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Electromagnetic Waves and Their Propagation: A Review of Fundamental Concepts

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***Abstract*—Electromagnetic (EM) waves are fundamental carriers of energy and information across diverse domains of science and technology. This review article provides a comprehensive overview of the fundamental concepts governing the generation, characteristics, and propagation of electromagnetic waves. Beginning with Maxwell's equations as the theoretical foundation, the paper explores the nature of EM wave formation, polarization, reflection, refraction, interference, diffraction, and attenuation phenomena. Various modes of propagation, such as ground wave, sky wave, and space wave, are discussed in relation to frequency, medium, and atmospheric conditions. The review also examines the role of dielectric and conductive materials in influencing wave transmission and absorption. Emphasis is placed on modern applications of EM wave theory in wireless communication, radar systems, remote sensing, and optical fiber technologies. By synthesizing classical principles with contemporary advancements, this article aims to bridge theoretical understanding with practical engineering relevance, offering valuable insights for researchers, educators, and professionals engaged in electromagnetic studies and related technological fields.**

Keywords—Electromagnetic waves, Maxwell's equations, Wave propagation, Wireless communication, Optical fiber, Electromagnetic theory.

Introduction

Electromagnetic waves are fundamental carriers of energy and information, representing the backbone of a vast number of scientific and engineering fields. Their properties are described by Maxwell's equations, which express how electric and magnetic fields interact in space to propagate energy. The study of the propagation of EM waves is essentially the study of different wave phenomena such as reflection, refraction, diffraction, and interference, which together explain the way waves interact with various media and surfaces [1]. Indeed, the Earth's natural electromagnetic environment affects wave propagation as well, adding variability in field strength and spectral characteristics relevant to both geophysical surveys and communication systems [2]. Advances in computational modeling have now allowed precise simulations of interactions of EM waves with complex scenarios through software such as gprMax, while finding applications in ground-penetrating radar and providing deeper insight into wave behavior in heterogeneous environments [3][4].

The absorption and manipulation of electromagnetic waves are now crucial in material science and device engineering. Metamaterials, carbon nanostructures, and metal-based composites belong to various classes of materials that have exhibited excellent wave-absorbing properties over broad frequency ranges [5][6]. For example, metamaterial absorbers enable active control of wave reflection and transmission by subwavelength structures engineered for this purpose [7], while carbon-based nanomaterials, including nanotubes and one-dimensional composites, offer tunable dielectric properties for wave attenuation at high frequencies [8][9]. Similarly, Fe-Co hollow fiber composites demonstrate an enhanced electromagnetic response because of their interesting geometries, thus allowing tailored absorption for a specific application [10]. Microplasmas and arrays of active elements were also investigated for dynamic control of EM waves, enabling adaptive response to time-varying incident conditions [11]. These material innovations are important not only for stealth and shielding applications but also for biomedical and industrial technologies, such as magnetic nanoparticle-mediated hyperthermia for cancer treatment [12].

Current areas of application of electromagnetic waves include wireless, sensing, and photonics, which involve the convergence between material science, electronics, and software-defined control. For instance, metasurfaces are programmed to modulate the wavefront of EM waves using software, thus enabling new methods of communication and very efficient polarization control devices [13][14]. Photonic topological insulators and all-dielectric three-dimensional structures exhibit robust waveguiding and immunity against backscattering, pointing to great potential in the manipulation of waves at both optical and microwave regimes [15]. Electromagnetic wave absorption and conversion technologies are also unceasingly evolving, standing up to the demands of ultrawideband performance, minimum losses, and being integrated onto compact system platforms. All these put together underpin the crucial role that theoretical understanding, materials, and applications play in bringing a comprehensive understanding toward the design of future technologies relevant to scientific, industrial, and medical applications. Figure 1 shows the general framework for EM waves and their properties in this review.

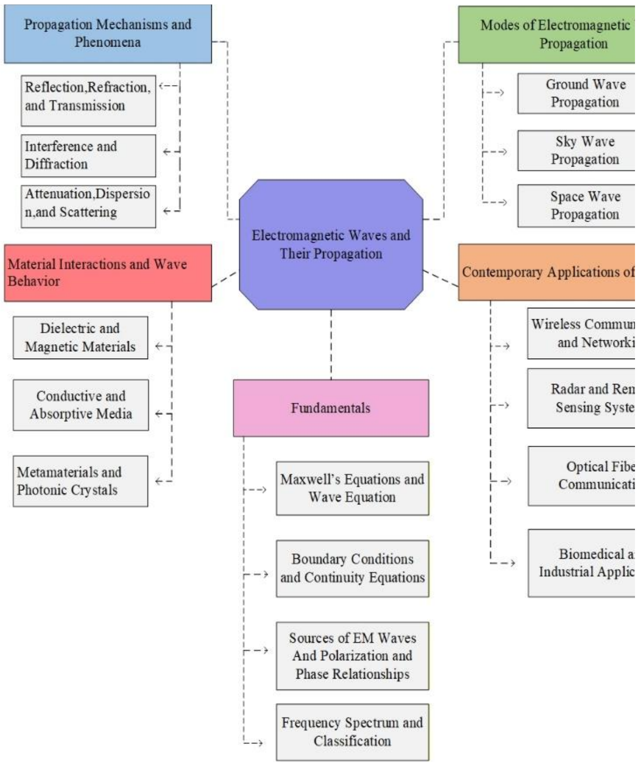

Figure 1. Framework for EM waves and their properties

Objectives of the Review

This review aims to unify and reinforce the theoretical bases of the EM wave propagation in Sections 2-5. It attempts to bring together classical ideas, like field equations, wave generation and propagation mechanisms, and a systematic discussion of reflection, refraction, interference, attenuation and other propagation modes. The goal makes the behavior of the EM energy in various media and environments coherent.

To combine classical theories of electromagnetism with their practical and material applications as provided in Sections 6 and 7. This involves the connection of concepts to real systems, the exploration of the effects of dielectric and magnetic properties and their applications to wireless communication, radar, optical fiber, and biomedical applications. It aims to show how theoretical electromagnetics and applied engineering design are continuous.

To define and point out new tendencies and directions of research in electromagnetics, as presented in Section 8. It is concerned with new paradigms, including quantum electromagnetics, terahertz communication, AI-based computational modeling, and sustainable EM design. This goal focuses on the shift of the field towards intelligent, energy-efficient, and high-performance electromagnetic systems.

2. Theoretical Framework of Electromagnetic Waves

Maxwell's Equations and Their Physical Interpretation

The equations of Maxwell form the basis of classical electromagnetism, explaining the production and interaction of electric and magnetic fields with charges and currents. They provide a theoretical framework for the propagation of electromagnetic waves in both vacuum and material media.

The Maxwell equations in vacuum explain the intrinsic properties of electric and magnetic fields without considering the properties of the material. The law of electricity by Gauss concerns the relationship between the electric flux and the net charge enclosed in a closed surface, and this has helped to understand how the stationary charges generate electric fields in space. The law of magnetism by Gauss proves that there are no magnetic monopoles, and it means that magnetic field lines are always closed and magnetic flux is conserved. The law of induction, as shown by Faraday, illustrates that when a magnetic field changes with time, it induces an electric field and forms the basis of electromagnetic induction effects and the basis of technologies like electric generators and transformers [16]. These equations can be written in either a differential form, which gives local, point-wise data on the variation of fields with space and time, or in an integral form, which gives information on the total flux or circulation across surfaces and closed paths, which is especially useful in solving practical engineering problems involving antennas, transmission lines and propagation of the free-space waves. All these forms together can represent the microscopic as well as the macroscopic view of the electromagnetic phenomena, and they provide the gap between theory and practice [17].

In cases where electromagnetic waves are traveling in material media, Maxwell's equations are changed to incorporate the influence of permittivity, permeability, and conductivity, which define the response of the medium to external fields. The polarization and magnetization of the material are explained by the introduction of the electric displacement vector D and the magnetic field intensity H, which allows us to study the propagation of waves in dielectrics, conductors and magnetic materials in detail [18]. Differential forms are still needed in such media to study local field distributions and interactions, and integral forms to give a global picture of quantities such as net flux, induced currents, and energy transfer. The study of these interactions can also be used to design more advanced devices like metamaterials, photonic crystals and high-frequency communication elements, where a fine control of wave propagation, reflection and transmission is possible by the precise control of permittivity and permeability [19].

The equations of Maxwell can therefore be used to give a complete description of the phenomena of electromagnetism in free space and in material media. Their differing and integrating forms provide a complementary theoretical analysis and practical application.

Wave Equation and Electromagnetic Field Components.

The wave equation is a mathematical model of the propagation of electromagnetic waves in space and material media, which connects time and spatial variations of electric and magnetic fields. It is directly based on the Maxwell equations and gives a basic insight into the nature of the transmission of energy and information by EM waves.

