

Why Maxwell's Electromagnetic Theory, Despite Serious Errors, Often Yields Correct Results

Shuang-Ren Zhao* 

Mutualenergy.org London, Canada

*Corresponding Author

Shuang-Ren Zhao, Mutualenergy.org London, Canada.

Submitted: 2026, Sep 01; Accepted: 2026, Oct 02; Published: 2026, Oct 06

Citation: Zhao, S. R. (2026). Why Maxwell's Electromagnetic Theory, Despite Serious Errors, Often Yields Correct Results. *OA J Applied Sci Technol*, 4(3), 01-41.

Abstract

In 1987, the author proposed the Mutual Energy Theorem and the concept of the electromagnetic inner product. Although initially met with skepticism from the academic community regarding its nomenclature and distinction from the reciprocity theorem, by 2017, it was further elevated to the Mutual Energy Flow Theorem (Law) and the Law of Energy Conservation. The author argues that energy is transferred via mutual energy flow, while the conventional view that self-energy flow (Poynting vector) transfers energy suffers from theoretical flaws. Research has revealed that the limitation of Maxwell's electromagnetic theory lies in defining the magnetic field as the curl of the vector potential function, which holds only under quasi-static conditions. In reality, the curl of the vector potential reflects the average magnetic field around a small loop. Despite this deviation, the theory has effectively solved numerous engineering problems for 160 years due to two main reasons: First, the quasi-static electromagnetic theories contributed by pioneers like Ampère and Faraday remain correct, ensuring the validity of basic calculations. Second, in radiation fields, Maxwell's theory mistakenly attributes energy transfer to self-energy flow instead of mutual energy flow; furthermore, Maxwell's theory erroneously calculates the phase of the magnetic field by 90 degrees. Remarkably, these two errors partially cancel each other out, leading to a calculated self-energy flow that numerically equals the mutual energy flow. This numerical coincidence allows Maxwell's theory to still yield correct results in engineering calculations such as antenna radiation patterns and power output. However, self-energy flow lacks the desirable physical property of mutual energy flow, which "starts from the source and extinguishes at the sink," and fails to fully satisfy Poynting's theorem in cases like dipole antennas. This theoretical discrepancy extends to the physics community, manifesting as the wave-particle duality paradox: Maxwell's theory attributes energy transfer to electromagnetic waves, while experiments prove energy is carried by photons. Although quantum mechanics introduces concepts like probability waves and collapse, fundamentally, electromagnetic waves are probabilistic, which aligns with the author's proposition that electromagnetic waves represent reactive power. The author finds that the energy transfer process described by the Schrödinger equation should also be represented by mutual energy flow, not self-energy flow (probability current). The complete calculation of mutual energy flow cannot be derived solely from the original Schrödinger equation but requires establishing and revising the theory of the magnetic field within the quantum framework.

1. Introduction

1.1. Historical Limitations and Skepticism of Electromagnetic Energy Flow Theory

Despite the tremendous success of Maxwell's electromagnetic theory in engineering, skepticism within the physics community regarding its underlying logic—particularly concerning fields, displacement current, energy flow, and radiation interpretation—has never ceased.

First, the **Displacement Current** is often seen as the most artificial assumption in Maxwell's equations. To maintain the mathematical consistency of charge conservation, Maxwell introduced the term $\partial \mathbf{D} / \partial t$ into Ampère's law. However, physicists like J. J. Thomson and H. A. Lorentz pointed out that the "flow" of displacement current in a vacuum is not accompanied by any charge motion, challenging

the physical essence of current. Modern scholar I. Cat (1978) even argued that displacement current is merely a mathematical "artifact" created to mask the inability of classical theory to describe the physical essence of transmission lines.

Second, long-standing controversy exists over the authenticity of the **Poynting Vector** as the sole energy flow density. K. J. van Vlaardingerbroek (2002) sharply noted in his book "Applied Electromagnetism" that the circulating energy flow derived from the Poynting vector in static fields is physically absurd and undetectable, suggesting the model might be merely a mathematical coincidence. Carver Mead (2000), in his renowned work "Collective Electrodynamics," further criticized the field-centric perspective, arguing that the curl definition of the magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$ has limitations in describing dynamic collective interactions. He advocated that the vector potential $\mathbf{A}$ and phase coupling between charges constitute physical reality, while the concept of displacement current reinforces the illusion of the electromagnetic field as an independent entity.

Furthermore, the "Absorber Theory" proposed by Wheeler and Feynman (1945), by introducing Advanced Waves, challenged the view of radiation as a single-entity behavior. They argued that radiation is a collective interaction between a source and all absorbers in the universe [1-5]. John Cramer (1986) extended this into the Transactional Interpretation of quantum mechanics, emphasizing the coupling of retarded and advanced waves [6,7]. The work of these pioneers is highly aligned with the author's argument that "energy is uniquely transferred by mutual energy flow, and photons consist of both retarded and **advanced waves**." The explorations by Born, Infeld (1934), and Dirac (1938) in dealing with point source self-energy and radiation reaction forces form the historical context for this re-examination of the electromagnetic edifice[8]. Additionally, Stephenson's theory of advanced waves has also significantly influenced the author[9].

If one were to claim that Maxwell's electromagnetic theory, one of the cornerstones of modern civilization, contains serious fundamental errors, most people might dismiss it with a laugh. However, scientific truths often lie hidden in the seams of seemingly flawless systems. This paper aims to point out that Maxwell's electromagnetic theory indeed contains two fundamental deviations. Astonishingly, these two deviations, in many scenarios, produce a "negative times negative equals positive" cancellation effect, allowing the theory to demonstrate high accuracy in engineering applications for 160 years.

The author has been perplexed by and explored this issue for a full 40 years. This article will recount this lengthy research journey, delving into why a system with serious theoretical flaws can still yield satisfactory results in antenna radiation and most engineering calculations.

1.2. The Germination of the Mutual Energy Theorem and Theoretical Controversy (1984-1987)

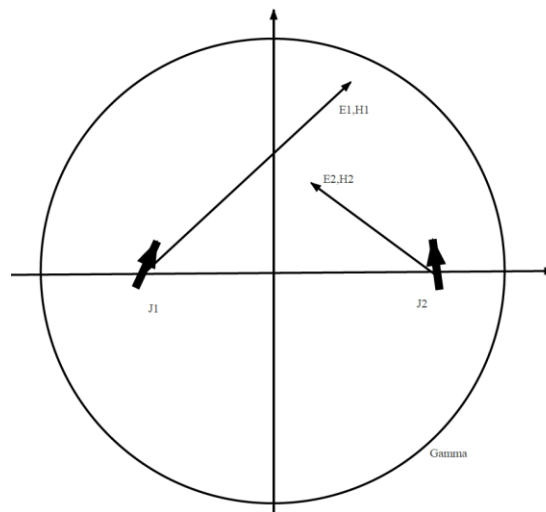


Figure 1: Two Current Elements J_1 and J_2 Inside Surface Γ .

The author's research began in 1984 during graduate studies in microwave electromagnetics at Xidian University. The focus then was the Lorentz Reciprocity Theorem. For two current elements J_1 and J_2 (and their generated fields ξ_1 and ξ_2) inside surface Γ , see Fig. 1. The classical reciprocity theorem states[10-12].

$$-\oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2 - \mathbf{E}_2 \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = \int_V (\mathbf{E}_1 \cdot \mathbf{J}_2 - \mathbf{E}_2 \cdot \mathbf{J}_1) dV \quad (1)$$

While studying J.A. Kong's "Electromagnetic Wave Theory", inspired by electromagnetic conjugate transformations, the author attempted a conjugate mapping on the physical quantities with subscript 2 [13]:

$$\mathbf{E}_2, \mathbf{H}_2, \mathbf{J}_2 \rightarrow \mathbf{E}_2^*, -\mathbf{H}_2^*, -\mathbf{J}_2^* \quad (2)$$

Substituting this transformation into the above equation, the reciprocity theorem instantly evolved into a formula with distinct energy significance:

$$-\oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = \int_V (\mathbf{E}_1 \cdot \mathbf{J}_2^* + \mathbf{E}_2^* \cdot \mathbf{J}_1) dV \quad (3)$$

Given that VI^* represents complex power in circuit theory, and the volume integral $\int_V (\mathbf{E} \cdot \mathbf{J}^*) dV$ transforms proportionally to VI^* via line element transformation, the author realized that Eq. (3) describes not just mathematical symmetry but also a physical law concerning power and energy. Accordingly, the author named it the **Electromagnetic Mutual Energy Theorem** and defined its surface integral term as the **inner product** of two electromagnetic fields:

$$(\xi_1, \xi_2) = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \quad (4)$$

Although the author attempted to prove this equation starting from the complex Poynting theorem to establish its energy status, no breakthrough was achieved at the time. Although related papers were published in 1987-1989, the mainstream academic community, including supervisors and professors, still regarded it as a variant of the reciprocity theorem, considering the name "Mutual Energy Theorem" an overstatement [14-16].

1.3. Theoretical Resonance Across Three Decades (2014-2017)

After a 30-year hiatus, the author resumed research in 2014. During this period, the author successively discovered the "cross-correlation reciprocity theorem" proposed by de Hoop (1987) and the time-domain reciprocity theorem proposed by Welch (1960) [17,18]. Research shows that the mutual energy theorem is actually the unified form of these theories in the frequency domain. The author derived Welch and Hoop's reciprocity theorems from Poynting's theorem and then derived the mutual energy theorem via Fourier transform. Since these theorems can be derived from Poynting's theorem, their physical legitimacy as energy theorems gained solid support.

The author subsequently elevated the electromagnetic inner product to **mutual energy flow** and further derived the mutual energy flow theorem:

$$\begin{aligned} & - \int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \\ &= \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \\ &= \int_V (\mathbf{E}_1 \cdot \mathbf{J}_2^*) dV \end{aligned} \quad (5)$$

Thus, the author proposed a groundbreaking viewpoint: electromagnetic energy is transferred by mutual energy flow, not by self-energy flow (Poynting vector); mutual energy flow is the physical essence of photons. This assertion is based on a profound logic: if both flows transferred energy simultaneously, it would lead to a violation of energy conservation.

1.4. Advanced Waves and the Transactional Interpretation of Quantum Mechanics

The key to establishing the core status of mutual energy flow lies in acknowledging the physical reality of Advanced Waves. Although mainstream electromagnetics holds reservations on this, the research of physics giants like Wheeler, Feynman, Dirac, Schwarzschild et al., as well as Cramer, and Stephenson provides a theoretical foundation for the existence of advanced waves [1-9].

In 2017, the author attempted to interpret quantum mechanics using mutual energy flow, which resonates with John Cramer's "Transactional Interpretation": photon formation involves not only the retarded wave emitted by the source but also the advanced wave produced by the sink [6,7]. The synchronization of the two constructs a closed channel for energy transfer. Unlike Cramer, the author's theory completely strips away the role of self-energy flow in energy transport.

1.5. The Final Breakthrough in 2022: The Limitation of Magnetic Field Definition

In 2022, the author finally pinpointed the core fallacy of Maxwell's theory: defining the magnetic field as the curl of the vector potential function,

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (6)$$

holds strictly only under quasi-static conditions. In the case of radiation fields, this traditional definition fails to accurately capture the dynamic characteristics of the field.

How could a theory applied for 160 years, solving countless practical problems, harbor such a fundamental error? This paper will unravel this mystery. As previously mentioned, Maxwell's theory simultaneously made two errors: one in the phase of the radiation source's magnetic field and the other in identifying the carrier of energy transfer. Remarkably, these two errors produce a canceling effect in engineering calculations, masking the underlying cracks in the theoretical foundation. Through detailed arguments, this paper will guide readers to re-examine the cornerstone of the electromagnetic edifice.

2.1 How the Author Discovered the Errors in Maxwell's Electromagnetic Theory

2.1. 1987

The author published the Mutual Energy Theorem in the *Journal of Electronics*[14]:

$$-\oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = \int_V (\mathbf{E}_1 \cdot \mathbf{J}_2^* + \mathbf{E}_2^* \cdot \mathbf{J}_1) dV \quad (7)$$

where $\xi_1 = [\mathbf{E}_1, \mathbf{H}_1]^T$, $\xi_2 = [\mathbf{E}_2, \mathbf{H}_2]^T$ are electromagnetic fields generated by currents $\mathbf{J}_1$ and $\mathbf{J}_2$, Γ is the boundary of region V , i.e., $\Gamma = \partial V$. See Fig. 1. The inner product of two electromagnetic fields is defined as:

$$(\xi_1, \xi_2) = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \quad (8)$$

The author knows that according to the Silver-Müller radiation condition, if both sources $\mathbf{J}_1, \mathbf{J}_2$ are within region V , the surface integral is zero,

$$(\xi_1, \xi_2) = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = 0 \quad (9)$$

Thus,

$$\int_V (\mathbf{E}_1 \cdot \mathbf{J}_2^* + \mathbf{E}_2^* \cdot \mathbf{J}_1) dV = 0 \quad (10)$$

or

$$-\int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV = \int_{V_2} (\mathbf{E}_1 \cdot \mathbf{J}_2^*) dV \quad (11)$$

In the above equation, V_1 is the region of current $\mathbf{J}_1$, and V_2 is the region of current $\mathbf{J}_2$. The above equation is also called the mutual energy theorem.

