Dean&Francis
ISSN 2959-6157

New Progress And Future Challenges In Basic Theory Of Electromagnetic Waves

Weiwei Yin

Suzhou High School of Jiangsu Province, Suzhou, Jiangsu, China
flybull2024@qq.com

Abstract:
Electromagnetic wave theory is the core part of modern science and technology, and these theories have made remarkable breakthroughs in recent years, driven by new materials, quantum technology, and artificial intelligence (AI). Unique electromagnetic properties are provided by new materials like topological insulators for applications; quantum technology expands the boundary of information processing; and artificial intelligence optimizes the design and analysis of electromagnetic systems. On the theoretical side, non-local theories, topological effects, and extreme condition models have become popular among researchers, providing a theoretical basis for the design of new electromagnetic equipment. However, the development of electromagnetic theories still faces many challenges, including the unification of quantum and classical theories, experimental substantiation under extreme conditions, and the computational complexity of multi-scale problems. In the future, interdisciplinary cooperation will be a crucial part of solving these core difficulties, and the combination of AI and electromagnetic theories is expected to drive the further development of electromagnetic technology and provide more efficient and safer solutions for 6G communication, quantum computing, and energy transmission.

Keywords: Electromagnetic wave, artificial intelligence, quantum key distribution.

1. Introduction

Maxwell‘s equations reveal the nature of electricity and magnetism, and they are important equations in electromagnetism [1]. Maxwell‘s system of equations was established in the framework of classical physics, and it has limitations in some extreme cases. For example, at the quantum scale, Maxwell‘s system of equations cannot accurately describe the electromagnetic interactions of microscopic particles, and the theory of quantum electrodynamics needs to be introduced. In addition, under strong field conditions, some assumptions of Maxwell‘s system of equations may no longer hold, such as the constitutive relationship. Constitutive relationship can be explained in three dimensions:

ISSN 2959-6157

Linearity: The traditional constitutive relations assume that the polarization strength of a medium is linearly related to the electric field strength, and the magnetization strength is linearly related to the magnetic field strength. For example, in some simple linear media, the polarization strength P is related to the electric field strength E as $P = \varepsilon_0 \chi E$, where ε_0 is the vacuum dielectric constant and χ is the electric susceptibility.

Local: The traditional constitutive relations consider the polarization and magnetization of a dielectric to be related only to the local electric and magnetic fields and do not take into account non-local effects. For example, in a homogeneous linear medium, the polarization strength at a point depends only on the electric field strength at that point and is not affected by the surrounding electric field.

Isotropic: The traditional constitutive relations assume that the electromagnetic properties of the medium are the same in all directions. For example, for an isotropic linear medium, the permittivity and permeability are the same in all directions. However, in practice, some materials may have anisotropic electromagnetic properties, such as crystalline materials, whose electromagnetic properties may vary depending on the direction.

On the contrary, several driving factors foster the development of electromagnetic waves, aiming to achieve interdisciplinary integration. First, the new materials contribute a lot toward the research for this field, such as the NiO-TiC composite materials, Graded Seismic Metamaterials with Structural Steel Sections, Membrane sound absorber with a granular activated carbon infill, ultra-wideband microwave metamaterial absorber, Conjugate impedance matched metamaterials, and so on [2-6]. Second, as technology has progressed, there has been an increase in the prevalence of information-based products, which has led to an increase in the volume of data that needs to be encrypted for transmission. Secure key distribution is especially important in large-scale communication scenarios [7]. Quantum Key Distribution (QKD) is one of the applications to decrease the risk and ensure security during communication.

The purpose of this article is to make progress in the basic theory of the supporting system and analyze the core difficulties that remain unsolved. Both difficulties and classical theories will be mentioned later, and this passage will also provide some potential development within wireless communication, which is based on electromagnetic waves.

2. Deepening and Expanding Classical Theories

2.1 Theory of Non-local and Nonuniform Media

The theory of non-local and nonuniform medium is an expansion of the traditional medium theory, which considers the non-locality and nonuniformity of the medium. Non-locality means that the electromagnetic response of the medium not only depends on the local electromagnetic field but also relates to the surrounding electromagnetic field; non-uniformity means that the electromagnetic parameters of the medium are spatially variable. One of the most recognized principles of classical (local) continuum mechanics is the influence of the strain field of distant elements on the reference element. The influence of these distant effects on the nonlocal elasticity theory is known as nonlocal effects.

2.1.1 Spacial dispersion model

Spatial Dispersion refers to the fact that the electromagnetic response of a medium. For example, the dielectric tensor $\epsilon(\omega,k)$ depends not only on the frequency of the electromagnetic wave ω but also on its wave vector k. This phenomenon indicates that the polarization or magnetization of a medium is not only determined by the local electric or magnetic field but is also affected by spatial variations (also called field gradients) in the surrounding electromagnetic field.