Beginning with Maxwell's equations in a homogeneous medium with no source, the electric field E and magnetic field B solve the standard wave equation as shown in Eq. (1)

$$\nabla^2 \mathrm{E} - \mu\epsilon \frac{\partial^2 \mathrm{E}}{\partial t^2} = 0, \nabla^2 \mathrm{B} - \mu\epsilon \frac{\partial^2 \mathrm{B}}{\partial t^2} = 0, \quad (1)$$

μ is the permeability and ε is the permittivity of the medium. These equations suggest that electric and magnetic fields travel as transverse waves, and E and B are perpendicular to one another and to the direction of propagation [20]. The two fields are also mutually dependent, in that a time-varying electric field produces a magnetic field and a changing magnetic field produces an electric field. This inherent coupling makes electromagnetic waves propagate through vacuum or media without the need to have a physical medium [21]. Knowledge of the relationships between E and B vectors are vital in the analysis of polarization, wave impedance and field orientation in antennas, transmission lines and optical fibers. The Poynting vector is defined as in Eq. (2)

$$\mathrm{S} = \mathrm{E} \times \mathrm{H}, \quad (2)$$

The power per unit area carried by an electromagnetic wave at any given moment, and the direction of the power flow, is denoted by the direction. The scale is the amount of energy passed per unit time, which connects the magnitudes of fields to real-world values of power in communication and radar systems [22]. In material media, the permittivity, permeability, and conductivity of the medium affect the transport of energy, which may weaken, absorb, or bend the wave. The Poynting vector is also a useful aid to the study of energy conservation and power distribution in complicated structures, such as waveguides, antennas and resonant cavities, and is thus an essential tool in both theoretical study and engineering design [23].

The Poynting vector and the wave equation can be used to both predict exactly the behavior of the waves in free space and in engineered media. These ideas give the basis of the explanation of the propagation of waves, the orientation of the field, and the transfer of energy.

Boundary Conditions and Continuity Equations

The electromagnetic fields at the interface between two different media have to meet certain boundary conditions to guarantee physically consistent behavior. These are the circumstances that dictate the way in which the electric and magnetic fields vary or stay continuous across the boundaries of the materials.

The boundary conditions are calculated as a direct consequence of the Maxwell equations and explain the behaviour of the components of the fields at interfaces. The tangential parts of the electric field E and magnetic field H are continuous across the interface, but the normal parts of the electric displacement D and magnetic flux density B may vary according to the existence of charges or currents at the interface. These conditions can be mathematically written as in Eq. (3)

$$\mathrm{E}_{1t} = \mathrm{E}_{2t}, \mathrm{H}_{1t} = \mathrm{H}_{2t}, \mathrm{D}_{1n} - \mathrm{D}_{2n} = \rho_s, \mathrm{B}_{1n} = \mathrm{B}_{2n}, \quad (3)$$

These relations define the partial reflection or transmission of incident waves on a change in material properties, including permittivity or permeability. Reflection and transmission coefficients, which are fundamental to the prediction of wave behaviour at interfaces in antennas, optical fibres, radar systems and layered dielectric structures, are also calculated using the boundary conditions [24].

In practice, the boundary conditions play a crucial role in the design of devices to control or manipulate the electromagnetic waves. In waveguides and transmission lines, as an example, proper matching at interfaces reduces energy loss and undesired reflections [25]. In optical systems, the angles of refraction and reflection are determined by the conditions, which allow the design of lenses, coatings and fibre optic systems. The correct implementation of these conditions can enable engineers and physicists to model and optimize the propagation of waves, energy distribution, and signal integrity in multi-layered and heterogeneous media [26].

Proper modeling of the electromagnetic wave interactions at interfaces is achieved by proper implementation of the boundary conditions. They connect the theoretical Maxwell equations to real-life applications in works in reflection, refraction, and transmission.

Generation and Characteristics of Electromagnetic Waves

Sources of EM Waves

The movement of electric charges and time-varying currents produces EM waves. These sources are important to understand in designing antennas and predicting the behavior of the waves in communication and sensing systems.

EM waves are generated by vibrating electric charges or alternating current distributions, which generate time-dependent electric and magnetic fields that travel through space [27]. The intensity, frequency and polarization of the radiated waves depend on the distribution and movement of charges. Theoretical analyses have been done on non-radiating sources and dynamic anapoles, in which some of the existing configurations can confine fields without radiating, indicating the significance of current geometry in regulating EM emission [28]. Techniques of estimating equivalent current distributions of modulated radiation sources offer viable information on the design of efficient wave-generating devices. The principles are essential in applications as small as sensors with low power, as well as massive communication transmitters.

Antennas are used to convert guided currents and free-space electromagnetic waves. Radiation patterns, efficiency and frequency response are regulated by the design of antennas: dipole, loop or more complicated arrays. Through appropriate design of the existing distributions along the antenna structure, engineers can maximise energy emission, directivity and bandwidth. Research on similar current estimation methods [29] also allows accurate radiation mechanisms modelling, and antennas to be designed to perform to the specifications of communication, radar, and sensing systems. Such methods combine both theoretical and practical concepts of the wave generation of conventional and modern electromagnetic applications.

The wave properties and propagation efficiency are determined by the charge motion and the design of the antennas, which determines the generation of electromagnetic waves. The ability to master these principles is the key to the creation of effective communication, sensing, and energy transmission systems.

Polarization and Phase Relationships.

The EM waves are characterized by polarization and phase characteristics that determine the orientation and temporal behavior of the waves. These properties are vital to control communication systems, imaging and advanced optical applications.

Depending on the relative orientation and relative phase of the components of the electric fields, electromagnetic waves may have linear, circular, or elliptical polarization. Ellipse-shaped metasurfaces have been designed as ultra-wideband polarization converters to convert linear polarization into circular polarization across a wide frequency spectrum to give greater flexibility in wave propagation and antenna design [30]. Pairs of orthogonal elliptically polarized base vectors are used as techniques to generate arbitrary vector fields, which allow the polarization orientation, beam shaping, and intensity distribution to be accurately controlled [31]. Polarization control is important in optical communication, remote sensing, and radar systems to reduce losses caused by the incompatibility of the wave orientation. In addition, higher polarization control enhances the performance of the system in imaging, optical manipulation and signal processing, enabling better target discrimination and higher resolution in complex electromagnetic fields. Figure 2 shows the types of polarization.

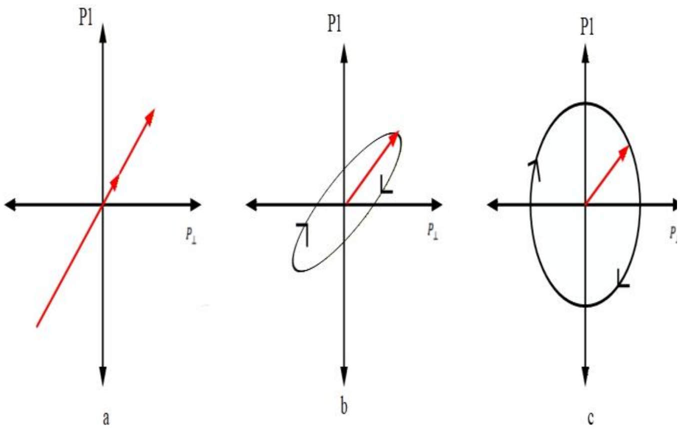

Figure 2. a, Linear b, Elliptical c, Circular

The coherence and phase stability are the keys to the ability to sustain the wave correlation in both time and space, which directly affect interference, signal quality, and system effectiveness. The optical coherence electromagnetic theory offers a basis on which the waves are predicted to behave when they interact and propagate in different media [32]. Phase-only spatial light modulators have been used to produce vector partially coherent optical sources, which allow the fine control of coherence properties to be used in imaging, beam shaping and optical communication systems [33]. Phase stability is required to maintain uniform signal behavior over long distances and over a wide range of environmental conditions, as is required in high-precision measurements, optical networks, and laser-based systems. Coherence control in combination with polarization management further increases the efficiency of wave-matter interaction, which is useful in a variety of advanced applications in classical and quantum optical technologies.

The important elements in the design of high-performance electromagnetic and optical systems are polarization and phase control. The control of such properties allows achieving a better quality of signals, efficient transmission of energy, and further manipulation of waves. Comparative analysis of major studies focusing on polarization and vector field generation is shown in Table 1.

TABLE I POLARIZATION AND VECTOR FIELD GENERATION TECHNIQUES AND APPLICATIONS

Focus	Technique	Applications	Reference
Asymmetric electromagnetic wave transmission	Polarization conversion using chiral metamaterial structures	Optical isolators, polarization filters, photonic devices	[30]
Generation and manipulation of vector beams	Orthogonally polarized base vectors, experimental beam shaping	Laser machining, optical trapping, quantum optics	[31]
Coherence and polarization analysis	Theoretical modeling & experimental measurement	Imaging systems, optical sensors, interferometry	[32]
Experimental control of vector fields	Phase-only spatial light modulators	Optical manipulation, microscopy, communications	[33]

Frequency spectrum and Classification

The electromagnetic waves have a wide spectrum of frequencies that range between the radio waves and the gamma rays. It is important to know the frequency spectrum to choose suitable wavebands when communicating, sensing and in industrial applications.