2.2. 1989

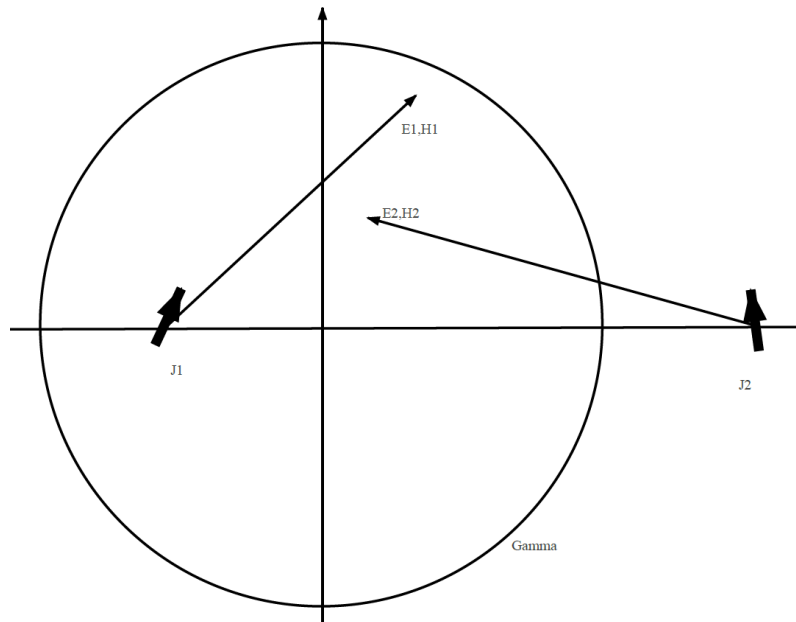


Figure 2: Current Elem#ent J_1 is INSIDE Surface Γ . Current Element J_2 is Outside Surface Γ

The author studied the case where one of the two current elements is outside region V , e.g., J_2 is outside V . Then, formula (7) becomes:

$$-\oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = \int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \quad (12)$$

Here $V = V_1$. The above can be rewritten as,

$$-\int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \quad (13)$$

Considering (11) and $\hat{n} = \hat{n}_{1 \rightarrow 2}$, where $\hat{n}$ is the normal to surface Γ , and $\hat{n}_{1 \rightarrow 2}$ is the outward normal from region 1 to 2,

$$\begin{aligned} & -\int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \\ &= \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n}_{1 \rightarrow 2} d\Gamma \\ &= \int_{V_2} (\mathbf{E}_1 \cdot \mathbf{J}_2^*) dV \end{aligned} \quad (14)$$

Further considering

$$\mathbf{J}_2 = \hat{x} \delta(\mathbf{x} - \mathbf{x}')$$

yields

$$\begin{aligned} & -\int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \\ &= \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n}_{1 \rightarrow 2} d\Gamma \end{aligned}$$

$$= \int_{V_2} (\mathbf{E}_1 \cdot \hat{\mathbf{x}} \delta(\mathbf{x} - \mathbf{x}')) dV \quad (15)$$

or

$$\begin{aligned} & - \int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \\ & = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{\mathbf{n}}_{1 \rightarrow 2} d\Gamma = \mathbf{E}_{1x}(x) \end{aligned} \quad (16)$$

The electromagnetic field $\mathbf{E}_2, \mathbf{H}_2$ in the above equation is generated by current $\mathbf{J}_2 = \hat{\mathbf{x}} \delta(\mathbf{x} - \mathbf{x}')$. We can write it as:

$$\begin{aligned} & - \int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \\ & = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_{2x}^* + \mathbf{E}_{2x}^* \times \mathbf{H}_1) \cdot \hat{\mathbf{n}}_{1 \rightarrow 2} d\Gamma \\ & = \mathbf{E}_{1x}(x) \end{aligned} \quad (17)$$

Or

$$\begin{aligned} \mathbf{E}_{1x}(x) & = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_{2x}^* + \mathbf{E}_{2x}^* \times \mathbf{H}_1) \cdot \hat{\mathbf{n}}_{1 \rightarrow 2} d\Gamma \\ & = - \int_{V_1} (\mathbf{E}_{2x}^* \cdot \mathbf{J}_1) dV \end{aligned} \quad (18)$$

$\mathbf{E}_{2x}$ is the electric field generated by current $\mathbf{J}_2 = \hat{\mathbf{x}} \delta(\mathbf{x} - \mathbf{x}')$. Similarly, assume $\mathbf{J}_2 = \hat{\mathbf{y}} \delta(\mathbf{x} - \mathbf{x}')$ generates electric field $\mathbf{E}_{2y}, \mathbf{H}_{2y}$; $\mathbf{J}_2 = \hat{\mathbf{z}} \delta(\mathbf{x} - \mathbf{x}')$ generates electromagnetic field $\mathbf{E}_{2z}$. Therefore,

$$\begin{aligned} \mathbf{E}_{1y}(x) & = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{\mathbf{n}}_{1 \rightarrow 2} d\Gamma \\ & = - \int_V (\mathbf{E}_{2y}^* \cdot \mathbf{J}_1) dV \end{aligned} \quad (19)$$

$$\begin{aligned} \mathbf{E}_{1z}(x) & = \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_{2z}^* + \mathbf{E}_{2z}^* \times \mathbf{H}_1) \cdot \hat{\mathbf{n}}_{1 \rightarrow 2} d\Gamma \\ & = - \int_V (\mathbf{E}_{2z}^* \cdot \mathbf{J}_1) dV \end{aligned} \quad (20)$$

Formulas (18-20) are known as the Huygens principle [15].

2.3. 2017

The author updated the concept of the inner product of two electromagnetic fields (8) to mutual energy flow [19]. Therefore,

$$\mathbf{S}_m = \mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1 \quad (21)$$

is the mutual energy flow density. Additionally, an intermediate formula (14) from the 1989 Huygens principle was updated to the mutual energy flow theorem [19]. The author considers

$$- \int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \quad (22)$$

as the power of work done by current $\mathbf{J}_1$ against electric field $\mathbf{E}_2$.

$$\int_V (\mathbf{E}_1 \cdot \mathbf{J}_2^*) dV \quad (23)$$

is the power received by current $\mathbf{J}_2$ from electric field $\mathbf{E}_1$, while

$$\oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n}_{1 \rightarrow 2} d\Gamma \quad (24)$$

is the energy flow passing through surface Γ . Surface Γ is any surface that can separate currents $\mathbf{J}_1$ and $\mathbf{J}_2$. This surface can be a closed surface surrounding $\mathbf{J}_1$ or $\mathbf{J}_2$, or an infinite open surface between $\mathbf{J}_1$ and $\mathbf{J}_2$. $\hat{n}_{1 \rightarrow 2}$ points from 1 to 2.

At this point, the author encountered a perplexing issue. Two types of energy flow appeared: one is the energy flow represented by the Poynting vector in classical electromagnetic theory,

$$\mathbf{S}_1 = \mathbf{E}_1 \times \mathbf{H}_1 \quad (25)$$

and the other is the new energy flow proposed by the author, i.e., mutual energy flow:

$$\mathbf{S}_m = \mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1 \quad (26)$$

The author felt that these two energy flow densities could not both transfer energy simultaneously. According to traditional electromagnetic theory, $\mathbf{S}_1$ already transfers sufficient electromagnetic energy; if $\mathbf{S}_m$ added even a tiny amount of energy, energy conservation would be violated. Additionally, mutual energy flow converges onto an absorbing charge, while self-energy flow is divergent. According to quantum mechanics, such a divergent wave requires collapse. Only if the collapse point of self-energy flow aligns with the convergence point of mutual energy flow can we obtain a single photon; otherwise, we would get two different types of photons: mutual energy flow photons and self-energy flow photons. Two types of photons have never been experimentally observed, making this scenario untenable.

The author discovered that the mutual energy flow theorem is a sub-theorem of Poynting's theorem. This is because from Poynting's theorem:

$$- \oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma = \int_V (\mathbf{E} \cdot \mathbf{J} + \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t}) dV \quad (27)$$

Considering the superposition principle:

$$\mathbf{J} = \sum_{i=1}^2 \mathbf{J}_i, \quad \mathbf{E} = \sum_{i=1}^2 \mathbf{E}_i, \quad \mathbf{H} = \sum_{i=1}^2 \mathbf{H}_i, \quad (28)$$

one can derive the Welch time-domain reciprocity theorem:

$$\begin{aligned} & - \int_{-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2 + \mathbf{E}_2 \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \\ & = \int_{-\infty}^{\infty} dt \int_V (\mathbf{E}_1 \cdot \mathbf{J}_2 + \mathbf{E}_2 \cdot \mathbf{J}_1) dV \end{aligned} \quad (29)$$

Applying the Fourier transform yields the mutual energy theorem (7). Therefore, the mutual energy theorem is a sub-theorem of Poynting's theorem; likewise, the mutual energy flow theorem is also a sub-theorem of Poynting's theorem. Thus, if Poynting's theorem holds, the mutual energy flow theorem must also hold. The validity of the mutual energy flow theorem implies that mutual energy flow transfers energy. This creates a paradox: Poynting's theorem already accounts for energy transfer, and now mutual energy flow adds another channel. Something seems amiss.

Incidentally, when proposing the mutual energy theorem, the author attempted to derive it from the complex Poynting theorem but failed [14-16]. That is because the complex Poynting theorem and Poynting's theorem are two distinct theorems. While it's not straightforward to prove the mutual energy theorem directly from the complex Poynting theorem, one can derive Welch and Hoop's reciprocity theorems from Poynting's theorem and then apply the Fourier transform to obtain the mutual energy theorem.

Assume Γ is a spherical surface. When the sphere's radius approaches infinity, the surface integral on the left side of the above equation can be zero. This is because $\zeta_1 = [\mathbf{E}_1, \mathbf{H}_1]_\Gamma$, $\zeta_2 = [\mathbf{E}_2, \mathbf{H}_2]_\Gamma$ represent a retarded wave and an advanced wave, respectively. One arrives at surface Γ at some past moment, the other at some future moment. They are not simultaneously non-zero on surface Γ . Therefore, this surface integral is zero. Consequently, the right side of the above equation is zero, or:

$$-\int_{-\infty}^{\infty} dt \int_{V_1} (\mathbf{E}_2 \cdot \mathbf{J}_1) dV = \int_{-\infty}^{\infty} dt \int_{V_2} (\mathbf{E}_1 \cdot \mathbf{J}_2) dV \quad (30)$$

The above equation is also a form of Welch's time-domain reciprocity theorem. Welch's time-domain reciprocity theorem and the author's proposed mutual energy theorem are mathematically identical (aside from the Fourier transform). However, the author believes it is not merely a reciprocity theorem but an energy theorem, while Welch and other scientists consider it only a reciprocity theorem. The above can be rewritten as:

$$\sum_{i=1}^2 \sum_{j=1, j \neq i}^2 \int_{-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV = 0 \quad (31)$$

This can be further generalized to:

$$\sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV = 0 \quad (32)$$

Faced with this formula, the author experienced a profound epiphany: this equation is not merely a mathematical energy theorem; it should be regarded as the law of energy conservation for the universe. The core logic is: if N is sufficiently large to encompass all current sources $\mathbf{J}_i$ in the universe, then the above equation precisely describes the exchange of energy within this closed-loop system. The author firmly believes that no energy can truly escape this complete system constituted by all interacting charges. If we consider the entire universe as this system and assume no currents exist beyond the universe's boundary, energy exchange is strictly confined within the system. Even if new currents $\mathbf{J}_i$ are discovered outside the universe, we can incorporate them by increasing N . From this global perspective, formula (32) is no longer merely a description of an energy theorem but emphasizes the law of energy conservation where "energy never spills over the universe."

