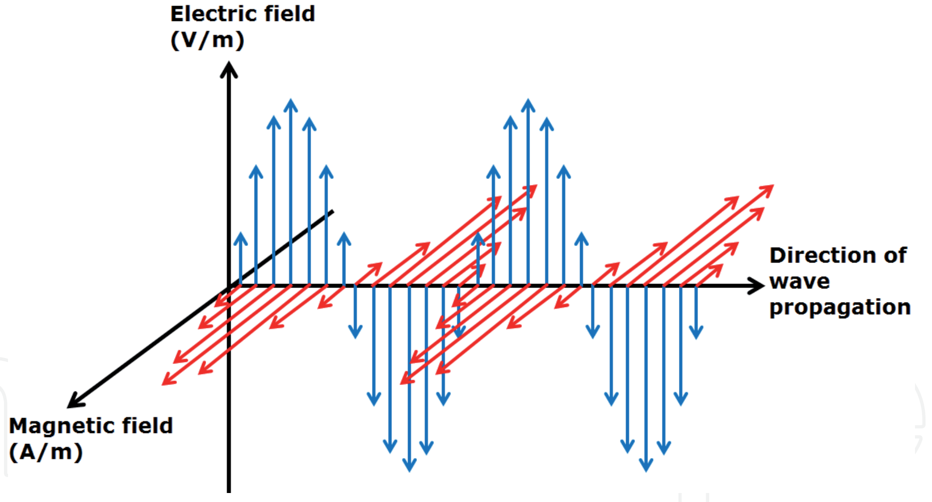

Figure 1.
Transverse electromagnetic wave propagation.

The distance between two adjacent troughs or crests of the electromagnetic wave is known as a wavelength. The wavelength is inversely proportional to the frequency of the wave (i.e., the tendency in which the wave repeats the same wave pattern). In other words, if the wave tends to repeat its cycle at a faster pace, the wavelength will become shorter. Likewise, if the pace of repetition decreases, the wavelength will become longer. The relationship between wavelength λ and frequency f can be expressed as (1) below:

$$\lambda = \frac{1}{f\sqrt{\mu\epsilon}} \tag{1}$$

where $\frac{1}{\sqrt{\mu\epsilon}}$ is the velocity of the wave propagation. Here, ε and μ are, respectively, the permittivity and permeability of the medium where the wave propagates. The permittivity ε measures the degree a material is polarized by the electric field, whereas the permeability μ dictates its ability in supporting the development of the magnetic field. Both electric and magnetic flux densities are, therefore, in direct proportion with ε and μ, respectively. Together with the conductivity parameter, σ, which describes the ease at which a charge can move freely in a material, these three parameters (i.e., ε, μ, and σ) are referred to as the constitutive properties of the material.

2. Electromagnetic spectrum

Electromagnetic waves propagate at different frequencies. The electromagnetic spectrum is the classification of the waves in accordance to their range of frequencies. The classification is necessary since waves which radiate at different frequencies may be generated by different sources and may exhibit different effects on matters. The names given to the bands of frequencies may be broadly classified, in the order of decreasing wavelength and increasing energy and frequency, as follows:

(i) radio wave and microwave

(ii) terahertz wave

(iii) infrared radiation

(iv) visible light

(v) ultraviolet radiation

(vi) X-rays

(vii) gamma rays

A summary of the spectrum is given in **Figure 2**. It is to be noted that the frequencies at each edge of the band are merely approximations. The boundaries of each band are difficult to be defined since the waves are continuous and the bands may fade into each other.

2.1 Radio wave and microwave

The radio wave band ranges from around 3 Hz to 300 GHz. At the lower end of the radio wave (i.e., from 3 Hz to 300 MHz), the band is typically designated for radio and television broadcasts and is commonly known as the radio frequency RF signal. At the higher end (i.e., from 300 MHz to 300 GHz), the signal is used for telecommunication, satellite communication, food heating, wireless networking, wireless power transmission [3, 4], etc. Due to its vast applications at the higher end, this range of frequencies is specifically denoted as microwave. The EHF band which spans from 30 to 300 GHz holds important spectral and spatial information in the field of astrophysics [5]. The cosmic microwave background (CMB) radiation, for instance, peaks in the frequency range of 100–300 GHz [6]. The study of the CMB provides an in-depth understanding of the physics of the Big Bang and