The electromagnetic spectrum is a continuous range of frequencies between very low frequencies of radio waves and very high frequencies of gamma rays [34]. Radio waves are commonly applied in communication, broadcasting and radar systems, whereas microwaves are applied in satellite communication, radar imaging and industrial heating. IR and visible light are used in remote sensing, imaging and optical communication, but ultraviolet, X-rays and gamma rays have applications in medical imaging, characterization of materials and high-energy physics investigations [35]. The nature and propagation of EM waves change drastically throughout the spectrum, and this influences their interaction with matter, depth of penetration and detection. The knowledge of these properties is important in the design of devices and systems that take advantage of the most appropriate frequency ranges when used in particular applications.

The frequency selection has a direct impact on the system performance, resolution and depth of penetration. As the case of frequency-dependent behavior modeling in energy storage and electronic systems, using hybrid optimization and fuzzy clustering techniques has been applied to understand the influence of wave properties on device performance [36]. Fast transients and impulsive transients may be simulated accurately in frequency-dependent time-domain line models, which is important in power systems, communication lines, and signal integrity analysis [37]. Frequency-dependent behavior predictability and control are necessary to design dependable networks, accurate sensors and fast communication channels. The frequency classification is also used to regulate compliance, interference control and effective spectrum allocation in crowded electromagnetic environments.

The electromagnetic spectrum offers a paradigm through which the behavior of waves is explained and suitable frequencies are chosen in the application of waves in various technologies. Effective classification and frequency analysis would guarantee a high performance in communication, sensing, and industrial systems.

Propagation Mechanisms and Phenomena

Reflection, Refraction, and Transmission

The interaction of electromagnetic waves with the surfaces of different media is characterized by reflection, refraction and transmission. These are basic phenomena in the study of wave propagation and optical and RF system design.

In some substances, including piezoelectric media, electrical and mechanical characteristics determine the reflection and refraction of waves. This creates complicated interactions at the interface, with the energy of the wave being able to divide into various modes based on the incident angle and polarization [38]. This is crucial in the design of sophisticated acoustic-electromagnetic devices whereby there is a need to have accurate control of the wave propagation and conversion.

The reflection and transmission may also take place at the temporal boundaries where the material properties vary abruptly with time rather than space. Here the wave may experience variations in frequency and amplitude as it traverses the time-varying region, just as it does change direction and speed as it crosses a spatial interface [39]. This principle is the basis of the construction of dynamic metamaterials and ultrafast optical modulators which control the light in space and time.

The refractive index controls the curvature of the waves entering a new medium, and impedance matching reduces reflections at interfaces and maximises the transmission of energy [40]. This is described by the Fresnel reflection coefficient of perpendicular polarization as in Eq. (4)

$$r_{\perp} = \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \tag{4}$$

Optical logic gates and broadband metamaterials methods are techniques based on precisely engineered impedance-matching layers to allow smooth propagation of waves [41]. Optical and acoustic systems use gradient index materials and specially designed impedance layers to improve transmission efficiency, minimize loses and improve the performance of devices. These parameters are important to understand to design high-performance antennas, optical components and energy-efficient communication systems.

The critical aspects of wave behavior at interfaces and system optimisation are dependent on reflection, refraction and transmission. Effective propagation of waves through various media can be achieved by proper use of Fresnel equations, Snell's law and impedance matching.

Interference and Diffraction

Interference and diffraction are basic phenomena which occur when electromagnetic waves interact and overlap. These effects play vital roles in optics, communication and imaging systems.

The principle of superposition is that the field at a point is the sum of the two or more fields of sources [42]. Interference happens when the coherent waves intersect and form constructive or destructive patterns based on the difference in the phases. The intensity distribution of two-beam interference is given as in Eq. (5)

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \tag{5}$$

$I_1 = I_2$intensities of individual waves and the phase difference. The use of enhanced interference visibility methods, which include multi-slit superposition methods, enables accurate imaging and spectroscopy through phase relationship and coherence property control [43]. The knowledge of interference is vital in optical metrology, holography and communication systems that depend on the coherence of the waves.

Diffraction refers to the curvature and dispersion of waves around objects and holes. The Huygens-Fresnel principle states that each point of a wavefront is a secondary source of spherical waves, and the field that results is the sum of the secondary waves [44]. This principle assists in modeling complicated wave propagation in imaging apparatus, ultrasonic assessment, and optical apparatus. Path integration methods permit simulations of diffraction patterns in multi-aperture and multi-obstacle systems at accuracy levels that enable the design of high-resolution optical instruments and non-destructive evaluation systems [45].

The behavior of waves in practical systems can be explained by interference and diffraction. The control of these phenomena allows one to accurately control the propagation of waves for imaging, sensing, and communication purposes. The key studies of interference and diffraction phenomena are summarized in Table 2.

TABLE II STUDIES ON INTERFERENCE AND DIFFRACTION ANALYSIS

Study Focus	Method	Observations	Reference
Superposition principle in interference experiments	Optical interference experiments	Interference visibility confirms linear superposition at the micro-scale	[42]
Multi-slit optical superposition for 2D Fourier spectroscopy	Multi-slit imaging setup	Enhanced interference-pattern visibility shows spatial resolution improvement	[43]
Path integration method for multiple diffraction simulation	Computational optical system modeling	Diffraction intensity patterns simulated; error is less when compared to experiments	[44]
Ultrasonic NDT modeling using Physical Theory of Diffraction (PTD)	Ultrasonic wave diffraction simulations	Diffraction efficiency, defect detection resolution.	[45]

Attenuation, Dispersion, and Scattering

Attenuation, dispersion and scattering are used to explain the decrease, spreading out and diversion of the electromagnetic waves as they travel through various media. These phenomena are important to understand to have reliable communication, sensing and material characterization.

Electromagnetic waves are also weakened as they travel through lossy materials, where the dielectric polarization and conductive currents change electromagnetic energy into heat. The amplitude of the wave attenuates exponentially with distance, and is given by the attenuation Eq. (6)

$$E(z) = E_0 e^{-\alpha z} \tag{6}$$

Where E_0 is the original field, alpha is the attenuation constant, and z is the propagation distance [46]. High-performance materials, including Koch fractal-structured composites and the magnetic composites, have been developed with the aim of optimizing absorption across broad frequency bands, enhancing electromagnetic shielding and microwave attenuation [47]. Knowledge of such absorption mechanisms can be used to design effective radar-absorbing materials, antennas with less signal loss and high-frequency components used in industry and communication. The attenuation rate and energy dissipation are directly proportional to material properties, such as permittivity, permeability, and conductivity; hence, they need to be carefully characterized to design a system.

Other than material absorption, electromagnetic waves are attenuated and scattered by the atmosphere and ionosphere. The lower ionosphere has self-absorption and alters the amplitude, phase and frequency content of the propagating signals, such as lightning and transmitter signals [48]. Unplanned couplings between atmosphere layers and ionosphere/magnetosphere cause scattering and dispersion, which may cause signal fading, multi-path interference or late arrival times [49]. These effects are especially important to long-range radio, satellite, and radar communications, where the ionospheric electron density and atmospheric conditions change both in time and space. Proper modeling of these interactions assists in the development of robust communication systems, enhancing the reliability of signals, and forecasting the behavior of high-frequency waves in space-weather-affected space.

The effective reach and fidelity of electromagnetic waves are controlled by attenuation, dispersion and scattering. The knowledge of these effects in both the materials and the atmospheric layers is critical in maximizing communication, sensing and protective applications.

Modes of Electromagnetic Wave Propagation

Ground Wave Propagation

The transmission of electromagnetic waves over the surface of the earth is referred to as ground wave propagation. These waves play an essential role in long-range low and medium-frequency communication in areas where line-of-sight is inadequate.

Surface waves or ground waves propagate along the Earth's curvature and are greatly influenced by the electrical conductivity, permittivity, and the roughness of the surface. The attenuation of a surface wave on a lossy Earth may be written as in Eq. (7):

$$E = E_0 \frac{e^{-\alpha r}}{r} \tag{7}$$

E_0 is the original field strength, 0 is the attenuation constant, which is a function of the conductivity of the earth, and r is the radius of distance between the source [50]. Propagation efficiency is also frequency-dependent and is limited not only by the conductivity of the ground but also by frequency, with lower frequencies attenuated less and having a larger range. The higher modeling methods, e.g., the finite-element parabolic equation methods, enable to simulation of the behavior of waves on the complicated terrain, i.e. hills, valleys, and different kinds of soil [51]. These simulations assist in estimating field strength, signal coverage and regions of possible interference. Ground wave propagation is especially applicable to AM radio broadcasting, maritime communications and military uses in which long-range coverage is required. With terrain information, engineers are able to design antennas and transmission systems to maximize energy delivery and minimise signal degradation by surface effects.