Admittedly, concluding that formula (32) is the law of energy conservation based solely on its form is not yet logically airtight. This is more a crucial step the author took amid exploratory uncertainty—we can view it as a physical postulate regarding the nature of energy. The subsequent rigorous challenge is: if this equation indeed represents energy conservation, can it be rigorously derived from Maxwell's equations? As is well known, Maxwell's equations underpin Poynting's theorem. Let us attempt to derive the universal energy conservation conclusion from the time-integrated Poynting theorem to verify self-consistency. If Maxwell's theory cannot derive this universal energy conservation conclusion, it may reveal inherent contradictions within classical electromagnetic theory regarding radiation. The time-integrated Poynting theorem is:

$$-\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma = \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E} \cdot \mathbf{J}) dV \quad (33)$$

where considering

$$U = \int_V (\mathbf{E} \cdot \mathbf{D} + \mathbf{H} \cdot \mathbf{B}) dV \quad (34)$$

$$\frac{\partial U}{\partial t} = \int_V (\mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t}) dV \quad (35)$$

Thus,

$$\begin{aligned} & \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t}) dV \\ &= \int_{t=-\infty}^{\infty} dt \frac{\partial U}{\partial t} = U(\infty) - U(-\infty) = 0 \end{aligned} \quad (36)$$

$U(\infty), U(-\infty)$ are the system's initial and final energies, which can be assumed both zero or equal. (33) becomes:

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma + \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E} \cdot \mathbf{J}) dV = 0 \quad (37)$$

Substituting the superposition principle (39) into the time-integrated Poynting theorem. Assuming the superposition principle in electromagnetic theory holds, i.e., current sources

$$\mathbf{J} = \sum_{i=1}^N \mathbf{J}_i \quad (38)$$

generate electromagnetic fields:

$$\mathbf{E} = \sum_{i=1}^N \mathbf{E}_i, \quad \mathbf{H} = \sum_{i=1}^N \mathbf{H}_i \quad (39)$$

we obtain

$$\sum_{i=1}^N \sum_{j=1}^N \int_{t=-\infty}^{\infty} dt (\oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV) = 0 \quad (40)$$

The above can be written as

$$\begin{aligned} & \sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV \\ &+ \sum_{i=1}^N \int_{t=-\infty}^{\infty} dt (\oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_i) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_i) dV) = 0 \end{aligned} \quad (41)$$

To derive the energy conservation law

$$\sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV = 0 \quad (42)$$

we require

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma = 0 \quad (43)$$

$$\int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_i) dV = 0 \quad (44)$$

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_i) \cdot \hat{n} d\Gamma = 0 \quad (45)$$

Among the above three equations, (43) can be satisfied provided surface Γ is large enough to enclose all currents, as mutual energy flow cannot escape the universe. The author is aware of this because the sources generating mutual energy flow, $\mathbf{J}_i$ and $\mathbf{J}_j$, are a source and a sink, respectively. The source produces a retarded wave, the sink produces an advanced wave; the retarded and advanced waves arrive at surface Γ at different times (one in the past, one in the future). They are not simultaneously non-zero on Γ , so this surface integral is identically zero.

However, according to Maxwell's electromagnetic theory, formula (45) is not zero. For any antenna current source $\mathbf{J}_i$, according to Maxwell's theory, (45) represents the antenna's radiated energy. If it were zero, the antenna would radiate no energy. According to Maxwell's theory, it is always:

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_i) \cdot \hat{n} d\Gamma \neq 0 \quad (46)$$

Due to the existence of formula (46), we cannot derive the energy conservation law (42) from Maxwell's electromagnetic theory. This implies that if energy conservation law (42) holds, then Maxwell's electromagnetic theory must contain a bug! The author believes energy conservation must hold; therefore, Maxwell's electromagnetic theory contains a bug and needs correction.

2.4. Proposed Solution

In 2017, the author's academic thinking underwent a major shift: a deep realization that self-energy flow is not the true carrier of energy transfer; energy should be carried solely by mutual energy flow [19]. This understanding implies that formula (45) should hold, and electromagnetic waves are essentially reactive power. However, this conclusion created a significant logical conflict with Maxwell's electromagnetic theory, which at the time showed no apparent flaws.

To bridge this theoretical gap, the author proposed an exploratory solution at the time: assume the existence of an as-yet-unobserved physical reality—time-reversed electromagnetic fields. Their mechanism would induce a so-called "reverse collapse" of self-energy flow, thereby physically canceling its energy contribution. This approach essentially constituted a "corrective preservation" of Maxwell's theory: without completely overturning the existing framework, by introducing a physical patch regarding "time-reversed electromagnetic waves," self-energy flow would collapse during output and no longer participate in energy transport. Thus, the validity of formula (45) could be maintained, establishing mutual energy flow as the sole mechanism for energy transfer.

3. Errors in Maxwell's Electromagnetic Theory

Previously, the author attempted to correct Maxwell's electromagnetic theory by introducing the concept of "reverse collapse of self-energy flow"[19]. However, it must be acknowledged that this mechanism is not a complete solution. Theoretical deduction shows that if time-reversed waves are introduced, they themselves might generate so-called "time-reversed mutual energy flow," which could cancel the real physical mutual energy flow. To eliminate this logical contradiction, the author had to postulate an additional axiom: time-reversed waves do not generate mutual energy flow.

Although this postulate maintains macroscopic self-consistency, it also makes the model appear asymmetrically imperfect. Currently, the author cannot experimentally prove the objective existence of time-reversed waves. Therefore, from a pure theoretical construction standpoint, the concepts of "reverse collapse" and "time-reversed waves" should currently be viewed as "theoretical patches" addressing existing framework loopholes.

Researchers in software engineering know that any patch for a complex system may induce unknown side effects. Currently, time-reversed waves and reverse collapse mechanisms are in this delicate and somewhat awkward theoretical position: they temporarily solve the logical closure problem of energy transport, but the universality of their underlying physical logic awaits deeper exploration. This status is not the end but suggests a simpler, more elegant physical picture awaits discovery.

3.1. Law of Energy Conservation

From around 2020 onward, the author began studying examples of energy transfer via mutual energy flow [20-40]. These include transformers with dual-plate currents, transformers with two dipoles, two-dipole antenna systems, and dual-plate current antenna

systems. The author found that transformers operating under magnetoquasistatic conditions satisfy formulas (43-45). Therefore, formula (42) indeed represents the law of energy conservation, at least for quasistatics. The law of energy conservation holds, i.e.:

$$\sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV = 0 \quad (47)$$

where energy is transferred by the mutual energy flow law formula:

$$\begin{aligned} & - \int_{t=-\infty}^{\infty} dt \int_{V_i} (\mathbf{E}_j \cdot \mathbf{J}_i) dV \\ & = \int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j + \mathbf{E}_j \times \mathbf{H}_i) \cdot \hat{n} d\Gamma \\ & = \int_{t=-\infty}^{\infty} dt \int_{V_j} (\mathbf{E}_i \cdot \mathbf{J}_j) dV \end{aligned} \quad (48)$$

However, under radiation conditions, formulas (45) no longer hold. The above two equations (47, 48) downgrade to energy theorems. The author began to realize this might be incorrect. Perhaps under radiation conditions, electromagnetic waves should remain non-energy-carrying by self-energy flow, similar to quasistatic conditions.

3.2. Radiation Electromagnetic Fields Should Degenerate to Quasistatic Electromagnetic Fields

The author began a comprehensive review of Maxwell's electromagnetic theory to identify its loopholes. The author established a set of criteria to examine the electric and magnetic fields generated by Maxwell's theory. The author believes quasistatic electromagnetic fields are correct, and Maxwell's radiation fields are an extension of quasistatic fields. Therefore, under conditions meeting quasistatic assumptions, radiation field formulas should degenerate to quasistatic fields. The degeneration condition is:

$$kr = \mathbf{k} \cdot \mathbf{r} \rightarrow 0 \quad (49)$$

This implies:

$$kr \ll 1 \quad (50)$$

$$\frac{2\pi}{\lambda} r \ll 1 \quad (51)$$

$$r \ll \frac{\lambda}{2\pi} < \lambda \quad (52)$$

$$r = ||\mathbf{x} - \mathbf{x}'|| \ll \lambda \quad (53)$$

The above indicates that when the distance r between field point $\mathbf{x}$ and source point $\mathbf{x}'$ is much smaller than the wavelength, radiation fields should degenerate to quasistatic fields. The electromagnetic field has three components: induced electric field $\mathbf{E}_I$, static electric field $\mathbf{E}_S$, and magnetic field $\mathbf{B}$,

$$\mathbf{E}_I = -\frac{\partial}{\partial t} \mathbf{A} \quad (54)$$

$$\mathbf{E}_S = -\nabla \phi \quad (55)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (56)$$

We now examine whether these three components successfully degenerate.

3.3. Retarded and Advanced Potentials

Under radiation conditions, the vector potential becomes the retarded potential:

$$\begin{cases} \mathbf{A}^{(r)} = \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}(\mathbf{x}', t-r/c)}{r} dV \\ \phi^{(r)} = \frac{1}{4\pi\epsilon_0} \int_V \frac{\rho(\mathbf{x}', t-r/c)}{r} dV \end{cases} \quad (57)$$

and the advanced potential:

$$\begin{cases} \mathbf{A}^{(a)} = \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}(\mathbf{x}', t+r/c)}{r} dV \\ \phi^{(a)} = \frac{1}{4\pi\epsilon_0} \int_V \frac{\rho(\mathbf{x}', t+r/c)}{r} dV \end{cases} \quad (58)$$

Superscript (r) denotes retarded, (a) denotes advanced. Assume $\mathbf{J}$ is AC, i.e.:

$$\mathbf{J} = \mathbf{J}_0 \exp(j\omega t) \quad (59)$$

$$\mathbf{A}^{(r)} = \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}_0 \exp(j(\omega t - \frac{\omega r}{c}))}{r} dV \quad (60)$$

where

$$k = \frac{\omega}{c} \quad (61)$$

Thus,

$$\begin{aligned} \mathbf{A}^{(r)} &= \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}_0 \exp(j(\omega t - kr))}{r} dV \\ &= \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}_0 \exp(j\omega t) \exp(-jkr)}{r} dV \\ &= \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J} \exp(-jkr)}{r} dV \end{aligned} \quad (62)$$

Similarly,

$$\phi^{(r)} = \frac{1}{4\pi\epsilon_0} \int_V \frac{\rho \exp(-jkr)}{r} dV \quad (63)$$

Similarly,

$$\mathbf{A}^{(a)} = \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J} \exp(jkr)}{r} dV \quad (64)$$

$$\phi^{(a)} = \frac{1}{4\pi\epsilon_0} \int_V \frac{\rho \exp(jkr)}{r} dV \quad (65)$$

3.4. Verifying the Induced Electric Field

$$\lim_{kr \rightarrow 0} \mathbf{E}_I^{(r)} = - \lim_{kr \rightarrow 0} \frac{\partial}{\partial t} \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J} \exp(-jkr)}{r} dV$$

$$\begin{aligned}
&= -\lim_{kr \rightarrow 0} j\omega \frac{\mu_0}{4\pi} \int_V \frac{J \exp(-jkr)}{r} dV \\
&= -j\omega \frac{\mu_0}{4\pi} \int_V \frac{J}{r} dV \\
&= -\frac{\partial}{\partial t} \frac{\mu_0}{4\pi} \int_V \frac{J}{r} dV \\
&= -\frac{\partial}{\partial t} \mathbf{A} \\
&= \mathbf{E}_I
\end{aligned} \tag{66}$$

That is,

$$\lim_{kr \rightarrow 0} \mathbf{E}_I^{(r)} = \mathbf{E}_I$$

This shows that $\mathbf{E}_I^{(r)}$ indeed degenerates to the quasistatic electric field $\mathbf{E}_I$ as $kr \rightarrow 0$. $\mathbf{E}_I^{(r)}$ passes our test. Therefore, $\mathbf{E}_I^{(r)}$ can serve as the radiation induced electric field.