Mathematically, the dielectric tensor can be expressed as:

$$D(\omega,k) = \epsilon(\omega,k) E(\omega,k) \quad (1)$$

Where $\epsilon(\omega,k)$ is the complex function tensor of frequency and wave vector

2.1.2 The law of conservation of energy in time-varying media

Time-varying medium is a medium in which the electromagnetic parameters of the medium vary with time. In a time-varying medium, the law of conservation of energy of electromagnetic waves is different from that of a static medium, and it is necessary to consider the effect of the time variation of the medium's parameters on the electromagnetic wave energy.

2.2 Nonlinear Electromagnetic Theory

Nonlinear electromagnetic theory studies the physical phenomenon that under the action of a strong electromagnetic field, the electromagnetic response of the medium no longer satisfies the linear relationship. In this case, the medium's polarization strength, magnetization strength, etc. and the relationship between the electric field and magnetic field is nonlinear, and this will produce high harmonics, self-focusing, self-phase modulation and other nonlinear effects. For example, in laser-matter interaction, when the laser intensity is high enough, the electromagnetic response of the matter will show obvious nonlinearity. For example, when a high-power laser beam passes through a nonlinear crystal, a frequency-doubling effect occurs. The frequency doubling effect refers to the fact that a nonlinear medium doubles the frequency of the incident laser under the action of an intense laser, producing a new frequency component. For example, with potassium dihydrogen phosphate (KDP) crystals, it is possible to double the frequency of a 1064 nm laser to 532 nm, resulting in a green light output. This nonlinear effect has a wide range of applications in laser technology, optical communications, and other fields.

2.2.1 Quantum electrodynamic effect under a strong field

Quantum electrodynamics (QED) is a quantum theory that describes the interaction of light with matter. Under strong field conditions, quantum electrodynamic effects become more significant. Strong-field QED effects include vacuum polarization, photon splitting, and the creation of electron-positron pairs. For example, in high-energy physics experiments, photon splitting occurs when an electron beam interacts with a strong laser field. Photon splitting refers to the action of a strong electromagnetic field, a high-energy photon can be split into multiple low-energy photons. For example, in a free electron laser (FEL), an electron beam emits high-brightness coherent light under the combined action of a strong magnetic field and a laser field. In this process, the strong-field QED effect leads to the splitting and re-radiation of photons, thus affecting the output characteristics and efficiency of the laser.

2.2.2 Nonlinear effects in topological photonics

Topological photonics combines topological theory and photonics to study the transport properties of light in topological structures. In topological photonics, nonlinear effects refer to the nonlinear interactions, such as the Kerr effect, excited Raman scattering, etc., that occur when light propagates in a topological structure due to sufficiently high light intensity. For example, in topological photonic crystals, when the light intensity is high enough, nonlinear effects cause the propagation path of light to change. For example, topology-preserving transmission of light can be realized using nonlinear effects. Suppose that in a topological photonic crystal waveguide, light is stably transmitted along a topological edge state when the input light intensity is low. When the light intensity increases to a certain level, nonlinear effects cause the refractive index of the light to change, resulting in a small shift in the propagation path of the light, but this shift remains within the topologically protected range and does not cause significant loss or scattering of the light.

2.3 Wave Mechanics in Complex Boundaries and Structures

Wave Dynamics in Complex Boundaries and Structures studies the propagation and scattering properties of electromagnetic waves in media with complex geometries and boundary conditions. Such studies are important for understanding and designing high-performance electromagnetic devices.

2.3.1 The theory of multiple scattering in random media

A random medium is one in which the electromagnetic parameters of the medium are randomly distributed in space. In a random medium, electromagnetic waves are scattered many times, resulting in changes in their propagation direction and intensity. Multiple scattering theory studies the propagation characteristics of electromagnetic waves in random media, including scattering intensity, propagation distance, and so on. For example, in atmospheric propagation, aerosols, water droplets and other particles in the atmosphere will cause electromagnetic waves to be scattered many times. For example, radar signals propagating in the atmosphere are affected by randomly distributed particles in the atmosphere. Through the theory of multiple scattering, the attenuation and scattering characteristics of radar signals can be predicted, thus improving the detection accuracy and reliability of radar. In practical applications, meteorological radars use the multiple scattering theory to analyze precipitation distribution and meteorological conditions in the atmosphere.

3. Theoretical Innovation In Frontier Interdisciplinary Fields

3.1 Quantum-classical Boundary Theory and Topological Electromagnetic Theory

Topological electromagnetic theory combines topology and electromagnetism to study the phenomenon of topological protection in electromagnetic systems. Topologically protected electromagnetic states are robust and maintain stable transmission characteristics even in the presence of defects or impurities.