Knowing how to behave surface waves and how the conductivity of the earth affects them is crucial in improving ground-based communication systems. The precise modeling enables the engineers to reduce the losses and maximize the signal coverage in a variety of terrains.

Sky Wave Propagation

Sky wave propagation refers to the process of electromagnetic waves being reflected and refracted by the ionosphere so that the signals can be transmitted over a long distance beyond the line of sight. This is the mechanism that is necessary to make long-distance communication across continents.

Once the electromagnetic waves hit the ionosphere, they interact with the ionized layers and bend the waves back to the earth, thus forming a signal path that extends significantly beyond the horizon [52]. This propagation depends on the density and structure of the ionospheric layers that change with the solar activity, geomagnetic conditions, and diurnal cycles. The HF and lower VHF bands are especially well suited to sky wave transmission and are used in such applications as international broadcasting, long-range maritime and aeronautical communications, and emergency services [53]. The ionospheric conditions, such as sporadic E-layers, storms, and seasonal variations, may influence the signal strength, clarity and reliability, and real-time monitoring and adaptive frequency selection are of paramount importance. Further development of terahertz and high-frequency waves has investigated hybrid methods of atmospheric reflection and guided-wave methods to extend communication distances further [54]. This knowledge is used by engineers and communication planners to maximize transmission power, antenna angles and propagation paths to achieve maximum coverage and minimum interference.

Long-range radio communication is still conducted by the use of sky wave propagation. Understanding of the behavior of the ionosphere guarantees better and consistent global connectivity.

Space Wave Propagation

Space wave propagation is a term that is used to describe electromagnetic waves that move in a straight line between the transmitter and the receiver, which is normally applied in line-of-sight (LOS) communication. This mode forms the basis of satellite connections, microwave relays, and high-frequency terrestrial communications.

LOS transmission involves the direct transmission of the electromagnetic signal between the transmitting antenna and the receiver without using the reflections of the ionosphere. The accuracy of these signals is very dependent on the height, orientation and alignment of the antennas because even the slightest of obstructions may lead to a considerable attenuation or total blockout. Microwave and millimetre-wave links are especially susceptible to LOS interruptions, and it is important that network planning be done carefully. Predictive tools, which take into account terrain, building density, and atmospheric conditions, are being actively applied to optimize satellite networks, high-altitude platforms (HAPs), and terrestrial relay networks. This kind of planning provides coverage in a variety of settings, including the busy cities and less-populated rural areas where clearance of signal paths and terrain difference can be a major factor in determining the effectiveness of communication [55].

Additional effects of space wave propagation are tropospheric effects such as scattering, ducting, and atmospheric refraction [56]. As an illustration, high-frequency waves can be directed over oceans or coastal areas that create evaporation ducts that extend the communication range of the marine and coastal connections. On the same note, tropospheric ducts can be formed by temperature inversion and humidity gradient, which can support long-distance point-to-point microwave communication. These effects must be properly modeled to reduce fading, signal loss, and multiple path interference to achieve robust and stable connections. Engineers combine tropospheric forecasts with LOS planning to optimize the location of the antennas, frequency choice, and network redundancy, which is essential in satellite communications, radar networks, and the new high-speed wireless connections [57]. The combined knowledge allows the development of robust communication networks that can perform effectively in different environmental and atmospheric conditions.

High-frequency and satellite communications heavily rely on space wave propagation. The awareness of LOS conditions and tropospheric effects will guarantee a consistent and efficient signal delivery. Figure 3 shows the modes of EM waves Propagation.

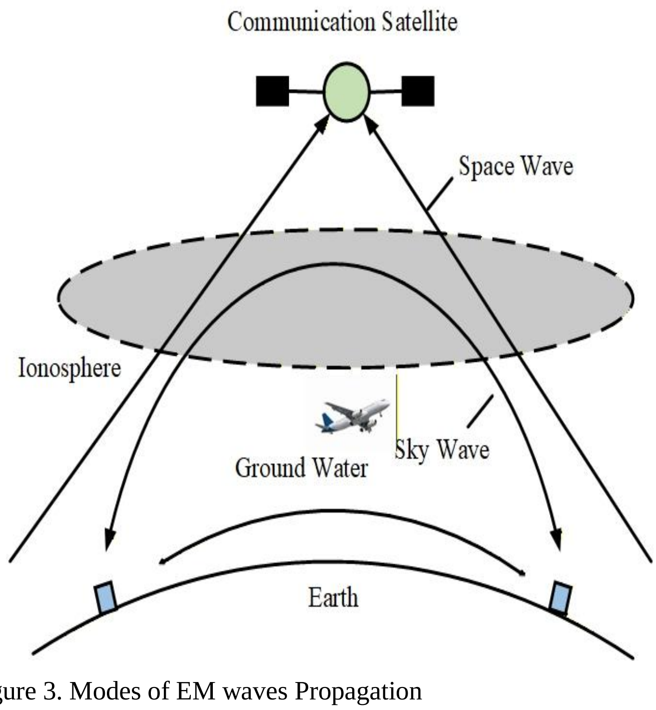

Figure 3. Modes of EM waves Propagation

Material Interactions and Wave Behavior

Dielectric and Magnetic Materials

Dielectric and magnetic materials are an important aspect that influences the behavior of electromagnetic waves. Their natural characteristics define the propagation, reflection, and absorption of waves in different media.

Dielectric permittivity is a measure of the capacity of a dielectric material to store electric energy in the presence of an electric field that directly affects the wave velocity and wavelength in the material. Highly permittivity materials may retard the wave propagation, and this introduces phase shifts which are essential in the design of capacitors, antennas and waveguides. The permeable magnetic materials also influence the magnetic part of the electromagnetic waves, changing the wave impedance and energy storage ability. The product of permittivity and permeability determines the refractive index, which determines the design of lenses, filters and metamaterials in more sophisticated electromagnetic applications [58]. Knowledge of these parameters enables engineers to design materials to suit desired wave manipulation, whether to improve signal transmission or to reduce unwanted reflections.

Another crucial aspect of the EM wave behavior is the loss tangent, which is the inherent dissipation of energy in a substance. Low-loss tangents are materials used in efficient transmission since they do not absorb energy and generate heat, whereas high-loss tangents are used in shielding, attenuation and absorption. The most recent nanocomposites include poly-lactide and graphene nanoplatelets, which are capable of tuning permittivity and loss, allowing the wave propagation and electromagnetic interference shielding to be finely controlled [59]. These dielectric and magnetic properties are important in the interaction of these properties in classical and modern applications, including RF circuits, microwave devices, wireless communication devices, and electromagnetic cloaking structures.

Dielectric and magnetic materials play a vital role in the propagation, storage and absorption of EM waves. Their properties are needed to design effective and controlled electromagnetic systems.

Conductive and Absorptive Media

Conductive and absorptive media play an important role in the electromagnetic wave propagation as they absorb the energy by dissipating it through resistive and inductive processes. The materials find extensive applications in shielding, absorption and measurement.

One of the parameters that defines the extent to which an electromagnetic wave can penetrate a conductive material is skin depth. In high conductivity, i.e., in metals, waves are trapped in a thin layer over the surface, which proves important in the design of cables, waveguides, and protective enclosures. This effect has a direct influence on the efficiency of signal transmission and energy loss because the deeper the penetration, the higher the absorption and heating. Induced by changing magnetic fields, Eddy currents cause local opposing fields, which in turn weaken the propagating wave. In non-destructive testing methods, engineers take advantage of such effects and measure material thickness, locate defects and determine conductivity, which will guarantee structural integrity in industrial components.

In power electronics, transformers, and induction heating, in particular, eddy current losses are of particular importance, as the undesirable energy loss should be kept to a minimum to achieve efficiency. The skin depth and the eddy current effects can be controlled by careful selection of materials, surface treatment, and optimization of frequencies by the designers. Conductivity in absorptive media can be used together with magnetic and dielectric losses to create materials that cut EM waves across a broad frequency range, and which are applicable in electromagnetic shielding, radar absorption, and stealth [60]. The sophisticated characterization methods allow an accurate adjustment of these properties to the needs of particular operations.

Wave attenuation, energy dissipation, and shielding effectiveness are critically determined by conductive and absorptive media. The knowledge of skin depth and eddy currents is necessary in designing effective EM systems.

Photonic Crystals and Metamaterials

Engineered structures Photonic crystals and metamaterials, are engineered structures that are designed to manipulate electromagnetic waves in a manner that is impossible with natural materials. Their customized characteristics allow them to have unprecedented control on the wave propagation, reflection and transmission.