3.5. Verifying the Magnetic Field

Now consider the magnetic field:

$$\begin{aligned}
\lim_{kr \rightarrow 0} \mathbf{B}^{(r)} &= \lim_{kr \rightarrow 0} \nabla \times \mathbf{A}^{(r)} \\
&= \lim_{kr \rightarrow 0} \nabla \times \frac{\mu_0}{4\pi} \int_V \frac{J \exp(-jkr)}{r} dV \\
&= \lim_{kr \rightarrow 0} \frac{\mu_0}{4\pi} \int_V \nabla \frac{\exp(-jkr)}{r} \times J dV \\
&= \frac{\mu_0}{4\pi} \int_V J \times \left(\frac{\mathbf{r}}{r^3} + jk \hat{\mathbf{r}} \frac{1}{r} \right) dV \\
&= \mathbf{B} + jk \frac{\mu_0}{4\pi} \int_V J \times \frac{\hat{\mathbf{r}}}{r} dV
\end{aligned} \tag{67}$$

We originally hoped:

$$\lim_{kr \rightarrow 0} \mathbf{B}^{(r)} = \mathbf{B} \tag{68}$$

so that the retarded magnetic field $\mathbf{B}^{(r)}$ would degenerate to the quasistatic magnetic field $\mathbf{B}$ as $kr \rightarrow 0$. However, this did not materialize; we actually obtained:

$$\lim_{kr \rightarrow 0} \mathbf{B}^{(r)} = \mathbf{B} + jk \frac{\mu_0}{4\pi} \int_V J \times \frac{\mathbf{r}}{r^2} dV \neq \mathbf{B} \tag{69}$$

That is, the retarded magnetic field $\mathbf{B}^{(r)}$ does not degenerate to the quasistatic magnetic field $\mathbf{B}$. This magnetic field $\mathbf{B}^{(r)}$ is problematic. The extra term is:

$$jk \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^2} dV \quad (70)$$

This term has a different phase compared to the quasistatic magnetic field:

$$\mathbf{B} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} dV \quad (71)$$

The author conjectures that the correct magnetic field should maintain the same phase as the quasistatic field, i.e.,

$$\mathbf{B}^{(r)} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \exp(-jkr) dV + k \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\hat{\mathbf{r}}}{r} \exp(-jkr) dV \quad (72)$$

The author defines

$$\begin{aligned} \mathbf{B}_{Maxwell}^{(r)} &\triangleq \nabla \times \mathbf{A}^{(r)} \\ &= \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \exp(-jkr) dV + jk \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\hat{\mathbf{r}}}{r} \exp(-jkr) dV \end{aligned} \quad (73)$$

$\mathbf{B}_{Maxwell}^{(r)}$ is the magnetic field defined according to Maxwell's theory. We now recognize it is not the correct magnetic field. Here,

$$\mathbf{B}_{Maxwell\ n}^{(r)} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \exp(-jkr) dV \quad (74)$$

is the near-field magnetic field defined by Maxwell.

$$\mathbf{B}_{Maxwell\ f}^{(r)} = jk \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\hat{\mathbf{r}}}{r} \exp(-jkr) dV \quad (75)$$

is the far-field magnetic field defined by Maxwell. Thus, we have:

$$\mathbf{B}_n^{(r)} = \mathbf{B}_{Maxwell\ n}^{(r)} \quad (76)$$

$$\mathbf{B}_f^{(r)} = (-j) \mathbf{B}_{Maxwell\ f}^{(r)} \quad (77)$$

$\mathbf{B}_n^{(r)}$ is the near-field of the correct magnetic field as defined by the author; $\mathbf{B}_f^{(r)}$ is the far-field of the correct magnetic field. Superscript (r) denotes retarded; subscript n denotes near. $\mathbf{B}^{(r)}$ is given by formula (72). Similarly,

$$\mathbf{B}_n^{(a)} = \mathbf{B}_{Maxwell\ n}^{(a)} \quad (78)$$

$$\mathbf{B}_f^{(a)} = (j) \mathbf{B}_{Maxwell\ f}^{(a)} \quad (79)$$

Superscript (a) denotes advanced; subscript n denotes near-field; f denotes far-field. The author-defined advanced magnetic field is:

$$\mathbf{B}^{(a)} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \exp(+jkr) dV + k \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\hat{\mathbf{r}}}{r} \exp(+jkr) dV \quad (80)$$

Here, defining the magnetic field may seem arbitrary. Indeed, the correction formulas (76-79) are merely the author's conjecture. Whether these formulas are correct must be ensured by the theory in the next chapter.

Thus, the author has relaxed the earlier degeneration strategy, no longer requiring complete degeneration as $k \cdot \mathbf{r} \rightarrow 0$, but at least ensuring phase consistency after degeneration, i.e., the degeneration condition is:

$$\lim_{kr \rightarrow 0} \text{Phase}(\mathbf{B}^{(r)}) = \text{Phase}(\mathbf{B}) \quad (81)$$

where "Phase($\cdot$)" denotes taking the phase.

3.6. Verifying the Static Electric Field

Additionally,

$$\begin{aligned} \mathbf{E}_S^{(r)} &= \lim_{kr \rightarrow 0} (-\nabla \phi^{(r)}) \\ &= \lim_{kr \rightarrow 0} \left(-\nabla \frac{1}{4\pi\epsilon_0} \int_V \frac{\rho \exp(-jkr)}{r} dV \right) \\ &= \lim_{kr \rightarrow 0} \left(\frac{1}{4\pi\epsilon_0} \int_V \rho \left(\frac{\mathbf{r}}{r^2} + jk\hat{\mathbf{r}} \right) \frac{\exp(-jkr)}{r} dV \right) \\ &= \mathbf{E}_S + jk \frac{1}{4\pi\epsilon_0} \int_V \rho \frac{\mathbf{r}}{r^2} dV \end{aligned} \quad (82)$$

Similar to the magnetic field, the retarded static electric field $\mathbf{E}_S^{(r)}$ does not degenerate to the quasistatic static electric field $\mathbf{E}_s$ as $k\mathbf{r} \rightarrow 0$. The author conjectures the correct static electric field is:

$$\begin{aligned} \mathbf{E}_S^{(r)} &= \frac{1}{4\pi\epsilon_0} \int_V \rho \left(\frac{\mathbf{r}}{r^3} \right) \exp(-jkr) dV \\ &\quad + k \frac{1}{4\pi\epsilon_0} \int_V \rho \frac{\mathbf{r}}{r^2} \exp(-jkr) dV \end{aligned} \quad (83)$$

Whereas the static electric field defined by Maxwell's electromagnetic theory is:

$$\begin{aligned} \mathbf{E}_{S \text{ Maxwell}}^{(r)} &= \frac{1}{4\pi\epsilon_0} \int_V \rho \left(\frac{\mathbf{r}}{r^3} \right) \exp(-jkr) dV \\ &\quad + jk \frac{1}{4\pi\epsilon_0} \int_V \rho \frac{\mathbf{r}}{r^2} \exp(-jkr) dV \end{aligned} \quad (84)$$

$$\mathbf{E}_{S \text{ Maxwell } n}^{(r)} = \frac{1}{4\pi\epsilon_0} \int_V \rho \left(\frac{\mathbf{r}}{r^3} \right) \exp(-jkr) dV \quad (85)$$

$$\mathbf{E}_{S \text{ Maxwell } f}^{(r)} = jk \frac{1}{4\pi\epsilon_0} \int_V \rho \frac{\mathbf{r}}{r^2} \exp(-jkr) dV \quad (86)$$

The corrected formulas are as follows:

$$\mathbf{E}_{S \text{ } n}^{(r)} = \mathbf{E}_{S \text{ Maxwell } n}^{(r)} \quad (87)$$

$$\mathbf{E}_{S \text{ } f}^{(r)} = (-j) \mathbf{E}_{S \text{ Maxwell } f}^{(r)} \quad (88)$$

Similarly,

$$\mathbf{E}_{S \text{ } n}^{(a)} = \mathbf{E}_{S \text{ Maxwell } n}^{(a)} \quad (89)$$

$$\mathbf{E}_{S \text{ } f}^{(a)} = (j) \mathbf{E}_{S \text{ Maxwell } f}^{(a)} \quad (90)$$

It is worth noting that for plane electromagnetic waves, the static electromagnetic field does not appear. In this case, the electric field consists only of the induced part:

$$\mathbf{E} = \mathbf{E}_I \quad (91)$$

Here, the electric field does not need correction; only the magnetic field requires correction. After this correction, electromagnetic waves become reactive power, meaning the electric and magnetic fields maintain a 90-degree phase difference. Such electromagnetic waves are reactive power waves. Reactive power waves do not transfer energy on time average. The author uses reactive power electromagnetic waves to replace the concept of reverse collapse of electromagnetic waves. Both aim to prevent self-energy flow from transferring energy.

The reverse collapse concept involving time-reversed waves does not modify Maxwell's theory but adds time-reversed electromagnetic waves to nullify self-energy flow. Reactive power electromagnetic waves directly correct Maxwell's theory so that the calculated self-energy flow itself is zero. Both achieve the same effect, but the latter has stronger self-consistency.

4. The Author's Electromagnetic Field Theory

The author has made corrections to Maxwell's electromagnetic theory in (76-79) and (87-90). However, these corrections are merely the author's conjecture, and their correctness remains unverified. In this section, the author presents his own electromagnetic theory.

4.1. Maxwell's Equations

Since Maxwell's electromagnetic field theory has bugs, the author must reconstruct an electromagnetic field theory to replace Maxwell's equations. Starting from Maxwell's equations, the author performs a relaxation process, releasing their degrees of freedom, and then adds electromagnetic postulates proposed by the author. We know Maxwell's equations are:

$$\begin{cases} \nabla \cdot \mathbf{E} = \rho / \epsilon_0 \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\frac{\partial}{\partial t} \mathbf{B} \\ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial}{\partial t} \mathbf{D} \end{cases} \quad (92)$$

4.2. Poynting's Theorem

From the latter two equations of Maxwell's equations, Poynting's theorem can be derived:

$$-\oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma = \int_V (\mathbf{E} \cdot \mathbf{J} + \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t}) dV \quad (93)$$

Poynting's theorem can actually replace the latter two formulas of Maxwell's equations, because Ampère's circuital law and Faraday's law are the main formulas in Maxwell's equations. Indeed, Poynting's theorem can replace these two Maxwell equation formulas.

Performing a relaxation process on Poynting's theorem, i.e., time-integrating it, yields:

$$-\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma = \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E} \cdot \mathbf{J}) dV \quad (94)$$

We see that through time integration, the energy term $\mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t}$ in the above formula is eliminated. Removing this energy term reduces the constraints on the electric and magnetic fields $\mathbf{E}, \mathbf{H}$ in this new Poynting theorem. That is, for the electric and magnetic fields $\mathbf{E}, \mathbf{H}$, the above formula (94) is easier to satisfy compared to Maxwell's equations (92). Therefore, we say time integration is a relaxation process. The above can be rewritten as:

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma + \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E} \cdot \mathbf{J}) dV = 0 \quad (95)$$

From the above, it is obvious that:

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_i) \cdot \hat{n} d\Gamma + \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_i) dV = 0 \quad (96)$$

Due to this relaxation process, the time-integrated Poynting theorem (94) gains more degrees of freedom. Using this formula to calculate the electric and magnetic fields, the resulting fields are allowed to deviate from the solutions of Maxwell's equations! At this point, we can add another postulate established by the author for such electromagnetic fields.

4.3. Postulate: Radiation Does Not Escape the Universe

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} d\Gamma = 0 \quad (97)$$

This, of course, implies simultaneously that self-energy flow does not escape the universe:

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_i) \cdot \hat{n} d\Gamma = 0 \quad (98)$$

and mutual energy flow does not escape the universe:

$$\int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma = 0 \quad (99)$$

Additionally, from formula (96):

$$\int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_i) dV = 0 \quad (100)$$

In the above, Γ is a large spherical surface that encloses all currents $\mathbf{J}$. The above equations (97-100) mean that radiation does not escape the universe. Therefore, we call (97) the postulate that radiation does not escape the universe. It is worth mentioning that Maxwell's electromagnetic theory does not satisfy this postulate. Thus, due to this postulate, the author's electromagnetic theory diverges from Maxwell's.

It is also worth noting that if we do not perform the relaxation process on Maxwell's theory and then add the postulate that radiation does not escape the universe, this postulate would conflict with Maxwell's theory. That is, the equations become overdetermined. Overdetermination would lead to no solutions.

4.4. Superposition Principle

Consider the superposition principle:

$$\mathbf{J} = \sum_{i=1}^N \mathbf{J}_i, \quad \mathbf{E} = \sum_{i=1}^N \mathbf{E}_i, \quad \mathbf{H} = \sum_{i=1}^N \mathbf{H}_i \quad (101)$$

Substituting formula (101) into (94):

$$\sum_{i=1}^N \sum_{j=1}^N \int_{t=-\infty}^{\infty} dt \left(\oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV \right) = 0 \quad (102)$$

Or

$$\begin{aligned} & \sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{t=-\infty}^{\infty} dt \left(\oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV \right) \\ & + \sum_{i=1}^N \int_{t=-\infty}^{\infty} dt \left(\oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_i) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_i) dV \right) = 0 \end{aligned} \quad (103)$$

Applying (98,100) to the above equation yields:

$$\sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{t=-\infty}^{\infty} dt \left(\oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j) \cdot \hat{n} d\Gamma + \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV \right) = 0 \quad (104)$$

4.5. Law of Energy Conservation

Considering that mutual energy flow does not escape the universe (99), we obtain:

$$\sum_{i=1}^N \sum_{j=1, j \neq i}^N \int_{t=-\infty}^{\infty} dt \int_V (\mathbf{E}_i \cdot \mathbf{J}_j) dV = 0 \quad (105)$$

The above is the law of energy conservation. This law can replace the postulate that radiation does not escape the universe. Therefore, for the author's electromagnetic theory, either the postulate that radiation does not escape the universe or the law of energy conservation is sufficient. Both are contradictory to Maxwell's electromagnetic theory.