Quantum-classical boundary theory studies transitions and interactions between quantum and classical systems. Below are some potential frontier fields the quantum-classical boundary theory can be used to achieve breakthrough.

3.1.1 Topological quantized response

In the field of topological physics, breakthroughs have also been made in the exploration of quantum-classical boundaries. In a study published in Nature Communications, Associate Professor Linhu Li and co-workers discovered a novel quantized steady-state response phenomenon based on the winding number of the non-Hermitian energy spectrum. This phenomenon shows that topologi-

ISSN 2959-6157

cal quantized responses can also be observed in classical systems, breaking through the traditional conception that classical systems cannot be described by linear response theory. This finding provides a new perspective for the study of quantum-classical boundaries, especially in classical systems such as photonic crystals and acoustic and circuit lattices, where topological properties can be manifested by topologically protected boundary eigenmodes.

3.1.2 Coupling of quantum mechanics with classical mechanics

At the microscopic scale, the phenomenon of coupling quantum effects with macroscopic mechanics has also attracted widespread attention. For example, Superconductivity is a macroscopic quantum phenomenon exhibited by certain materials at low temperatures, characterized by zero electrical resistance, complete antimagnetism (Meissner effect), and flux quantization. These phenomena cannot be explained by classical electromagnetic theory, but rather stem from the collective behavior of quantum mechanics on macroscopic scales, in particular the formation of Cooper pairs and long-range quantum coherence.

3.1.3 Topological insulator

Topological insulator materials have emerged as promising for photonic devices due to their unique properties, including robust edge states that demonstrate resistance to defects and disorder, making them ideal for reliable energy transport in photonic systems [8].

Due to their unique spin-polarized surface states and robust electronic properties, topological insulators are extremely versatile and are expected to be used in quantum information processing [9]. For example, 3D topological insulators are insulators in their bulk form but conduct electricity. With this characteristic, it can be used as an innovative alternative for γ-ray shielding [10].

3.2 The Transformation Empowered by Artificial Intelligence (AI)

Nowadays AI deeply influences our daily life. Ranging from study and daily life to technological research, AI becomes smarter and smarter, and they have the ability to do critical thinking. For example, they can deeply learn and solve Maxwell's equations. In addition, they can create multi-dimension models according to the requirements we insert.

3.2.1 Deep learning to solve Maxwell's system of equations

Deep learning techniques can be used to solve complex systems of Maxwell's equations, especially in cases that are difficult to handle by traditional numerical methods. By training neural networks, the distribution of electromagnetic fields and the propagation characteristics of electromagnetic waves can be predicted quickly and accurately.

3.2.2 Generative Models and Optimization theories in Reverse Design

Reverse design is the process of starting from desired electromagnetic properties and reverse designing electromagnetic structures that satisfy those properties. Generative modeling and optimization theory play a key role in reverse design, where candidate structures can be generated through generative modeling, and these structures can be optimized to achieve the best performance through optimization theory.

3.2.3 Quantum Computing in AI

Quantum Machine Learning: The combination of quantum computing and artificial intelligence is one of the hotspots of current research. By utilizing the parallel processing capability of quantum computing to accelerate the training of machine learning algorithms, quantum machine learning algorithms are expected to accelerate data processing and model training. In the future, quantum machine learning is expected to play an important role in big data processing and complex model training, promoting the development of artificial intelligence.

4. Crucial Difficulties

4.1 Difficulty Of Theoretical Unity

4.1.1 The contradiction in the interface between classical theories and quantum descriptions

The contradiction in the interface between classical theories (e.g., Newtonian mechanics, Maxwell's electromagnetic theory) and quantum descriptions (e.g., quantum mechanics, quantum field theory) is mainly reflected in the following aspects:

1. Microscopic and macroscopic inconsistency: classical theories apply to the macroscopic scale, while quantum theories apply to the microscopic scale. However, under certain extreme conditions like the black holes and the Big Bang, the predictions of classical and quantum theories can differ significantly.
2. Conflict between quantum non-definiteness and definite-domain positivism: the phenomenon of quantum entanglement exhibits non-definite-domain correlations, i.e., measurements of one particle far apart instantly affect the state of the other particle (although no information can be actively transmitted). This is in fundamental conflict with the classical notion of causality based on fixed-domain positivism (Einstein's fixed-domain nature) and has been

confirmed by the Bell inequality experiment." Emphasizing that the conflict centers on "fixed-domain positivism" rather than „information superluminalism.

3. Difficulties in quantizing gravity: quantum field theory successfully describes the electromagnetic, weak, and strong forces, but the quantization of gravity has been unsuccessful. The quantum theory of gravity has a mathematical divergence problem that cannot be eliminated by reorganization.