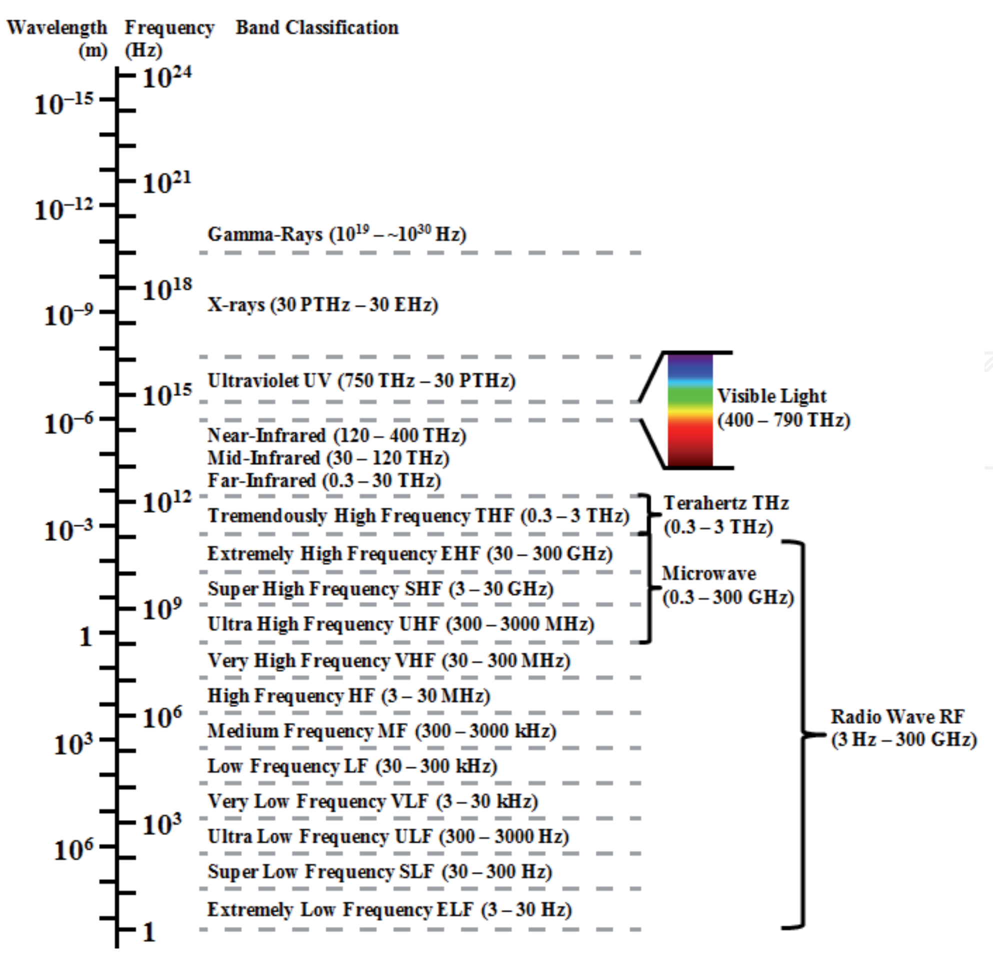

Figure 2.
The electromagnetic spectrum.

the formation of the early universe. Since this range of frequencies corresponds to wavelengths from 1 to 10 mm, it is also sometimes called the millimeter band.

Information is modulated in the radio wave signal and is emitted from a transmitter circuit to a receiver circuit, via antennas. In order to mediate effective communication, the antennas are required for [7]:

(i) efficient signal coupling and radiation

(ii) impedance matching, so as to minimize reflection when coupling the signal to the transmission line

Some of the common types of antennas used for RF communication are of the dipole [8–10], monopole [11–13], patch [14–17] and loop [18–21] configurations.

2.2 Terahertz wave

Sandwiched between the microwave and optical bands and falling within the 10^{12} Hz regime, the tremendously high-frequency (THF) band is more popularly known as the terahertz (THz) band. Since its wavelengths lie in the range of 0.1–1 mm, this band is therefore referred to as the submillimeter band as well.