4.6. Mutual Energy Flow Law

The above is the law of energy conservation. From (104), we can derive the mutual energy flow law:

$$\begin{aligned} & - \int_{t=-\infty}^{\infty} dt \int_{V_i} (\mathbf{E}_j \cdot \mathbf{J}_i) dV \\ & = \int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_i \times \mathbf{H}_j + \mathbf{E}_j \times \mathbf{H}_i) \cdot \hat{n} d\Gamma \\ & = \int_{t=-\infty}^{\infty} dt \int_{V_j} (\mathbf{E}_i \cdot \mathbf{J}_j) dV \end{aligned} \quad (106)$$

(105,106) are the author's electromagnetic laws, replacing Maxwell's equations. This is because formula (105) can only replace the postulate that radiation does not escape the universe, and there is no law yet to replace the relaxed Poynting theorem (95). If we add formula (106), it can completely replace Poynting's theorem or Maxwell's equations.

However, since these formulas are not differential equations like Maxwell's equations with a set of effective solution methods, solving them can only be done by guessing a solution and substituting it into the above formulas. If it satisfies, it is the correct solution; if not, re-guess.

Although the above method is not very efficient, we can use it to verify solutions. We can use the guessing method, such as (76-79), to solve for the magnetic field. We know that (76-79) is not strict; whether this solution is correct still needs to be verified by substituting it into formulas (105, 106).

5. Why Maxwell Made Mistakes

5.1. Displacement Current

We have already described the errors in Maxwell's electromagnetic theory and provided correction methods and verification methods for the corrected results. This section discusses why Maxwell made mistakes. We say the greatness of Maxwell's electromagnetic theory lies in proposing the displacement current, and the mistakes of Maxwell's electromagnetic theory are also due to this mysterious displacement current.

We know that Maxwell's electromagnetic theory started from magnetoquasistatic equations. The following are the quasistatic equations:

$$\begin{cases} \nabla \cdot \mathbf{E}_S = \rho / \epsilon_0 \\ \mathbf{B} = \nabla \times \mathbf{A} \\ \mathbf{E} = -\nabla \phi - \frac{\partial}{\partial t} \mathbf{A} \\ \nabla \times \mathbf{H} = \mathbf{J} \\ \nabla \cdot \mathbf{J} = -\mu_0 \epsilon_0 \frac{\partial}{\partial t} \rho \end{cases} \quad (107)$$

The above are formulas proposed by Maxwell, including the vector potential $\mathbf{A}$, scalar potential ϕ , and the current continuity equation—five formulas in total. Maxwell found that taking the divergence of the left side of Ampère's circuital law gives [41,42]:

$$\nabla \cdot \nabla \times \mathbf{H} = 0 \quad (108)$$

Taking the divergence of the right side of Ampère's circuital law gives:

$$\nabla \cdot \mathbf{J} = -\mu_0 \epsilon_0 \frac{\partial}{\partial t} \rho \quad (109)$$

The results are inconsistent. Maxwell proposed the total current:

$$\mathbf{J}_{total} = \mathbf{J} + \mathbf{J}_{displacement} \quad (110)$$

$$\mathbf{J}_{displacement} = \frac{\partial}{\partial t} \mathbf{D} \quad (111)$$

and changed Ampère's circuital law to:

$$\nabla \times \mathbf{H} = \mathbf{J}_{total} \quad (112)$$

That is,

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial}{\partial t} \mathbf{D} \quad (113)$$

Thus, we obtain:

$$\begin{cases} \nabla \cdot \mathbf{E}_S = \rho / \epsilon_0 \\ \mathbf{B} = \nabla \times \mathbf{A} \\ \mathbf{E} = -\nabla \phi - \frac{\partial}{\partial t} \mathbf{A} \\ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial}{\partial t} \mathbf{D} \\ \nabla \cdot \mathbf{J} = -\mu_0 \epsilon_0 \frac{\partial}{\partial t} \rho \end{cases} \quad (114)$$

We see that the electric Gauss's law used by Maxwell is still not today's Gauss's law. Our modern electric Gauss's law is:

$$\nabla \cdot \mathbf{E} = \rho/\epsilon_0 \quad (115)$$

Maxwell always used the Coulomb gauge, and $\nabla \cdot \mathbf{E}_s = \rho/\epsilon_0$ fits the Coulomb gauge. However, Maxwell's successors revised the electric Gauss's law. After revision, Maxwell's equations became:

$$\begin{cases} \nabla \cdot \mathbf{E} = \rho/\epsilon_0 \\ \mathbf{B} = \nabla \times \mathbf{A} \\ \mathbf{E} = -\nabla\phi - \frac{\partial}{\partial t} \mathbf{A} \\ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial}{\partial t} \mathbf{D} \\ \nabla \cdot \mathbf{J} = -\mu_0\epsilon_0 \frac{\partial}{\partial t} \rho \end{cases} \quad (116)$$

We find that Maxwell's electromagnetic theory today made the following two revisions in total:

$$\mathbf{J} \rightarrow \mathbf{J}_{total} = \mathbf{J} + \frac{\partial}{\partial t} \mathbf{D} \quad (117)$$

$$\mathbf{E}_s = -\nabla\phi \rightarrow \mathbf{E} = -\nabla\phi - \frac{\partial}{\partial t} \mathbf{A} \quad (118)$$

Maxwell equation made not one but two modifications to the magnetoquasistatic equations. Usually, textbooks only mention the correction of displacement current and not the second correction.

Now the question is: we have this set of equations. When such significant changes are made to the equations, can the quantities in the equations, such as $\mathbf{E}$ and $\mathbf{H}$, maintain the same physical meaning as before? Actually, it cannot be guaranteed. When we make such substantial substitutions (117, 118), the meanings of $\mathbf{E}$ and $\mathbf{B}$ in the formulas have actually changed greatly. This change occurs imperceptibly and is very difficult to detect!

5.2. Conflict Between Two Definitions of Magnetic Field

We know the original definition of the magnetic field is given by Ampère's force law:

$$\mathbf{F} = kI d\mathbf{l} \times \mathbf{B} \quad (119)$$

When we place a current element $I d\mathbf{l}$ into a magnetic field $\mathbf{B}$, the Ampère force experienced is $\mathbf{F}$. The above defines the magnetic field, which can be measured by a Hall effect device. From this definition, we see the magnetic field is defined on a straight-line current element $I d\mathbf{l}$.

Now let's look at another definition of the magnetic field:

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (120)$$

Considering the definition of curl:

$$\hat{n} \cdot \mathbf{B} = \lim_{\sigma \rightarrow 0} \frac{1}{\sigma} \oint_C \mathbf{A} \cdot d\mathbf{l} \quad (121)$$

Thus, according to this magnetic field definition, the magnetic field is defined on a loop C . Therefore, these two definitions (119, 120) are fundamentally different! One is defined on a straight-line current element, the other on a closed loop C . They coincidentally coincide under magnetoquasistatic conditions. Under magnetoquasistatic conditions, the magnetic field is given by the Biot-Savart law:

$$\mathbf{B} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \quad (122)$$

The vector potential is:

$$\mathbf{A} = \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}}{r} dV \quad (123)$$

The curl of the vector potential is:

$$\nabla \times \mathbf{A} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \quad (124)$$

Thus, we have:

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (125)$$

Maxwell thus defined:

$$\mathbf{B} \triangleq \nabla \times \mathbf{A} \quad (126)$$

$\triangleq$ means "is defined as". This definition is certainly not wrong, but all this is achieved only under quasistatic electromagnetic field conditions. However, Maxwell further extended this formula to radiation electromagnetic fields:

$$\mathbf{B}^{(r)} \triangleq \nabla \times \mathbf{A}^{(r)} \quad (127)$$

$$\mathbf{B}^{(a)} \triangleq \nabla \times \mathbf{A}^{(a)} \quad (128)$$

These two formulas become problematic. This issue is very hidden and difficult to detect. Here, the author adds superscripts (r) and (a) to radiation electromagnetic fields to make it easier for everyone to realize the problem. Usually, radiation electromagnetic fields are not labeled with superscripts and are indistinguishable from formula (126), making it hard to notice that we have quietly changed the definition of the magnetic field!

The author found that $\nabla \times \mathbf{A}$ is actually not the magnetic field but the average magnetic field $\overline{\mathbf{B}}$ along loop C [39]:

$$\nabla \times \mathbf{A} = \overline{\mathbf{B}} \quad (129)$$

$$\nabla \times \mathbf{A} \neq \mathbf{B} \quad (130)$$

The average magnetic field coincidentally equals the magnetic field under quasistatic conditions:

$$\overline{\mathbf{B}} = \mathbf{B} \quad (131)$$

But for radiation electromagnetic fields:

$$\overline{\mathbf{B}} \neq \mathbf{B} \quad (132)$$

5.3. Measuring Magnetic Field with a Coil

It is worth mentioning that we usually use small coils to measure the magnetic field of alternating electromagnetic fields, especially high-frequency electromagnetic fields. Such measurements actually measure the average magnetic field $\overline{\mathbf{B}}$, see Fig. 3. To obtain the correct magnetic field, conversion is needed. We measure the induced electromotive force:



Figure 3: Coil Probe for Measuring Alternating Magnetic Fields

$$\mathcal{E} = -\frac{\partial}{\partial t} \iint_S \mathbf{B}_{Maxwell} \cdot \hat{n} dS = -j\omega \mathbf{B}_{Maxwell} \cdot \hat{n} S \quad (133)$$

$\mathcal{E}$ is the induced electromotive force on the coil. $S = \iint_S dS$. The above becomes:

$$\mathbf{B}_{Maxwell} \cdot \hat{n} = j \frac{\mathcal{E}}{\omega S} \quad (134)$$

Considering $\mathbf{B}_{Maxwell} = \bar{\mathbf{B}}$, we get:

$$\bar{\mathbf{B}} \cdot \hat{n} = j \frac{\mathcal{E}}{\omega S} \quad (135)$$

If this magnetic field belongs to the near field, according to the author's electromagnetic theory, we should have $\mathbf{B} = \bar{\mathbf{B}}$, so:

$$B_n = \mathbf{B} \cdot \hat{n} = \bar{\mathbf{B}} \cdot \hat{n} = j \frac{\mathcal{E}}{\omega S} \quad (136)$$

If the measured magnetic field is a plane electromagnetic wave, or far field, belonging to a retarded wave, then $\mathbf{B} = -j\mathbf{B}_{Maxwell}$:

$$B_f = \mathbf{B} \cdot \hat{n} = -j\bar{\mathbf{B}} \cdot \hat{n} = \frac{\mathcal{E}}{\omega S} \quad (137)$$

Therefore, measuring the magnetic field with a coil essentially measures the average magnetic field. As for what the actual magnetic field is, it depends on whether it is under quasistatic conditions or radiation far-field conditions, requiring further conversion according to the author's electromagnetic theory.

5.4. How Did Maxwell's Contemporary Electromagnetic Masters Deal with This Issue?

Maxwell's contemporary electromagnetic masters mainly include Kirchhoff and Lorenz. One of them discussed electromagnetic wave problems earlier than Maxwell. Kirchhoff's paper was published in 1857, proposing the telegraph equation and the virtual wave equation on conductors [43]. Lorenz's work was slightly later than Maxwell's, in 1867 [44]. Both of them did not introduce the concepts of electric and magnetic fields. For example, for Ohm's law, Maxwell would write:

$$\mathbf{E} = -\frac{\partial}{\partial t} \mathbf{A} - \nabla \phi \quad (138)$$

$$\mathbf{J} = \sigma \mathbf{E} \quad (139)$$

σ is conductivity. For Ampère's circuital law, Maxwell wrote:

$$\mathbf{H} = \frac{1}{\mu_0} \nabla \times \mathbf{A} \quad (140)$$

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (141)$$

For Kirchhoff and Lorenz, they used:

$$\mathbf{J} = \sigma \left(-\frac{\partial}{\partial t} \mathbf{A} - \nabla \phi \right) \quad (142)$$

$$\nabla \times (\nabla \times \mathbf{A}) = \mu_0 \mathbf{J} \quad (143)$$

That is, they completely avoided introducing the concepts of electric and magnetic fields, using only the magnetic vector potential and scalar potential. It may seem that formulas (142, 143) are no different from formulas (138-141), but there is a significant difference. Following Maxwell's method, one must be responsible for whether the definitions of electric and magnetic fields are correct. For Kirchhoff and Lorenz, they only needed to ensure the formulas for the vector potential and scalar potential were correct.