Periodic structures of subwavelength structures, including split-ring resonators or coupled plasmonic elements, can be used to realize metamaterials with tunable permittivity and permeability [61]. These characteristics allow the flow of wave energy, velocity of phase, and impedance to be controlled, resulting in its use in antennas, sensors, and sophisticated telecommunication systems [62]. Photonic crystals utilize periodic dielectric arrays to form photonic band gaps, which forbid propagation of particular frequency bands, permitting extremely selective waveguiding, filtering, and light confinement [63]. The fine structure of such materials enables the engineers to act on the wave fronts, dispersion, and perform other functions like beam steering or wavelength-selective transmission that are essential in optical and microwave technologies [64].

Among the most remarkable characteristics of metamaterials is their capability to have a negative refractive index, a property that enables light or microwaves to bend in the opposite direction of what would have been expected. This application is the basis of electromagnetic cloaking applications, where the waves are guided around the object to make it virtually invisible, and in superlenses that overcome the diffraction limit in imaging. Combining metamaterials with photonic crystals gives the capability to be flexible in the management of electromagnetic wave propagation over a broad spectrum, spanning microwaves to optical frequencies, enabling novel cloaking devices, compact waveguides, and future communication elements.

Photonic crystals and metamaterials provide revolution capabilities in the control of EM waves. Their engineered structures allow applications in negative refractive index devices, cloaking and highly selective waveguides.

Contemporary Applications of EM Wave Theory

Wireless Networking and Communication

Wireless communication is based on EM waves, which are used to transmit data and signals without the use of physical conductors. Their actions define the effectiveness, dependability, and ability of communication systems.

With recent wireless technology, and with the advent of 5G and future 6G networks, millimetre-wave frequencies and sophisticated beamforming are making it possible to transmit data at an unprecedented speed, with low latency, and high levels of device interconnectivity. RF-MEMS (Radio Frequency Micro-Electro-Mechanical Systems) have been rediscovered because they are miniaturized, tunable, energy-efficient passive components, which are needed by compact, high-performance mobile and IoT devices. Although RF-MEMS have had some difficulties in large-scale use, they will become important to next-generation communication systems as reconfigurable filters, switches, and antennas will be essential in managing dynamic spectrums. Moreover, AI and adaptive signal processing integration boost the reliability of the network, whereas electromagnetic modeling guarantees the performance of the system in a complicated environment [65].

To conclude, wireless communication is still in its developmental phase as it is being developed by integrating electromagnetics, micro-systems, and intelligent computing, which will lead to scalable and sustainable connectivity around the world.

Radar and Remote Sensing Systems.

Radar and remote sensing systems play an important role in the detection, location, and tracking of objects and features of the environment with the help of electromagnetic waves. They use the bouncing and timing of the signals sent to them to retrieve spatial and movement data.

The main principle of radar is the transmission of electromagnetic or acoustic pulses, and the time required for the reflected signal to come back to the source. Embedded radar systems, like those created with Arduino and ultrasonic sensors, are cheap, real-time detection systems with short-range applications [66]. These systems are capable of determining the distance and motion of objects accurately by processing the pulse echo time, and this illustrates how the radar can be made accessible using microcontroller-based systems to educational, industrial and security purposes. Precision and reliability are guaranteed by signal processing methods and proper system calibration, even in small and low-powered systems. These methods underscore the need to combine both hardware and software in to detect the target in real-world situations.

Radar systems are also used for imaging surfaces and checking the weather conditions, in addition to basic detection. Arduino-based ultrasonic radar and other embedded systems can be used to map surface profiles and identify obstacles, and offer spatial information in a controlled environment. Such systems may be expanded to sense surface variations, structural variations or track moving objects. Microcontroller-based radar is modular and programmable, which makes it adaptable to adaptive sensing and quick prototyping and provides information on wave reflection, scattering, and signal interpretation. These embedded platforms represent a transition between the traditional radar concepts and the new low-cost and generalized sensing applications.

Radar and remote sensing technologies are still under development by incorporating embedded systems and microcontrollers. The developments increase both accessibility and accuracy as well as real-time monitoring in a broad spectrum of environmental and industrial applications.

Optical Fiber Communication.

Modern high-speed data transmission is based upon optical fiber communication, which depends on controlled transmission of light with minimum loss. Complete internal reflection and accurate wave direction enable effective and reliable transmission of information at long distances.

Optical fibers are made by directing light through a core that has a greater refractive index than the surrounding cladding, such that the core-cladding interface is totally reflected. Optical fibers have Bloch surface wave structures, which increase the light confinement and sensitivity in sensing applications [67]. It is also possible to exploit total internal reflection geometries to efficiently modulate terahertz light, which effectively controls the flow of waves and signal processing [68]. These plans show that engineered fiber interfaces and wave confinement methods can directly enhance the propagation efficiency, signal integrity, and device performance.

The attenuation in optical fibers is caused by absorption, scattering and bending losses. Antiresonant hollow fibers are used to minimize attenuation by minimizing interaction between light and the fiber material, and permit longer transmission distances with reduced power loss [69]. Photonic crystal coating and custom fiber geometries are further integrated to improve performance, including high-speed telecommunication, terahertz transmission, and environmental or biomedical sensing. These designs are necessary to ensure stable, low-loss signal propagation and high data rates and performance of the network.

Optical fiber communication is still developing with the development of high-level fiber engineering and waveguide optimization. Low-loss fibers, total internal reflection, and wave modulation methods are still essential in getting high-speed, reliable, and efficient communication systems. Figure 4 shows the application EM

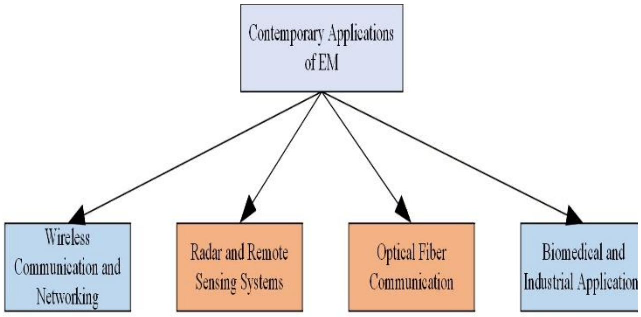

Figure 4. Applications of EM

Biomedical and Industrial Applications

EMs are very important in biomedical and industrial processes, as they allow imaging, treatment therapy, and characterization of materials. Their contact with biological tissues and manufactured materials enables non-invasive diagnostics and accurate energy delivery.

Microwave and magnetic fields are widely used in imaging and therapy, such as MRI and microwave ablation. Dielectric characterization of thermoplastics has played a critical role in the design of microwave diagnostic and therapeutic devices, where it is important to make sure that the energy is properly absorbed and that it is safe in clinical practice [70]. Microwave ablation by Coaxial slot applicators can be used to heat specific tissues, which may lead to minimally invasive therapies [71]. Also, modeling of electromagnetic interactions to aid in diagnostic imaging and treatment planning can be accurately done with characterization of breast cancer tissues over a broad frequency range [72]. These investigations indicate that tissue and material properties are important to optimize the imaging resolution, therapeutic efficacy, and patient safety.

Material characterization and environmental monitoring are also done by electromagnetic methods. Magnetic polymer nanocomposites are customizable dielectric and magnetic nanocomposites that are applicable in industrial sensing, biomedical devices and environmental applications [73]. Proper determination of the permittivity, permeability and the loss properties is used to design sensors, actuators and energy delivery systems. Material engineering coupled with the electromagnetic wave theory can be used to improve the functionality, sensitivity and efficiency of industrial and biomedical devices, which can help to introduce innovation in the healthcare and manufacturing industry.

The electromagnetic waves have been used in biomedical and industrial applications, which are ever-growing, providing better imaging, therapeutic and material analysis. The bright characterization and accurate control of the wave-matter interaction are the main factors to realize the reliable, efficient and safe applications. A summary of Electromagnetic Wave Applications in Biomedical and Industrial Systems is shown in Table 3.

TABLE III ELECTROMAGNETIC APPLICATIONS IN BIOMEDICAL STUDIES

Application	Material/Medium	Parameter Measured	Reference
Hyperthermia treatment	Magnetic nanoparticles	Temperature rise	[12]
Microwave diagnostic and therapeutic	PCL-based thermoplastic	Dielectric constant	[70]
Breast tissue characterization	Human breast tissues	Dielectric properties	[72]
biomedical nanocomposites	Magnetic polymer nanocomposites	EM absorption and shielding	[73]

New Trends and Future Projections

The study of the EM waves is still in its development phase, which is pushing the discoveries in both science and practice. The recent developments revolve around the use of advanced materials, high-frequency communication, sustainability and computational methods to address the increasing technological needs.

Recent developments in the field of plasmonics are creating tangible opportunities to quantum technologies, by allowing strong light-matter interactions at subwavelengths, improved control over spontaneous emission, and interfaces between photons and solid-state qubits that are small in size [74]. Articles on work that focus on the application of plasmonic architectures in quantum devices have pointed out both opportunities (field confinement, enhanced nonlinearity) and challenges (loss, fabrication tolerances) of integrating plasmonic elements into quantum information platforms. These points are additionally confirmed by the literature that uses quantum models to plasmonic photovoltaic effects, which highlights the necessity of quantum-conscious design techniques that reduce losses, but use nanoscale field enhancement [75].