Compared to microwaves, THz radiation has a shorter wavelength, and, thus, it possesses more energy to penetrate deeper and make sharper images. The radiation also scatters less than visible and near-infrared frequencies [22]. Unlike X-rays and ultraviolet (UV) light, THz waves are nonionizing. Hence, the radiation does not impose detrimental implications on living tissues [22]. Besides, the following characteristics are also shown when a material is illuminated with THz waves: polar liquids, such as water, absorb strongly in THz radiation, and metals are opaque to such radiation, whereas non-metals such as plastics, paper products, and non-polar substances are transparent [22]. Dielectrics, on the other hand, have characteristic absorption features peculiar to each material [22]. Due to the unique properties of this wave, THz waves are useful in an increasingly wide variety of applications, such as biology and medical sciences, homeland security, quality control of food and agricultural products, global environmental monitoring, etc. [23].

The THz region in the electromagnetic spectrum is of considerable importance in astrophysics. Like the millimeter band, the submillimeter band consists of spectral and spatial information of cosmic sources [5, 24]. The cold material (10–30 K) associated with the early stages of star and planet formation, as well as the earliest stages of galaxy formation, has its peak emission in the millimeter and submillimeter range [25]. By analyzing and mapping the lines in the THz band, it is possible to build complete models of astrophysical objects, which include temperature, density, large-scale movement of material, magnetic field strengths, isotope abundance, etc. [6].

Parabolic reflector antennas are used to detect THz waves in radio telescopes [24, 26, 27]. Due to the skin effect, transmission lines become very lossy at THz frequencies. Hence, waveguides are used instead to couple the signal and to channel it to the receivers [28–30].

2.3 Infrared radiation

The infrared IR radiation ranges from around 300 GHz to 400 THz and constitutes about 50% of the total sunlight. Since objects which radiate or sensors which detect IR radiation are only restricted to certain limited bandwidth, the band is further subdivided into three smaller parts, i.e., the far-infrared (FIR) (300 GHz–30 THz), mid-infrared (MIR) (30–120 THz) and near-infrared (NIR) (120–400 THz) sections.

The far-infrared (FIR) section behaves somewhat similar to the THz band. Waves in this band can be absorbed by the movements of molecules. Celestial sources such as cold clouds of gas and dust emit FIR waves. Detection of the FIR radiation can therefore be used to observe the formation of protostar in these clouds.

The mid-infrared (MIR) section is strongly absorbed by the earth atmosphere—particularly, by water vapor and carbon dioxide. It is also susceptible to molecular vibrations. This spectrum is also essentially important in astronomy. Planets absorb heat from the sun and reradiate it in the MIR spectrum. Also, interstellar dust and protoplanetary disks emit strongly in the MIR region. The 'heat-seeking' missiles used by the military are also designed to operate within this range. Black bodies, such as the heat from human bodies, radiate intensely in the MIR and FIR regions. Hence, the FIR and MIR signals are also used for thermal imaging.

The near-infrared (NIR) section is the closest to the lower end of the visible light frequencies. Hence, it is typically used in fiber optics communication. In astronomy, cooler stars such as the red giant stars and red dwarfs radiate very intensely at the NIR spectral region. Night vision devices, image sensors and NIR spectroscopy which finds wide applications in the medical field also make use of signals which oscillate at this range.

2.4 Visible light

The visible light is the most familiar spectrum to humans, and it constitutes about 40% of the total sunlight. Ranging from approximately 400 to 790 THz, this spectral region is the most sensitive to human eyes. Molecules and atoms absorb or release energy in this range of frequencies, allowing electrons to move to different energy levels. The change of bond structure in the retina of human eyes allows this spectrum to be visible to humans. Unlike signals from the radio wave to the infrared spectrum where radio telescopes are built to detect the signals, optical telescopes are used to visualize celestial objects which radiate at this spectrum. Visible light also excites chemical reactions in plants, mediating the process of photosynthesis.

2.5 Ultraviolet radiation

As the frequency increases above those of the visible light, the energy carried by the photons becomes very energetic—so much so that it can ionize atoms and disrupt molecular bonds. This is to say that electromagnetic waves in the ultraviolet (UV), X-rays and gamma rays bands cause ionizing radiations and that they could be detrimental to living things as a whole and human beings in particular.