I think it's not that Kirchhoff and Lorenz didn't understand the concepts of electric and magnetic fields, but rather they felt introducing these concepts was risky. Although under quasistatic conditions we have:

$$\mathbf{E} = -\frac{\partial}{\partial t} \mathbf{A} - \nabla \phi \quad (144)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (145)$$

But who can guarantee that these two formulas definitely hold under radiation electromagnetic field conditions? So the most straightforward approach is that $\nabla \times \mathbf{A}$ is simply the curl of the magnetic vector potential—this is not wrong. As for whether it is the magnetic field, that can be left for future generations to resolve. Similarly, there's no need to consider whether $-\frac{\partial}{\partial t} \mathbf{A} - \nabla \phi$ is the electric field.

6. Maxwell's Electromagnetic Theory Has Serious Errors, So Why Are Its Results Mostly Correct?

6.1 Two Errors Canceling Each Other

This issue is actually very simple. Maxwell's electromagnetic theory made two errors in total, but the effects of these two errors cancel each other out. This is the so-called result of "a negative times a negative equals a positive." However, this cancellation does not occur everywhere; it happens in most places. There are still some important aspects that expose the problems of Maxwell's electromagnetic theory. We have already explained that the correct energy flow should be mutual energy flow, for example, the mutual energy flow density function is:

$$\mathbf{S}_m = \frac{1}{2} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \quad (146)$$

But Maxwell's electromagnetic theory believes that energy is transferred by self-energy flow, i.e., the Poynting vector:

$$\mathbf{S}_{1Maxwell} = \mathbf{E}_{1Maxwell} \times \mathbf{H}_{1Maxwell}^* \quad (147)$$

In the above Poynting vector, the electromagnetic fields are all calculated by Maxwell's electromagnetic theory. For the far field:

$$\mathbf{E}_{1Maxwell} = \mathbf{E}_1 \quad (148)$$

In the above, $\mathbf{E}_1$ is the correct electric field, also the electric field of the author's electromagnetic theory. Hence:

$$\mathbf{S}_{1Maxwell} = \mathbf{E}_1 \times \mathbf{H}_{1Maxwell}^* \quad (149)$$

For the far field, since:

$$\mathbf{H}_1 = (-j)\mathbf{H}_{1Maxwell} \quad (150)$$

Here $\mathbf{H}_1$ is the magnetic field defined by the author, which is the correct magnetic field. Or:

$$\mathbf{H}_{1Maxwell} = j\mathbf{H}_1 \quad (151)$$

From (146), energy transfer requires $\mathbf{E}_2^* \times \mathbf{H}_1$ and $\mathbf{E}_2^* \times \mathbf{H}_1$ to transfer energy, so it requires:

$$\mathbf{E}_1 \times \mathbf{H}_2^* = \text{Real}, \quad \mathbf{E}_2^* \times \mathbf{H}_1 = \text{Real} \quad (152)$$

This further requires:

$$\mathbf{H}_1 \sim \mathbf{E}_2 \quad (153)$$

" $\sim$ " means proportional, i.e., maintaining the same phase. However:

$$\mathbf{E}_2 \sim \mathbf{H}_{2Maxwell} \quad (154)$$

$$\mathbf{H}_1 \sim \mathbf{H}_{2Maxwell} \quad (155)$$

We also know $\mathbf{H}_2$ is an advanced wave, so:

$$\mathbf{H}_2 = (j)\mathbf{H}_{2Maxwell} \quad (156)$$

$\mathbf{H}_2$ is the magnetic field defined by the author. Or:

$$\mathbf{H}_{2Maxwell} = -j\mathbf{H}_2 \quad (157)$$

Thus:

$$\mathbf{H}_1 \sim \mathbf{H}_{2Maxwell} \sim -j\mathbf{H}_2 \quad (158)$$

So:

$$\begin{aligned} \mathbf{S}_{1Maxwell} &= \mathbf{E}_1 \times \mathbf{H}_{1Maxwell}^* \\ &= \mathbf{E}_1 \times (j\mathbf{H}_1)^* \\ &= \mathbf{E}_1 \times (j(-j\mathbf{H}_2))^* \\ &= \mathbf{E}_1 \times \mathbf{H}_2^* \end{aligned} \quad (159)$$

We know that for plane electromagnetic waves:

$$\mathbf{E}_1 \times \mathbf{H}_2^* = \mathbf{E}_2^* \times \mathbf{H}_1 \quad (160)$$

Therefore:

$$\mathbf{S}_{1Maxwell} = \mathbf{E}_1 \times \mathbf{H}_2^* = \frac{1}{2}(\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) = \mathbf{S}_m \quad (161)$$

Thus:

$$\mathbf{S}_{1Maxwell} = \mathbf{S}_m \quad (162)$$

We find that Maxwell's electromagnetic theory made two mistakes. The first mistake is that the energy carrier should be mutual energy flow:

$$S_m = \frac{1}{2}(\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \quad (163)$$

But Maxwell's electromagnetic theory believes energy is transferred by self-energy flow:

$$\mathbf{S}_{1Maxwell} = \mathbf{E}_{1Maxwell} \times \mathbf{H}_{1Maxwell}^* \quad (164)$$

However, coincidentally, Maxwell's calculation of the electric field happens to be:

$$\mathbf{E}_{1Maxwell} = \mathbf{E}_1 \quad (165)$$

Maxwell's calculation of the magnetic field is wrong:

$$\mathbf{H}_{1Maxwell} = j\mathbf{H}_1 \quad (166)$$

But this error leads to:

$$\mathbf{H}_{1Maxwell} = \mathbf{H}_2 \quad (167)$$

So:

$$\mathbf{S}_{1Maxwell} = \mathbf{E}_1 \times \mathbf{H}_2^* \quad (168)$$

This in turn makes our calculated Poynting vector actually calculate the mutual energy flow $\mathbf{E}_1 \times \mathbf{H}_2^*$.

Although $\mathbf{S}_{1Maxwell}$ calculated by Maxwell's electromagnetic theory suffers from two errors that cancel each other out, this cancellation is only partial and does not occur in all situations. For example, below we will use examples to illustrate that mutual energy flow $\mathbf{S}_m$ is generated at the source and annihilated at the sink, while $\mathbf{S}_{1Maxwell}$ does not possess this property.

6.2. Dual-Plane Antenna System

Dual-plane current antenna system, see Fig. 4. Assume $\mathbf{J}_1$ is responsible for transmitting electromagnetic waves, and $\mathbf{J}_2$ is responsible for receiving them.

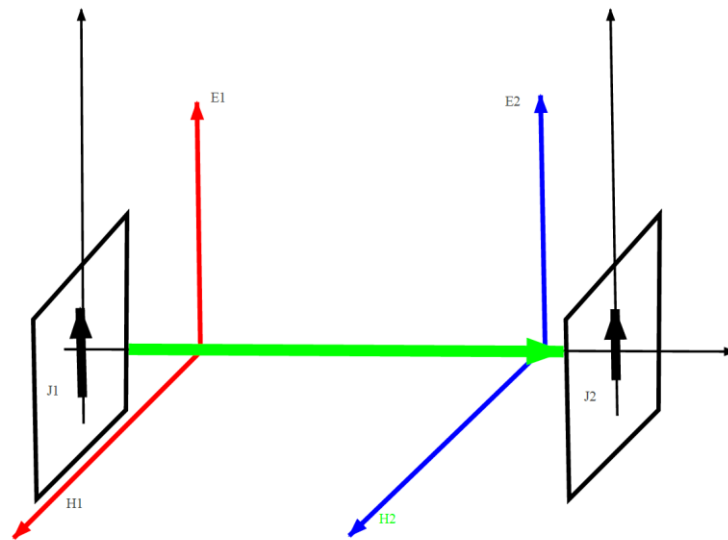


Figure 4: System of Dual-Plane Antennas

6.2.1. Electromagnetic Field of a Single Plane

The current density of a plane current is:

$$\mathbf{J} = J_0 \hat{x} \delta(z - 0) \quad (169)$$

The quasistatic magnetic field produced by this current is:

$$\mathbf{H} = \hat{y} \frac{1}{2} J_0 \begin{cases} 1 & z < 0 \\ -1 & z > 0 \end{cases} \quad (170)$$

The radiation magnetic field is:

$$\mathbf{H} = \hat{y} \frac{1}{2} J_0 \exp(-jkz) \begin{cases} 1 & z < 0 \\ -1 & z > 0 \end{cases} \quad (171)$$

Regarding the calculation of magnetic fields and electromagnetic wave propagation, this paper adopts a modeling path drastically different from traditional Maxwell theory. The author believes that a current source does not solely produce retarded waves but simultaneously excites both retarded waves and advanced waves. Based on the directionality of energy transfer, this paper sets an asymmetric boundary selection: exciting advanced waves on the left side of the current source and retarded waves on its right side. The physical intention of this choice is to ensure that energy flow is always directed along the +z direction, consistent with the Presets scenario where a receiving plane (sink) exists in that direction. As for the electromagnetic wave component propagating to the left, since there is no sink on the left to absorb energy flow, this component only manifests as reactive power and does not produce substantive energy transfer; hence, it is omitted in the calculation model.

Readers may have doubts about the mechanism of transforming spherical waves into plane waves. In fact, the transmitting source initially radiates spherical retarded waves in a "broadcast mode" into all space. Simultaneously, the sink at the receiving end also randomly radiates spherical advanced waves. When the retarded wave emitted by the source reaches the sink's location, and happen to the sink excites a coherent advanced wave of the same frequency, the two achieve phase synchronization and locking. This interference between retarded and advanced waves causes the electromagnetic field strength to be greatly constructively enhanced along the line connecting the transmitter and receiver, while rapidly attenuating through destructive interference in other non-coherent directions. In this state, the retarded and advanced waves are no longer diffuse spherical radiations but guide each other, jointly constructing a directional "photon waveguide mode." Within this specific mode, the electromagnetic wavefront undergoes localized evolution, presenting an ideal quasi-plane wave form. This means that even if the physical dimensions of the source and sink are extremely limited (e.g., dipole antennas) and the distance between them is extremely far, upon entering the photon waveguide mode, the mutual energy flow density between them can still be accurately described by the plane wave formula (171).

The quasistatic electric field is:

$$\mathbf{E} = (-j)\hat{x}\frac{\eta}{2}J_0 \quad (172)$$

where $(-j)$ is due to:

$$\mathbf{E} = -\frac{\partial}{\partial t}\mathbf{A} = -j\omega\mathbf{A} \sim -jJ_0 \quad (173)$$

η is because we know the vacuum impedance relating the electric and magnetic fields is η , i.e.:

$$|\mathbf{E}| = \eta|\mathbf{H}| \quad (174)$$

Therefore, the radiation electric field of the plane current is:

$$\mathbf{E} = (-j)\hat{x}\frac{\eta}{2}J_0\exp(-jkz) \quad (175)$$

This electric field propagates to the right.

6.2.2. Electromagnetic Field of Dual Planes

We simply have two currents at $z = 0$ and $z = L$:

$$\mathbf{J}_1 = J_{10}\hat{x}\delta(z - 0) \quad (176)$$

$$\mathbf{J}_2 = J_{20}\hat{x}\delta(z - L) \quad (177)$$

The generated electromagnetic fields according to formulas (175, 171) are:

$$\mathbf{E}_1 = (-j)\hat{x}\frac{\eta}{2}J_{10}\exp(-jkz) \quad (178)$$

$$\mathbf{H}_1 = \hat{y}\frac{1}{2}J_{10}\exp(-jkz)\begin{cases} 1 & z < 0 \\ -1 & z > 0 \end{cases} \quad (179)$$

$$\mathbf{E}_2 = (-j)\hat{x}\frac{\eta}{2}J_{20}\exp(-jk(z - L)) \quad (180)$$

$$\mathbf{H}_2 = \hat{y}\frac{1}{2}J_{20}\exp(-jk(z - L))\begin{cases} 1 & z < L \\ -1 & z > L \end{cases} \quad (181)$$

Considering the load circuit is purely resistive, the current $\mathbf{J}_2$ is proportional to the electric field $\mathbf{E}_1$.