The terahertz (THz) band is quickly emerging as a dual-use band at ultra-high capacity wireless links and sensitive spectroscopic instruments. Principles Surveys The applications of THz photonics have been proposed as facilitating short-range, high-data-rate wireless communications and have been identified as being useful in imaging and material characterization [76]. The sources and detector efficiency and atmospheric absorption are identified as challenges in complementary research, and hardware and propagation modeling innovation is the next-generation THz systems [77].

Electromagnetic compatibility (EMC) has become a crucial concern as more devices are packed in and as wireless devices coexist, and sustainability demands that materials and design are directed to be less harmful of the environment. The literature on biodegradable and biocompatible materials in the context of electronics in the green economy focuses on substituting non-recyclable and non-degradable components with recyclable or degradable ones, matching EMC with life cycle conscious design and less e-waste [78].

Recent applications of EM problems Multiscale geometries and wideband responses Modern EM problems encourage the combination of classical computational electromagnetism (CEM) solvers with AI-based optimization to accelerate analysis [79]. The foundation of AI-assisted modeling that enhances convergence and predictive accuracy is based on efficient model-reduction algorithms, including Krylov subspace methods, and advanced models of the process of learning. This synergy allows shorter and faster antenna design, metamaterials and THz component design over different operational conditions [80].

New developments in electromagnetics are broadening the basic knowledge and applications. The future of EM research and applications is being determined by quantum technologies, THz communication, sustainable materials, and AI-based computational methods.

Challenges and Research Gaps

Recent advancements in electromagnetic wave research have emphasized the design and characterization of novel materials and structures to enhance wave absorption, propagation, and control. Metamaterials and engineered composites have been extensively explored to tailor electromagnetic responses, enabling applications in broadband absorption, polarization conversion, and tunable dielectric behavior [5, 8, 31]. Despite significant progress, challenges persist in achieving perfect absorption across wide frequency ranges, maintaining structural stability under environmental variations, and ensuring reproducibility in fabrication. Fractal-based composites and carbon/SiC nanostructures have demonstrated promising broadband absorption properties; however, limitations in scalability and material uniformity continue to hinder large-scale deployment [46, 47]. Additionally, the accurate modeling of EM interactions with complex materials requires sophisticated computational tools, yet simulations often struggle to capture all real-world effects, such as multi-layer interference, surface roughness, and temperature-dependent behavior [79, 80].

Beyond material design, practical implementation in realistic environments introduces further constraints. For instance, trans horizon communication and terahertz wave propagation face challenges due to atmospheric attenuation, multipath effects, and line-of-sight variability [54, 55, 57]. Similarly, EMI shielding using polymer composites has shown potential, but its effectiveness is sensitive to frequency, filler distribution, and environmental factors [58]. Emerging quantum and plasmonic technologies offer novel opportunities for controlling EM waves at subwavelength scales, supporting high-frequency communication and sensing applications, yet practical integration into devices remains limited due to fabrication complexities and material losses [74, 76, 77]. Furthermore, biomedical applications relying on EM fields, such as microwave therapy or tissue characterization, confront challenges in material heterogeneity, precise targeting, and safety constraints [70, 72]. Collectively, these studies highlight that while material innovations and computational modeling have advanced the field, real-world applicability often faces limitations arising from environmental, structural, and operational factors, which necessitate ongoing research and optimization.

Conclusion

EM waves underpin modern science and technology, forming the gateway between fundamental theories and practical applications in communication, sensing, medical, and industrial fields. This review has revisited the general principles inferred from Maxwell's equations to describe wave generation, propagation, and interaction phenomena such as reflection, refraction, diffraction, and attenuation. It has further shown how properties of material media, such as dielectric, magnetic, and conductive properties, prescribe wave behavior while CENs, such as metamaterials and photonic crystals, grant abilities hitherto unseen by natural materials to engineer electromagnetic responses. From wireless networks and radar systems to optical fiber communication and biomedical imaging, the versatility of EM waves underpins contemporary innovation. New areas, such as terahertz communication, quantum electromagnetics, and AI-driven computational modeling, push the boundaries of electromagnetic research, promising ever-faster, wiser, and more sustainable technologies. Future electromagnetic science will be enabled by the continued interplay of theoretical principles, advanced materials, and intelligent system design.

References

[1] C. Watts, X. Liu, and W. J. Padilla, "Metamaterial electromagnetic wave absorbers," *Adv. Mater.*, vol. 24, no. 23, pp. OP98–OP120, 2012. https://doi.org/10.1002/adma.201200674

[2] C. Constable, "Earth's electromagnetic environment," *Surveys Geophys.*, vol. 37, no. 1, pp. 27–45, 2016. https://doi.org/10.1007/s10712-015-9351-1

[3] C. Warren, A. Giannopoulos, and I. Giannakis, "gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar," *Comput. Phys. Commun.*, vol. 209, pp. 163–170, 2016. https://doi.org/10.1016/j.cpc.2016.08.020

[4] Chen, K., Feng, Y., Yang, Z., Cui, L., Zhao, J., Zhu, B. and Jiang, T., 2016. Geometric phase coded metasurface: from polarization dependent directive electromagnetic wave scattering to diffusion-like scattering. Scientific reports, 6(1), p.35968. https://doi.org/10.1038/srep35968

[5] Y. Ra'di, C.R. Simovski, and S.A. Tretyakov, "Thin perfect absorbers for electromagnetic waves: theory, design, and realizations," *Phys. Rev. Appl.*, vol. 3, no. 3, p. 037001, 2015. https://doi.org/10.1103/PhysRevApplied.3.037001

[6] Sun, X., He, J., Li, G., Tang, J., Wang, T., Guo, Y. and Xue, H., 2013. Laminated magnetic graphene with enhanced electromagnetic wave absorption properties. *Journal of Materials Chemistry C*, *1*(4), pp.765-777. https://doi.org/10.1039/C2TC00159D

[7] Huang, C., Feng, Y., Zhao, J., Wang, Z. and Jiang, T., 2012. Asymmetric electromagnetic wave transmission of linear polarization via polarization conversion through chiral metamaterial structures. *Physical Review B—Condensed Matter and Materials Physics*, *85*(19), p.195131. https://doi.org/10.1103/PhysRevB.85.195131

[8] P. Wang, L. Cheng, and L. Zhang, "One-dimensional carbon/SiC nanocomposites with tunable dielectric and broadband electromagnetic wave absorption properties," *Carbon*, vol. 125, pp. 207–220, 2017. https://doi.org/10.1016/j.carbon.2017.09.052

[9] T. Zhao et al., "Electromagnetic wave absorbing properties of amorphous carbon nanotubes," *Sci. Rep.*, vol. 4, no. 1, p. 5619, 2014. https://doi.org/10.1038/srep05619

[10] S. Cho et al., "Electro-magnetic properties of composites with aligned Fe-Co hollow fibers," *AIP Adv.*, vol. 6, no. 5, 2016. https://doi.org/10.1063/1.4943925