UV radiation ranges approximately from 750 THz to 30 PHz, and it constitutes almost 10% of the total sunlight. The spectrum can be further divided into the ultraviolet A (UVA) section which spans roughly from 750 to 950 THz, ultraviolet B (UVB) section which spans roughly from 950 to 1000 THz, and ultraviolet C (UVC) section which spans roughly from 1 to 30 PHz. The UVC emission carries the highest energy and is the most hazardous. But it is literally absorbed by the ozone and atmosphere layers before reaching the earth. Likewise, the UVB emission is also absorbed mostly by the stratospheric ozone layer. Hence, only the UVA emission and a very small fraction of the UVB emission reach the earth surface. The UVA emission carries the lowest energy and is the least damaging of all. Besides the sun, UV radiation can also be artificially produced, such as from electric arc, gas discharge lamps, etc.

Due to its ionizing behavior, UV light is known to be the main cause of skin cancer and skin burn. The high energy level carried by the wave at this spectral range may damage the DNA molecules, resulting in the formation of thymine dimers. In order to prevent from being directly exposed to the UV radiation, sunscreens are usually used. The active ingredients in sunscreens can either be organic (such as dioxybenzone and oxybenzone) or inorganic compound (such as titanium dioxide and zinc oxide).

Although being constantly exposed to UV radiation is harmful, moderate exposure may actually be beneficial to the human body. This is because UV radiation mediates the production of vitamin D in the human body. Vast applications may also be found using UV radiation. In the biomedical field, UV light is used in phototherapy to treat severe skin problems such as psoriasis and eczema. The photolithography process in the semiconductor industries [31] also uses UV radiation to print circuits onto the photoresists deposited on wafers. Since fluorescent dyes and certain fluids illuminate brightly under UV light, the radiation is also used in the security and forensic areas. In astronomy, wave signals at this range are detected to analyze the composition of interstellar and intergalactic medium. However, since UV is greatly absorbed by the ozone layer, the UV telescope has to be placed in space. An example of such telescope is the Hubble Space Telescope (HST) [32].

2.6 X-rays

X-rays which were also named as the X-radiation by its discoverer, Wilhelm Röntgen, have frequencies much higher than the UV radiation, which ranges around 30 PHz–30 EHz. X-rays with higher energy levels are known as hard X-rays, whereas those with lower energy levels are known as soft X-rays. Since soft X-rays are susceptibly absorbed in air, it is less useful than hard X-rays. Hence, the term 'X-rays' is generally referred to hard X-rays when they are being applied.

X-rays can be generated via synchrotron radiation, X-ray fluorescence or bremsstrahlung, and they can be detected via imaging detectors which uses photographic films.

X-rays have significantly shorter wavelengths than the visible light. They can therefore penetrate most tissues in the human body. When they propagate through the human body, different amount of the energy is absorbed by different types of tissues. The absorption rate depends on the radiological density of the tissues. Bones which has high radiological density absorbs the energy considerably more than tissues with lower densities, such as muscle, fat and air-filled cavity in the lungs. When images are produced using X-rays, the parts with bones will appear whitish, whereas those with softer tissues will appear shadowy. Because of this reason, X-rays are widely used for medical imaging, such as radiography and computed tomography (CT) scanning. The employment of X-rays in luggage scanning in airport security is based on a similar concept as medical imaging. Besides imaging, X-rays are also used in radiation therapy for cancer treatments in the medical field. Since some of the cosmic sources emit waves in this spectral range, it is therefore useful in the field of astrophysics—the detection of which, like the case of UV radiation, is conducted using orbiting telescopes. Also, in a technique called X-ray crystallography, X-rays are applied to study the structures of crystals.

Like UV radiations, X-rays are highly ionizing and may cause deleterious effects on humans. Hence, the applications of X-rays are often conducted in lead-shielded rooms, and the practitioners are to wear lead aprons and gloves. The amount of X-ray exposure is measured using an ionization chamber, and the dosage of X-rays, in which the user is exposed to, is measured using a dosimeter.

2.7 Gamma rays

The distinction between X-rays and gamma rays is not unanimous. One general definition to distinguish between these two is that X-rays are generated via the acceleration of electrons, whereas gamma rays are generated from the radioactive decay of atomic nuclei. However, this definition may not always be valid since the source of radiation could not always be identified. The lowest frequency of the gamma rays is about 10^{19} Hz, while the highest known frequency that has been detected hitherto reaches about 10^{30} Hz.

Gamma rays are generated from the following processes:

(i) Nuclear fusion. Nuclear fusion is a natural phenomenon in which hydrogen nuclei fuse into helium nuclei, releasing energy in the form of gamma rays. Stars, such as the sun in the Milky Way galaxy, are powered by nuclear fusion. The creation of new elements in this process is known as stellar nucleosynthesis.