$$\mathbf{J}_2 \sim \mathbf{E}_1(z = L)$$

$$= (-j)\hat{x}\frac{\eta}{2}J_{10}\exp(-jkL) \quad (182)$$

We have reason to assume:

$$|\mathbf{J}_1| = |\mathbf{J}_2| \quad (183)$$

This is because the current of the source $\mathbf{J}_1$ emits a photon, and the current of the sink $\mathbf{J}_2$ receives a photon. Imagine inside an atom, an electron jumps from energy level 2 to level 1, emitting a photon; in the sink, an electron in an atom jumps from level 1 to level 2,

absorbing a photon. These two situations are completely symmetric, and their currents should be exactly equal. Therefore:

$$J_2 = (-j)\hat{x}J_{10}\exp(-jkL)$$

$$J_2 = \hat{x}J_{20} \quad (184)$$

$$J_{20} = (-j)J_{10}\exp(-jkL) \quad (185)$$

$$\begin{aligned} H_2 &= \hat{y}\frac{1}{2}J_{20}\exp(-jk(z-L))\begin{cases} 1 & z < L \\ -1 & z > L \end{cases} \\ &= \hat{y}\frac{1}{2}((-j)J_{10}\exp(-jkL))\exp(-jk(z-L))\begin{cases} 1 & z < L \\ -1 & z > L \end{cases} \\ &= \hat{y}(-j)\frac{1}{2}J_{10}\exp(-jkz)\begin{cases} 1 & z < L \\ -1 & z > L \end{cases} \end{aligned} \quad (186)$$

$$\begin{aligned} E_2 &= (-j)\hat{x}\frac{\eta}{2}J_{20}\exp(-jk(z-L)) \\ &= (-j)\hat{x}\frac{\eta}{2}((-j)J_{10}\exp(-jkL))\exp(-jk(z-L)) \end{aligned}$$

6.2.3. Calculating Mutual Energy Flow

$$= -\hat{x}\frac{\eta}{2}J_{10}\exp(-jkz) \quad (187)$$

$$S_m = E_1 \times H_2^* + E_2^* \times H_1$$

$$= (E_1 H_2^* + E_2^* H_1)\hat{z}$$

$$\begin{aligned} &= \hat{z} \begin{cases} \frac{-j\eta J_{10}}{2} \alpha \left(\frac{-jJ_{10}}{2} \alpha\right)^* + \left(\frac{-\eta J_{10}}{2} \alpha\right)^* \frac{J_{10}}{2} \alpha & z < 0 \\ \frac{-j\eta J_{10}}{2} \alpha \left(\frac{-jJ_{10}}{2} \alpha\right)^* + \left(\frac{-\eta J_{10}}{2} \alpha\right)^* \frac{-J_{10}}{2} \alpha & 0 < z < L \\ \frac{-j\eta J_{10}}{2} \alpha \left(\frac{jJ_{10}}{2} \alpha\right)^* + \left(\frac{-\eta J_{10}}{2} \alpha\right)^* \frac{-J_{10}}{2} \alpha & L < z \end{cases} \\ &= \hat{z} J_{10} J_{10}^* \frac{\eta}{4} \begin{cases} (-j)(-j)^* + (-1)^*(1) & z < 0 \\ (-j)(-j)^* + (-1)^*(-1) & 0 < z < L \\ (-j)(j)^* + (-1)^*(-1) & L < z \end{cases} \\ &= \hat{z} J_{10} J_{10}^* \frac{\eta}{2} \begin{cases} 0 & z < 0 \\ 1 & 0 < z < L \\ 0 & L < z \end{cases} \end{aligned} \quad (188)$$

Where $\alpha = \exp(-jkz)$. It can be seen that the mutual energy flow density S_m is generated at $z = 0$ and annihilated at $z = L$, exhibiting particle-like behavior.

6.2.4. Verifying Satisfaction of the Mutual Energy Flow Law

In the previous chapter, the author provided the calculation method for his electromagnetic field theory. First, the magnetic and electric fields are obtained under magnetoquasistatic conditions, then the propagation factor $\exp(-jkz)$ is considered. This method is merely the author's conjecture, consistent with the proposed correction method for electromagnetic fields (76-79), and cannot guarantee absolute correctness. To prove the correctness of this method, in principle, the calculated electromagnetic fields must be substituted into the mutual energy flow law to see if it is satisfied. The mutual energy flow law is (14):

$$\begin{aligned} & - \int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV \\ &= \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \\ &= \int_{V_2} (\mathbf{E}_1 \cdot \mathbf{J}_2^*) dV \end{aligned} \quad (189)$$

If both $\mathbf{J}_1$ and $\mathbf{J}_2$ are surface currents, the above can be written as:

$$\begin{aligned} & - \iint_{\Gamma_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) d\Gamma \\ &= \iint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \\ &= \iint_{\Gamma_2} (\mathbf{E}_1 \cdot \mathbf{J}_2^*) d\Gamma \end{aligned} \quad (190)$$

Γ_1 , Γ , Γ_2 are planes of identical size, so the surface integrals can be ignored:

$$-(\mathbf{E}_2^* \cdot \mathbf{J}_1)|_{\Gamma_1} = (\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{z}|_{\Gamma} = (\mathbf{E}_1 \cdot \mathbf{J}_2^*)|_{\Gamma_2} \quad (191)$$

From formula (188):

$$(\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) \cdot \hat{z}|_{\Gamma} = J_{10} J_{10}^* \frac{\eta}{2} \quad (192)$$

We can directly calculate:

$$\begin{aligned} -(\mathbf{E}_2^* \cdot \mathbf{J}_1)|_{\Gamma_1} &= -(-\hat{x} \frac{\eta}{2} J_{10} \exp(-jkz))^* \cdot (\hat{x} J_{10})|_{z=0} \\ &= -(-\frac{\eta}{2} J_{10})^* (J_{10}) = \frac{\eta}{2} J_{10} J_{10}^* \end{aligned} \quad (193)$$

We directly calculate:

$$\begin{aligned} (\mathbf{E}_1 \cdot \mathbf{J}_2^*)|_{\Gamma_2} &= (-j) \hat{x} \frac{\eta}{2} J_{10} \exp(-jkL) \cdot ((-j) \hat{x} J_{10} \exp(-jkL))^* \\ &= (-j) \hat{x} \frac{\eta}{2} J_{10} \cdot ((-j)^* \hat{x} J_{10}^*) \\ &= \frac{\eta}{2} J_{10} J_{10}^* \end{aligned} \quad (194)$$

Formulas (192), (193), and (194) show that the formula (191) of the mutual energy flow law is satisfied, indicating that the electromagnetic fields obtained by the author are correct.

6.2.5. Calculating the Poynting Vector

From formula (188), we see that the mutual energy flow is generated at $z = 0$ and annihilated at $z = L$. Therefore, we consider the mutual energy flow as the energy flow of a photon, and we can regard the mutual energy flow itself as a photon. From (178) we already have:

$$\mathbf{E}_{Maxwell\ 1} = \mathbf{E}_1 = (-j)\hat{x}\frac{\eta}{2}J_{10}\exp(-jkz)$$

According to Maxwell's electromagnetic theory, the magnetic field is in phase with the electric field, so:

$$\mathbf{H}_{Maxwell\ 1}(z > 0) = (-j)\hat{y}\frac{1}{\eta}J_{10}\exp(-jkz)$$

$$\begin{aligned}\mathbf{S}_{1Maxwell} &= \mathbf{E}_{1Maxwell} \times \mathbf{H}_{1Maxwell} \\ &= (-j)\hat{x}\frac{\eta}{2}J_{10}\exp(-jkz) \times ((-j)\hat{y}\frac{1}{\eta}J_{10}\exp(-jkz))^* \\ &= \eta\frac{1}{4}J_{10}J_{10}^*\hat{z}\end{aligned}\quad (195)$$

Comparing (188) and (195), we have:

$$\mathbf{S}_m = 2\mathbf{S}_{1Maxwell}\quad (196)$$

It is worth noting that formula (196) still has a constant factor 2 difference. To make them completely identical, it seems that the mutual energy flow $\mathbf{S}_m$ should be compressed by $\frac{1}{2}$, thus defining the mutual energy flow density as:

$$\mathbf{S}_m' = \frac{1}{2}(\mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1) = \frac{1}{2}\mathbf{S}_m\quad (197)$$

Then:

$$\mathbf{S}_m' = \mathbf{S}_{1Maxwell}\quad (198)$$

Regarding the choice of the coefficient 1/2 in mutual energy flow calculation, the author has engaged in long-term theoretical deliberation and now has a clear physical explanation. When calculating the direct energy coupling from the primary to the secondary of a transformer, or from a transmitting antenna to a receiving antenna, the mutual energy flow density $\mathbf{S}_m$ does not require the introduction of the 1/2 factor. However, when we need to equivalently replace mutual energy flow with traditional self-energy flow (Poynting vector), this coefficient must be introduced to obtain $\mathbf{S}_m'$. This difference is not a calculation error but stems from the different fundamental models used by the two theories to describe radiation directionality: Poynting's theorem describes energy diffusion in opposite directions (e.g., left and right, or omnidirectionally); whereas the author's dual-plane radiation model strictly defines unidirectional energy transmission from source to sink. Therefore, formula (196) itself is physically complete and correct. The introduction of the 1/2 factor serves merely as a "conversion interface," aiming to align the mutual energy flow numerically with the conventional definition of the Poynting vector. Further analysis shows that the numerical validity of Eq. (198) is strictly limited to the specific spatial region $0 < z < L$. Once outside this region, the physical characteristics of mutual energy flow and the Poynting vector diverge sharply. Mutual energy flow $\mathbf{S}_m'$ exhibits distinct discrete dynamics: generated at $z = 0$ and annihilated at $z = L$. In contrast, the Poynting vector $\mathbf{S}_{1Maxwell}$ lacks such localized generation and annihilation characteristics. This discovery explains why the Poynting vector remains effective in solving macroscopic engineering problems but fails to explain the nature of photons in the microscopic realm. Mutual energy flow $\mathbf{S}_m'$ not only reveals the physical picture of photons being generated at the transmitting antenna and annihilated at the receiving antenna but also provides a key theoretical key to solving the 160-year paradox of wave-particle duality: wave descriptions correspond to reactive field evolution, while true particle characteristics are carried by mutual energy flow with source and sink properties.

6.2.6. Calculating Mutual Energy Flow According to Maxwell's Electromagnetic Theory

We calculate the mutual energy flow between $0 < z < L$:

$$\begin{aligned}\mathbf{S}_{Maxwell\ m} \\ &= \mathbf{E}_{Maxwell\ 1} \times \mathbf{H}_{Maxwell\ 2}^* + \mathbf{E}_{Maxwell\ 2}^* \times \mathbf{H}_{Maxwell\ 1}\end{aligned}\quad (199)$$

If we calculate the mutual energy flow density according to Maxwell's electromagnetic theory, we know that the electric field $E_{Maxwell\ 1}$ is a retarded wave:

$$E_{Maxwell\ 1} = E_1 = -j\frac{1}{2}\eta J_{10}\exp(-jkz)\hat{x} \quad (200)$$

According to Maxwell's electromagnetic theory, the magnetic field is in phase with the electric field:

$$H_{Maxwell\ 1} = -j\frac{1}{2}J_{10}\exp(-jkz)\hat{y} \quad (201)$$

$$J_2 \sim E_{Maxwell\ 1}|_{z=L} = -j\eta J_{10}\exp(-jkL)\hat{x} \quad (202)$$

Considering:

$$|J_2| = |J_1| \quad (203)$$

$$J_2 = -jJ_{10}\exp(-jkL)\hat{x} \quad (204)$$

Considering $E_{2Maxwell}$ is an advanced wave, and for $z < L$:

$$\begin{aligned} E_{2Maxwell} &= (-j)\eta\frac{1}{2}J_{20}\exp(jk|z-L|)\hat{x} \\ &= (-j)J_{20}\eta\frac{1}{2}\exp(-jk(z-L))\hat{x} \\ &= (-j)(-jJ_{10}\eta\frac{1}{2}\exp(-jkL))\exp(-jk(z-L))\hat{x} \\ &= -J_{10}\eta\frac{1}{2}\exp(-jkz)\hat{x} \end{aligned} \quad (205)$$

$H_{Maxwell\ 2}$ should be in phase with $E_{2Maxwell}$, differing in magnitude by a factor of η .

$$H_{Maxwell\ 2} = -\frac{1}{2}J_{10}\exp(-jkz)\hat{y} \quad (206)$$

$S_{Maxwell\ m}$

$$\begin{aligned} &= E_{Maxwell\ 1} \times H_{Maxwell\ 2}^* + E_{Maxwell\ 2}^* \times H_{Maxwell\ 1} \\ &= (E_{Maxwell\ 1}H_{Maxwell\ 2}^* + E_{Maxwell\ 2}^*H_{Maxwell\ 1})\hat{z} \\ &= ((-j\frac{1}{2}\eta J_{10}\alpha)(-\frac{1}{2}J_{10}\alpha)^* + (-J_{10}\eta\frac{1}{2}\alpha)^*(-j\frac{1}{2}J_{10}\alpha))\hat{z} \\ &= ((-j\frac{1}{2}\eta J_{10})(-\frac{1}{2}J_{10})^* + (-J_{10}\eta\frac{1}{2})^*(-j\frac{1}{2}J_{10}))\hat{z} \\ &= \frac{1}{4}\eta J_{10}J_{10}^*((-j)(-1)^* + (-1)^*(-j))\hat{z} \\ &= (-j)\frac{1}{4}\eta J_{10}J_{10}^*((-1)^* + (-1)^*)\hat{z} \end{aligned}$$

$$= j \frac{1}{2} \eta J_{10} J_{10}^* \hat{z} \quad (207)$$

where $\alpha = \exp(-jkz)$, hence,

$$S_{Maxwell\ m} = \text{imaginary} \quad (208)$$

The above shows that if we calculate the mutual energy flow density according to Maxwell's electromagnetic theory, it is imaginary. That is, according to Maxwell's theory, mutual energy flow density does not transfer energy. Although we obtained this for a specific case, it can be generalized: Maxwell's electromagnetic theory is inherently a theory of self-energy flow. In this theory, self-energy flow transfers energy, while mutual energy flow does not. The author believes this may be the fundamental reason why everyone has always called the mutual energy theorem (Welch reciprocity theorem) "reciprocal" rather than "mutual energy." In Maxwell's theory, mutual energy flow does not transfer energy; energy is transferred by self-energy flow or the Poynting vector. Only in the author's theory does mutual energy flow truly transfer energy, whereas self-energy flow or the Poynting vector instead does not transfer energy or is reactive.