[11] C. Qu, P. Tian, A. Semnani, and M.J. Kushner, "Properties of arrays of microplasmas: Application to control of electromagnetic waves," *Plasma Sources Sci. Technol.*, vol. 26, no. 10, p. 105006, 2017. https://doi.org/10.1088/1361-6595/aa8d53
[12] M. Bañobre-López, A. Teijeiro, and J. Rivas, "Magnetic nanoparticle-based hyperthermia for cancer treatment," *Rep. Pract. Oncol. Radiother.*, vol. 18, no. 6, pp. 397–400, 2013. https://doi.org/10.1016/j.rpor.2013.09.011
[13] C. Liaskos et al., "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Commun. Mag.*, vol. 56, no. 9, pp. 162–169, 2018. https://doi.org/10.1109/MCOM.2018.1700659
[14] X. Gao et al., "Ultrawideband and high-efficiency linear polarization converter based on double V-shaped metasurface," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3522–3530, 2015. DOI: 10.1109/TAP.2015.2434392
[15] A. Slobozhanyuk et al., "Three-dimensional all-dielectric photonic topological insulator," *Nat. Photonics*, vol. 11, no. 2, pp. 130–136, 2017. https://doi.org/10.1038/nphoton.2016.253
[16] Chang, D.C., 2017. Physical interpretation of Planck's constant based on the Maxwell theory. Chinese Physics B, 26(4), p.040301. https://doi.org/10.1088/1674-1056/26/4/040301
[17] Arthur, J.W., 2013. The evolution of Maxwell's equations from 1862 to the present day. IEEE Antennas and Propagation Magazine, 55(3), pp.61-81. https://doi.org/10.1109/MAP.2013.6586627
[18] Warnick, K., & Russer, P. H. (2014). Differential forms and electromagnetic field theory. *Progress In Electromagnetics Research*, *148*, 83-112.doi:10.2528/PIER14063009
[19] Peng, Z., Wang, X.C. and Lee, J.F., 2011. Integral equation based domain decomposition method for solving electromagnetic wave scattering from non-penetrable objects. *IEEE Transactions on Antennas and Propagation*, *59*(9), pp.3328-3338.**DOI:** 10.1109/TAP.2011.2161542
[20] Eibert, T.F., Kilic, E., Lopez, C., Mauermayer, R.A., Neitz, O. and Schnattinger, G., 2015. Electromagnetic field transformations for measurements and simulations. *Progress In Electromagnetics Research*, *151*, pp.127-150.doi:10.2528/PIER14121105
[21] Kletzing, C.A., Kurth, W.S., Acuna, M., MacDowall, R.J., Torbert, R.B., Averkamp, T., Bodet, D., Bounds, S.R., Chutter, M., Connerney, J. and Crawford, D., 2013. The electric and magnetic field instrument suite and integrated science (EMFISIS) on RBSP. *Space Science Reviews*, *179*(1), pp.127-181. https://doi.org/10.1007/s11214-013-9993-6
[22] Yoshida, T., Matsushita, M., Kubota, T. and Yoshikado, S., 2017. Analysis of power flow by poynting vectors for electromagnetic wave absorbers using frequency selective surfaces. Progress In Electromagnetics Research B, 78, pp.61-74. http://dx.doi.org/10.2528/PIERB17062401
[23] Moradi, A., 2017. Bohm potential and inequality of group and energy transport velocities of plasmonic waves on metal-insulator waveguides. *Physics of Plasmas*, *24*(7). https://doi.org/10.1063/1.4990079
[24] Lācis, U. and Bagheri, S., 2017. A framework for computing effective boundary conditions at the interface between free fluid and a porous medium. *Journal of Fluid Mechanics*, *812*, pp.866-889. https://doi.org/10.1017/jfm.2016.838
[25] Ahmadi, E., Cortez, R. and Fujioka, H., 2017. Boundary integral formulation for flows containing an interface between two porous media. *Journal of Fluid Mechanics*, *816*, pp.71-93. DOI: https://doi.org/10.1017/jfm.2017.42
[26] Costa, F., Borgese, M., Degiorgi, M. and Monorchio, A., 2017. Electromagnetic characterisation of materials by using transmission/reflection (T/R) devices. *Electronics*, *6*(4), p.95. https://doi.org/10.3390/electronics6040095
[27] Kottou, S., Nikolopoulos, D., Vogiannis, E., Koulougliotis, D., Petraki, E., & Yannakopoulos, P. H. (2014). How safe is the environmental electromagnetic radiation. *Journal of Physical Chemistry & Biophysics*, *4*(3), 1-10. http://dx.doi.org/10.4172/2161-0398.1000146
[28] Nemkov, N. A., Basharin, A. A., & Fedotov, V. A. (2017). Nonradiating sources, dynamic anapole, and Aharonov-Bohm effect. *Physical Review B*, *95*(16), 165134. https://doi.org/10.1103/PhysRevB.95.165134
[29] Nishina, B., & Chen, Q. (2016). Estimation of equivalent current distribution of modulated EM radiation source. *IEEE Transactions on Antennas and Propagation*, *64*(4), 1334-1341. **DOI:** 10.1109/TAP.2016.2526080
[30] Huang, C., Feng, Y., Zhao, J., Wang, Z. and Jiang, T., 2012. Asymmetric electromagnetic wave transmission of linear polarization via polarization conversion through chiral metamaterial structures. Physical Review B—Condensed Matter and Materials Physics, 85(19), p.195131. https://doi.org/10.1103/PhysRevB.85.195131
[31] Xu, D., Gu, B., Rui, G., Zhan, Q., & Cui, Y. (2016). Generation of arbitrary vector fields based on a pair of orthogonal elliptically polarized base vectors. *Optics Express*, *24*(4), 4177-4186.https://doi.org/10.1364/OE.24.004177
[32] Friberg, A. T., & Setälä, T. (2016). Electromagnetic theory of optical coherence. *Journal of the Optical Society of America A*, *33*(12), 2431-2442.https://doi.org/10.1364/JOSAA.33.002431
[33] Hyde IV, M. W., Bose-Pillai, S., Voelz, D. G., & Xiao, X. (2016). Generation of vector partially coherent optical sources using phase-only spatial light modulators. *Physical Review Applied*, *6*(6), 064030. https://doi.org/10.1103/PhysRevApplied.6.064030
[34] Ambroselli, M., Poulos, P. and Roychoudhuri, C., 2011. Nature of EM waves as observed and reported by detectors for radio, visible, and gamma frequencies. *The Nature of Light: What are Photons? IV*, *8121*, pp.466-474. https://doi.org/10.1117/12.894021
[35] Rani, B., Krichbaum, T.P., Fuhrmann, L., Böttcher, M., Lott, B., Aller, H.D., Aller, M.F., Angelakis, E., Bach, U., Bastieri, D. and Falcone, A.D., 2013. Radio to gamma-ray variability study of blazar S5 0716+ 714. *Astronomy & Astrophysics*, *552*, p.A11. https://doi.org/10.1051/0004-6361/201321058
[36] Kumar, M. R., Ghosh, S., & Das, S. (2016). Frequency dependent piecewise fractional-order modelling of ultracapacitors using hybrid optimization and fuzzy clustering. *Journal of Power Sources*, *335*, 98-104.https://doi.org/10.1016/j.jpowsour.2016.10.024
[37] Caballero, P. T., Costa, E. C. M., & Kurokawa, S. (2016). Frequency-dependent line model in the time domain for simulation of fast and impulsive transients. *International Journal of Electrical Power & Energy Systems*, *80*, 179-189.https://doi.org/10.1016/j.ijepes.2016.01.051
[38] Yuan, X. and Zhu, Z., 2012. Reflection and refraction of plane waves at interface between two piezoelectric media. Acta Mechanica, 223(12), pp.2509-2521. https://doi.org/10.1007/s00707-012-0728-7
[39] Xiao, Y., Maywar, D.N. and Agrawal, G.P., 2014. Reflection and transmission of electromagnetic waves at a temporal boundary. *Optics letters*, *39*(3), pp.574-577. https://doi.org/10.1364/OL.39.000574
[40] Tribelsky, M.I., Geffrin, J.M., Litman, A., Eyraud, C. and Moreno, F., 2015. Small dielectric spheres with high refractive index as new multifunctional elements for optical devices. Scientific reports, 5(1), p.12288. https://doi.org/10.1038/srep12288
[41] Ding, Y., Statharas, E.C., Yao, K. and Hong, M., 2017. A broadband acoustic metamaterial with impedance matching layer of gradient index. *Applied Physics Letters*, *110*(24). https://doi.org/10.1063/1.4986472
[42] Sinha, A., H. Vijay, A. and Sinha, U., 2015. On the superposition principle in interference experiments. *Scientific reports*, *5*(1), p.10304. https://doi.org/10.1038/srep10304
[43] Qi, W., Suzuki, Y., Sato, S., Fujiwara, M., Kawashima, N., Suzuki, S., ... & Ishimaru, I. (2015). Enhanced interference-pattern visibility using multislit optical superposition method for imaging-type two-dimensional Fourier spectroscopy. *Applied optics*, *54*(20), 6254-6259. https://doi.org/10.1364/AO.54.006254
[44] Mout, M., Wick, M., Bociort, F., Petschulat, J., & Urbach, P. (2016). Simulating multiple diffraction in imaging systems using a path integration method. *Applied optics*, *55*(14), 3847-3853. https://doi.org/10.1364/O.55.003847
[45] Darmon, M., Dorval, V., Djakou, A. K., Fradkin, L., & Chatillon, S. (2016). A system model for ultrasonic NDT based on the Physical Theory of Diffraction (PTD). *Ultrasonics*, *64*, 115-127. https://doi.org/10.1016/j.ultras.2015.08.006
[46] Xia, Shaoxu, Bin Yao, Qiping Chen, Xinhai Yu, and Qilin Wu. "Composites with Koch fractal activated carbon fiber felt screens for strong microwave absorption." *Composites Part B: Engineering* 105 (2016): 1-7. https://doi.org/10.1016/j.compositesb.2016.08.031
[47] Morchenko, A.T., 2014. Modeling the structure and conditions of the absorption of electromagnetic radiation in magnetic composites using effective medium approximations. *Bulletin of the Russian Academy of Sciences: Physics*, *78*(11), pp.1209-1217. https://doi.org/10.3103/S1062873814110203
[48] Marshall, R. A. (2014). Effect of self-absorption on attenuation of lightning and transmitter signals in the lower ionosphere. *Journal of Geophysical Research: Space Physics*, *119*(5), 4062-4076. **https://doi.org/10.1002/2014JA019921**

[49] Pilipenko, V.A., 2012. Impulsive coupling between the atmosphere and ionosphere/magnetosphere. *Space science reviews*, *168*(1), pp.533-550. https://doi.org/10.1007/s11214-011-9859-8