(ii) Nuclear fission, which is pretty much the reverse process of nuclear fusion. In nuclear fission, a nucleus splits into smaller and lighter nuclei. In the process of doing so, the energy is released as gamma rays.

(iii) Alpha decay. In alpha decay, a nucleus emits an alpha particle, and it, subsequently, reduces its atomic number by 2 and its mass by 4. The excess energy is emitted as gamma rays.

(iv) Gamma decay. When a nucleus contains too much energy, the energy is emitted as gamma ray photons. Since there is no particle released in the process, the charge and mass compositions of the nucleus remain unchanged.

Shielding materials such as lead are to be used for protection since gamma rays can cause the mutation of genes, resulting in the contraction of cancer. Quite ironically, however, gamma rays are also used to kill malignant cancerous tumors. In gamma knife radiosurgery, surgeons focus gamma ray beams toward the targeted region to kill the cancerous cells. Likewise, gamma rays are also used in food irradiation to kill microorganisms and to sterilize medical equipment. In astrophysics, gamma rays are detected to study pulsars, quasars, nebulae, and gamma ray bursts (GRBs).

3. Maxwell's equations

The discoveries made by scientists over the past millennia have contributed towards the profound understanding of electromagnetics that we have today. Among these scientific discoveries, it is the experimental observations reported independently by Ampere, Faraday and Gauss which inspired James Clerk Maxwell to establish the unified theory of electricity and magnetism. In 1873, Maxwell published his formulations in his textbook *A Treatise on Electricity and Magnetism*. The complexity of the formulations in the textbook was later reduced by Oliver Heaviside in 1881 to four sets of differential equations.

More popularly referred to as Maxwell's equations today, these four sets of notable mathematical equations which outline the fundamental principles of electromagnetism are tabulated in **Table 1**. Eq. (2.1) in the table describes the observation reported by the English physicist, Michael Faraday. According to Faraday, when the magnetic field intensity ($\mathbf{H}$) or magnetic flux density ($\mu\mathbf{H}$) varies with time (t), a force $V = \oint_C \mathrm{E} \cdot dl$ will be induced, where $\mathbf{E}$ is the electric field intensity and the line integral is performed over a line contour C bounding an arbitrary surface. Established by the French physicist Andre-Marie Ampere, Ampere's circuital law in Eq. (2.2) states that the circulation of $\mathbf{H}$ around a closed loop will result

Differential form	Integral form	Law	
$\nabla \times \mathrm{E} = -\mu \frac{\partial \mathrm{H}}{\partial t}$	$\oint_C \mathrm{E} \bullet d\boldsymbol{l} = -\int_S \mu \frac{\partial \mathrm{H}}{\partial t} \bullet d\boldsymbol{S}$	Faraday's law	(2.1)
$\nabla \times \mathrm{H} = \mathrm{J} + \varepsilon \frac{\partial \mathrm{E}}{\partial t}$	$\oint_C \mathrm{H} \bullet d\boldsymbol{l} = \int_S \left(\mathrm{J} + \varepsilon \frac{\partial \mathrm{E}}{\partial t}\right) \bullet d\boldsymbol{S}$	Ampere's law	(2.2)
$\nabla \bullet \mathrm{E} = \frac{\rho}{\varepsilon}$	$\oint_S \mathrm{E} \bullet d\boldsymbol{S} = \int_V \frac{\rho}{\varepsilon} \bullet dV$	Gauss' law for electricity	(2.3)
$\nabla \bullet \mathrm{H} = 0$	$\oint_S \mathrm{H} \bullet d\boldsymbol{S} = 0$	Gauss' law for magnetism	(2.4)

Table 1.
Maxwell's equations.

in current traversing through the surface bounded by the loop. Here, **J** is the convection current density, while $\varepsilon \frac{\partial \mathrm{E}}{\partial t}$ is the displacement current density. Eqs. (2.3) and (2.4) are formulated based on the observations made by the German physicist, Carl Friedrich Gauss. According to Gauss, the total electric flux density (ε**E**) flowing out from an enclosed surface *S* is equivalent to the total charge (ρ) encapsulated within *S*, i.e. (2.3), whereas the net outward **H** from *S* is invariably zero, i.e. Eq. (2.4).

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