4.1.2 Lack of coupling between relativistic electromagnetic fields and gravitational theory

The lack of coupling between relativistic electromagnetic fields, which is described by special relativity, and Maxwell's equations and gravitational theory, which is described by general relativity, is mainly reflected in the aspects below:

1. Incompatibility between quantum field theory and general relativity: quantum field theory is based on a flat spacetime background, while general relativity describes a dynamic curved spacetime. Mathematical inconsistencies arise when combining the two.

2. Quantization of Gravity Problem: The existence of gravitons (the quantum carriers of gravity) has not been experimentally confirmed, and quantization of gravity in the framework of quantum field theory leads to infinite divergence.

3. Black hole information loss paradox: Hawking discovered that black hole evaporation leads to information loss, which contradicts the information conservation principle of quantum mechanics.

4.2 Computational And Verification Difficulties

Computational Complexity of Multi-scale Problems (Nano-Macro Coupling): How to bridge Microscopic and Macroscopic Models; the connection between microscopic such as molecular dynamics and macroscopic such as mechanics of continuum media models is a critical issue; microscopic models are usually based on physical laws at the atomic or molecular level, while macroscopic models rely on the continuum medium assumption; and high-precision multiscale simulations usually require huge computational resources, how to smoothly transition between scales and maintain physical consistency is a major challenge.

Limitations of experimental probes under extreme conditions: Experiments under extreme conditions are often very expensive and difficult to reproduce, leading to a scarcity of data that can be used to validate numerical simulations.

The computational complexity of multiscale problems (nano-macroscopic coupling) and the limitations of experimental detection under extreme conditions are major challenges in current scientific research. Solving these problems requires interdisciplinary collaborations, including joint efforts in theoretical physics, computational mathematics, materials science, and experimental techniques.

5. Future Directions And Application Prospects

5.1 Theory Integration

The coupling of quantum and classical theories is a major challenge in modern physics. The contradiction between the nonlocal nature of quantum mechanics and the localization of classical mechanics makes it extremely complicated to build unified models in multiscale problems (e.g., nano- to macroscopic).

Future research will be devoted to improving multiscale simulation methods, especially in the boundary treatment of coupled quantum and classical systems. For example, by optimizing boundary conditions and energy calculations to reduce the influence of unphysical forces.

The establishment of a quantum-classical continuum unified model is the key to solving multiscale problems and extreme conditions of computational complexity and experimental detection limitations. Through the "resolution" matching between quantum and classical systems, the development of hybrid quantum-classical machine learning models, and the improvement of multiscale simulation methods, future research is expected to make theoretical and experimental breakthroughs and provide more comprehensive solutions for quantum-classical coupling.

5.2 Disruptive Application Scenarios

The first one is the quantum communication link. One of the core technologies of quantum communication is Quantum Teleportation, a protocol that utilizes pre-shared quantum entanglement resources and classical communication channels to enable a receiver to reconstruct an unknown quantum state at a distance while the sender destroys it. Although entanglement correlations are non-deterministic, the complete invisible state transfer process relies on classical communication, which does not exceed the speed of light and requires a physical medium to establish the initial entanglement and transmit classical information. Quantum communication links are key to the realization of quantum networks and long-distance quantum information transmission. The second one is AI-defined electromagnetic virtual materials. The application of artificial intelligence (AI) in electromagnetic

ISSN 2959-6157

material design is rapidly evolving, especially in defining and optimizing electromagnetic virtual materials. AI algorithms, such as deep learning and reinforcement learning, can optimize the structure and properties of EM virtual materials. In general, quantum communication links and AI-defined EM virtual materials are current cutting-edge research directions in science and technology. Quantum communication links enable the secure transmission of information through the transmission of quantum states, while AI provides powerful tools for the design and optimization of electromagnetic materials. As quantum and AI technologies continue to develop, they will play an increasingly important role in fields such as communications, materials science, and information technology.

6. Conclusion

Focusing on new advances and cutting-edge challenges in electromagnetic wave theory, this paper delves into key areas such as quantum communication and artificial intelligence. Breakthroughs in these fields cannot be separated from the innovation of fundamental theories, especially the core issues of quantum information processing, computational complexity of multi-scale problems, and experimental detection under extreme conditions. The solution to these problems requires the deep integration and interdisciplinary cooperation of multiple disciplines such as mathematics, physics, materials science, and information theory. For example, the establishment of the quantum-classical continuum unification model and the exploration of the coupling of quantum and classical theories provide a new theoretical foundation for the future development of electromagnetic wave theory.

Looking into the future, the new paradigm of intelligent electromagnetic theory will become a key force in promoting the development of electromagnetic technology. The optimization of electromagnetic material design through intelligent algorithms and the deep integration of quantum and classical communications are expected to realize more efficient and safer communication and energy transmission systems. I call for strengthening interdisciplinary cooperation to overcome the core difficulties of electromagnetic wave theory, laying a solid foundation for the future development of science and technology, and promoting electromagnetic technology to new heights.

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