[50] terrain. *IEEE Transactions on antennas and propagation*, *59*(4), pp.1254-1260.D**OI:** 10.1109/TAP.2011.2109693

[51] Apaydin, G., Ozgun, O., Kuzuoglu, M. and Sevgi, L., 2011. A novel two-way finite-element parabolic equation groundwave propagation tool: Tests with canonical structures and calibration. *IEEE transactions on geoscience and remote sensing*, *49*(8), pp.2887-2899.**DOI:** 10.1109/TGRS.2011.2114889

[52] Carvalho, F.L., Uman, M.A., Jordan, D.M., Hill, J.D., Cummer, S.A., Kotovsky, D.A. and Moore, R.C., 2017. Triggered lightning sky waves, return stroke modeling, and ionosphere effective height. *Journal of Geophysical Research: Atmospheres*, *122*(6), pp.3507-3527. https://doi.org/10.1002/2016JD026202

[53] Somu, V.B., Rakov, V.A., Haddad, M.A. and Cummer, S.A., 2015. A study of changes in apparent ionospheric reflection height within individual lightning flashes. Journal of Atmospheric and Solar-Terrestrial Physics, 136, pp.66-79. https://doi.org/10.1016/j.jastp.2015.09.007

[54] Islam, M.S., Sultana, J., Rana, S., Islam, M.R., Faisal, M., Kaijage, S.F. and Abbott, D., 2017. Extremely low material loss and dispersion flattened TOPAS based circular porous fiber for long distance terahertz wave transmission. *Optical Fiber Technology*, *34*, pp.6-11. https://doi.org/10.1016/j.yofte.2016.11.014

[55] Aydın, V., Çavdar, İ.H. and Hasırcı, Z., 2016. Line of sight (los) probability prediction for satellite and haps communication in trabzon, turkey. *International Journal of Applied Mathematics Electronics and Computers*, (Special Issue-1), pp.155-160. https://doi.org/10.18100/ijamec.269190

[56] Akpootu, D.O. and Iliyasu, M.I., 2017. Estimation of tropospheric radio refractivity and its variation with meteorological parameters over Ikeja, Nigeria. *Journal of Geography, environment and Earth science International*, *10*(1), pp.1-12. https://doi.org/10.9734/JGEESI/2017/32534

[57] Dinc, E. and Akan, O.B., 2014. Beyond-line-of-sight communications with ducting layer. IEEE Communications Magazine, 52(10), pp.37-43.

[58] Kashi, S., Gupta, R.K., Baum, T., Kao, N. and Bhattacharya, S.N., 2016. Morphology, electromagnetic properties and electromagnetic interference shielding performance of poly lactide/graphene nanoplatelet nanocomposites. *Materials & Design*, *95*, pp.119-126. https://doi.org/10.1016/j.matdes.2016.01.086

[59] Baker-Jarvis, J. and Kim, S., 2012. The interaction of radio-frequency fields with dielectric materials at macroscopic to mesoscopic scales. *Journal of research of the National Institute of Standards and Technology*, *117*, p.1. https://doi.org/10.6028/jres.117.001

[60] Tang, A.Y. and Stake, J., 2011. Impact of eddy currents and crowding effects on high-frequency losses in planar Schottky diodes. IEEE Transactions on Electron Devices, 58(10), pp.3260-3269.

[61] Kourtzanidis, K., Pederson, D.M. and Raja, L.L., 2016. Electromagnetic wave energy flow control with a tunable and reconfigurable coupled plasma split-ring resonator metamaterial: A study of basic conditions and configurations. *Journal of Applied Physics*, *119*(20). https://doi.org/10.1063/1.4952575

[62] Iwanaga, M., 2012. Photonic metamaterials: a new class of materials for manipulating light waves. *Science and Technology of Advanced Materials*, *13*(5), p.053002. https://doi.org/10.1088/1468-6996/13/5/053002

[63] Islam, S.S., Faruque, M.R.I. and Islam, M.T., 2015. A near zero refractive index metamaterial for electromagnetic invisibility cloaking operation. *Materials*, *8*(8), pp.4790-4804. https://doi.org/10.3390/ma8084790

[64] Liu, R., Zhao, Z., Ji, C. and Zhou, T., 2016. Metamaterials beyond negative refractive index: Applications in telecommunication and sensing. *Science China Technological Sciences*, *59*(7), pp.1007-1011. https://doi.org/10.1007/s11431-016-6066-6

[65] Iannacci, J., 2015. RF-MEMS: an enabling technology for modern wireless systems bearing a market potential still not fully displayed. *Microsystem Technologies*, *21*(10), pp.2039-2052. https://doi.org/10.1007/s00542-015-2665-6

[66] Onoja, A.E., Oluwadamilola, A.M. and Ajao, L.A., 2017. Embedded system based radio detection and ranging (RADAR) system using Arduino and ultra-sonic sensor. *American Journal of Embedded Systems and Applications*, *5*(1), pp.7-12. https://doi:10.11648/j.ajesa.20170501.12

[67] Tan, X.J. and Zhu, X.S., 2016. Optical fiber sensor based on Bloch surface wave in photonic crystals. *Optics Express*, *24*(14), pp.16016-16026. https://doi.org/10.1364/OE.24.016016

[68] Liu, X., Parrott, E.P., Ung, B.S.Y. and Pickwell-MacPherson, E., 2016. Exploiting total internal reflection geometry for efficient optical modulation of terahertz light. *APL Photonics*, *1*(7). https://doi.org/10.1063/1.4963141

[69] Belardi, W. and Knight, J.C., 2014. Hollow antiresonant fibers with reduced attenuation. *Optics letters*, *39*(7), pp.1853-1856. https://doi.org/10.1364/OL.39.001853

[70] Aguilar, S.M., Shea, J.D., Al-Joumayly, M.A., Van Veen, B.D., Behdad, N. and Hagness, S.C., 2011. Dielectric characterization of PCL-based thermoplastic materials for microwave diagnostic and therapeutic applications. *IEEE transactions on biomedical engineering*, *59*(3), pp.627-633. **DOI:** 10.1109/TBME.2011.2157918

[71] Haynes, M., Stang, J. and Moghaddam, M., 2014. Real-time microwave imaging of differential temperature for thermal therapy monitoring. IEEE Transactions on Biomedical Engineering, 61(6), pp.1787-1797.

[72] Martellosio, A., Pasian, M., Bozzi, M., Perregrini, L., Mazzanti, A., Svelto, F., Summers, P.E., Renne, G., Preda, L. and Bellomi, M., 2016. Dielectric properties characterization from 0.5 to 50 GHz of breast cancer tissues. *IEEE Transactions on Microwave Theory and Techniques*, *65*(3), pp.998-1011. **DOI:** 10.1109/TMTT.2016.2631162

[73] Kalia, S., Kango, S., Kumar, A., Haldorai, Y., Kumari, B. and Kumar, R., 2014. Magnetic polymer nanocomposites for environmental and biomedical applications. *Colloid and Polymer Science*, *292*(9), pp.2025-2052. https://doi.org/10.1007/s00396-014-3357-y

[74] Bozhevolnyi, S.I. and Mortensen, N.A., 2017. Plasmonics for emerging quantum technologies. *Nanophotonics*, *6*(5), pp.1185-1188. https://doi.org/10.1515/nanoph-2016-0179

[75] Kluczyk, K., David, C. and Jacak, W.A., 2017. On quantum approach to modeling of plasmon photovoltaic effect. *Journal of the Optical Society of America B*, *34*(10), pp.2115-2127. https://doi.org/10.1364/JOSAB.34.002115

[76] Seeds, A.J., Shams, H., Fice, M.J. and Renaud, C.C., 2014. Terahertz photonics for wireless communications. *Journal of Lightwave Technology*, *33*(3), pp.579-587.

[77] Akyildiz, I.F., Jornet, J.M. and Han, C., 2014. Terahertz band: Next frontier for wireless communications. *Physical communication*, *12*, pp.16-32. https://doi.org/10.1016/j.phycom.2014.01.006

[78] Irimia-Vladu, M., 2014. "Green" electronics: biodegradable and biocompatible materials and devices for sustainable future. *Chemical Society Reviews*, *43*(2), pp.588-610. https://doi.org/10.1039/C3CS60235D

[79] Bonotto, M., Cenedese, A. and Bettini, P., 2017. Krylov subspace methods for model order reduction in computational electromagnetics. *IFAC-PapersOnLine*, *50*(1), pp.6355-6360. https://doi.org/10.1016/j.ifacol.2017.08.1019

[80] Qian, J.W., Zhang, H.L. and Xia, M.Y., 2017. Modelling of Electromagnetic Scattering by a Hypersonic Cone-Like Body in Near Space. *International journal of antennas and propagation*, *2017*(1), p.3049532. https://doi.org/10.1155/2017/3049532