6.3. Dual Dipole Antennas

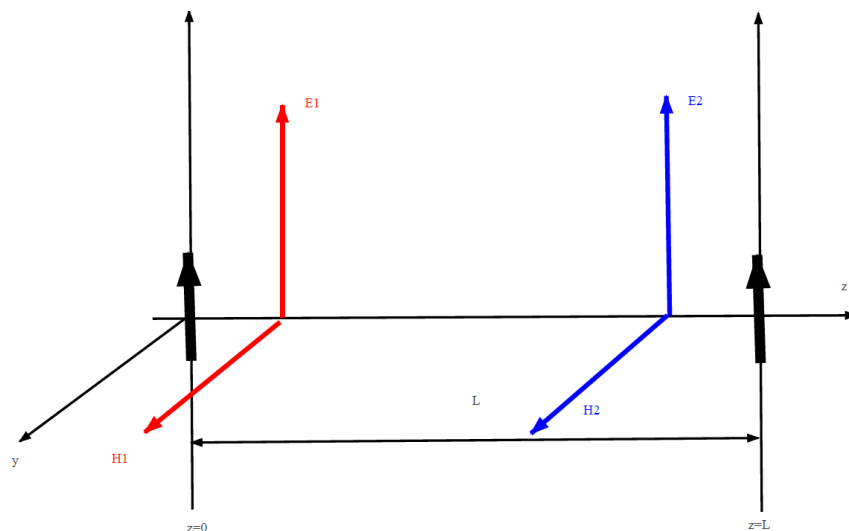


Figure 5: Radiation from Dual Dipole Antennas

The physical mechanism described for dual-plane radiation is essentially highly consistent with that of a dual-dipole antenna system. The author believes that a dipole source initially operates in "Broadcast Mode," where its radiated spherical electromagnetic waves exhibit reactive power characteristics. In this mode, the source does not experience substantial energy loss; all radiated energy automatically returns to the source via a time-reversal mechanism. This return is instantaneous, meaning the energy emission process neither loses energy nor consumes effective time. In this state, energy can continuously undergo this closed-loop emission and recovery until a photon is formally emitted, at which point the source's energy decreases by one photon.

Photon generation depends on the synergistic coupling between the source and the sink. The sink, like the source, randomly generates advanced waves of a reactive power nature. When the retarded wave emitted by the source reaches the sink and synchronizes in phase with the advanced wave radiated by the sink, strong coherent superposition occurs. This interference effect greatly enhances the electromagnetic field along the line connecting the source and sink, while weakening it in other directions due to destructive interference.

Through this synchronized interference, the retarded and advanced waves guide each other, forming the so-called "Photon Waveguide Mode." In this mode, electromagnetic waves transform from diffuse spherical waves into directional quasi-plane waves. This means that even if two plane antennas are not infinite and are spaced far apart, as long as they enter the photon waveguide mode, the energy flow between them transports directionally in the form of plane (or quasi-plane) waves. This conclusion also applies to electrically small dipole sources. Therefore, the mutual energy flow density formula (188) derived earlier based on a plane wave background remains universally applicable and accurate for point source systems.

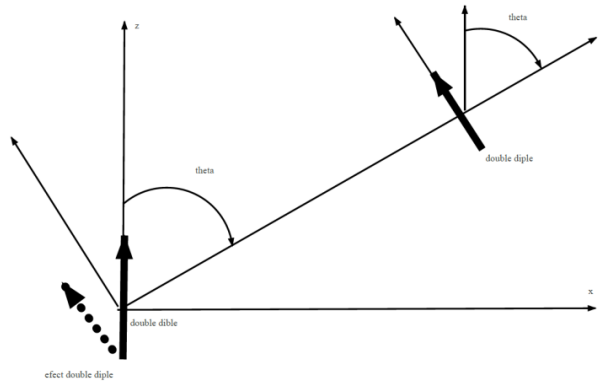


Figure 6: Radiation from Dual Dipole Antennas

If there is an angle between the two dipoles, as shown in Fig. 6, consider the radiation situation. Assume one dipole is at the position shown in Fig. 6. We can project dipole 1 onto the direction of dipole 2, so the effective dipole 1 is:

$$J_1^{effect} = J_1 \cdot \sin(\theta) \quad (209)$$

J_1^{effect} is at the dashed line position in Fig. 6.

$$S_m = \hat{r} J_{10}^{effect} (J_{10}^{effect})^* \frac{\eta}{2} \begin{cases} 0 & z < 0 \\ 1 & 0 < z < L \\ 0 & L < z \end{cases} \quad (210)$$

Or:

$$S_m = \hat{r} (J_{10} J_{10}^* \cdot \sin^2(\theta)) \frac{\eta}{2} \begin{cases} 0 & z < 0 \\ 1 & 0 < z < L \\ 0 & L < z \end{cases} \quad (211)$$

For $0 < z < L$:

$$S_m = \hat{r} (J_{10} J_{10}^* \cdot \sin^2(\theta)) \frac{\eta}{2} \quad (212)$$

Here we assume only one dipole sink, so only one photon is produced. In reality, dipoles cover the entire spherical surface Γ . Considering we should calculate the energy flow each dipole can receive, this energy flow should divide the above expression by the spherical surface area. Therefore, the total radiation energy flow from the dipole to the entire sphere should be:

$$S_m = \frac{1}{4\pi r^2} \hat{r} (J_{10} J_{10}^* \cdot \sin^2(\theta)) \frac{\eta}{2} \quad (213)$$

The above calculation actually tells us:

$$S_m \sim \frac{1}{r^2} \sin^2(\theta) \quad (214)$$

The above is the radiation pattern, often measured in antenna measurements.

6.4. Radiation of a Dipole Antenna

6.4.1. Calculation According to Maxwell's Electromagnetic Theory

If we calculate the radiation of a dipole antenna according to Maxwell's electromagnetic theory, see Fig. 7. We assume only the dipole current J_1 exists at the coordinate origin, and there are no other currents in space. The far-field boundary is handled according to the Silver-Müller condition.

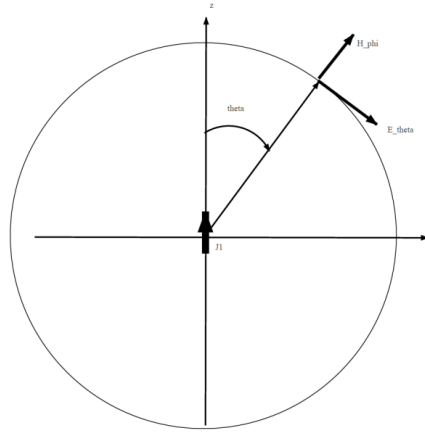


Figure 7: Calculating Dipole Transmitting Antenna Radiation According to Maxwell's Electromagnetic Theory.

According to Poynting's theorem:

$$\begin{aligned}
 & - \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \\
 & = \int \mathbf{E}_1 \cdot \mathbf{J}_1 dV + \int (\mathbf{E}_1 \cdot \frac{\partial}{\partial t} \mathbf{D}_1 + \mathbf{H}_1 \cdot \frac{\partial}{\partial t} \mathbf{B}_1) dV
 \end{aligned} \quad (215)$$

Time-integrating both sides:

$$- \int_{t=-\infty}^{\infty} dt \oint_{\Gamma} (\mathbf{E}_1 \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = \int_{t=-\infty}^{\infty} dt \int \mathbf{E}_1 \cdot \mathbf{J}_1 dV \quad (216)$$

Applying the Fourier transform yields:

$$- \oint_{\Gamma} (\mathbf{E}_1^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma = \int \mathbf{E}_1^* \cdot \mathbf{J}_1 dV \quad (217)$$

Or:

$$- \int \mathbf{E}_1^* \cdot \mathbf{J}_1 dV = \oint_{\Gamma} (\mathbf{E}_1^* \times \mathbf{H}_1) \cdot \hat{n} d\Gamma \quad (218)$$

It is worth noting that the above is actually a calculation based on Maxwell's electromagnetic theory; we should add subscripts to indicate this. So:

$$- \int \mathbf{E}_{1Maxwell}^* \cdot \mathbf{J}_1 dV = \oint_{\Gamma} (\mathbf{E}_{1Maxwell}^* \times \mathbf{H}_{1Maxwell}) \cdot \hat{n} d\Gamma \quad (219)$$

Considering $\mathbf{E}_{1Maxwell} = \mathbf{E}_1$:

$$- \int \mathbf{E}_1^* \cdot \mathbf{J}_1 dV = \oint_{\Gamma} \mathbf{S}_{1Maxwell} \cdot \hat{n} d\Gamma \quad (220)$$

6.4.2. Calculation According to the Author's Electromagnetic Theory

To calculate the radiation of a dipole antenna according to the author's electromagnetic theory, see Fig. 8. We do not use the Silver-Müller boundary condition but instead replace it with currents $\mathbf{J}_2$ enclosing the entire antenna. $\mathbf{J}_2$ can be assumed to be on a sphere of infinite radius. $\mathbf{J}_2$ corresponds to the black foam absorbers in an anechoic chamber.

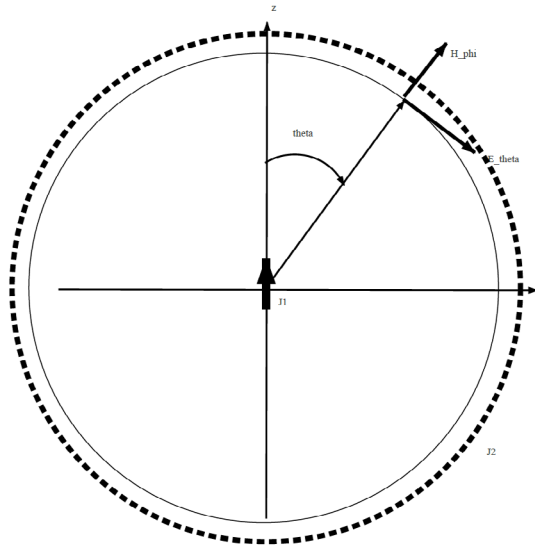


Figure 8: Calculating dipole transmitting antenna radiation according to the author's electromagnetic theory. Absorbers J_2 need to be placed on a sphere of infinite radius.

According to the mutual energy flow law, the left equality of (14):

$$-\int_{V_1} (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV = \oint_{\Gamma} \mathbf{S}_m \cdot \hat{n} d\Gamma \quad (221)$$

where:

$$\mathbf{S}_m = \mathbf{E}_1 \times \mathbf{H}_2^* + \mathbf{E}_2^* \times \mathbf{H}_1 \quad (222)$$

In this case, we need to use $\mathbf{S}_m'$ instead of $\mathbf{S}_m$, so:

$$-\int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV = \oint_{\Gamma} \mathbf{S}_m' \cdot \hat{n} d\Gamma \quad (223)$$

Since we already know (198), the above can be written as:

$$-\int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV = \oint_{\Gamma} \mathbf{S}_{1Maxwell} \cdot \hat{n} d\Gamma \quad (224)$$

We find that the right-hand sides of the equations are the same as the output of Poynting's theorem (220). However, the left-hand sides are different. The sameness of the right-hand sides is the reason why Maxwell's theory yields results consistent with the author's method in calculating electromagnetic radiation. But the difference in the left-hand sides precisely reveals which method is correct and which is erroneous.

6.4.3. Electromagnetic Radiation Calculated via Poynting's theorem in Maxwell's Theory

$$\mathbf{A} = \int_V \mu_0 \mathbf{J} \frac{\exp(-jkR)}{4\pi R} dv' = \iiint \mu_0 \frac{\exp(-jkR)}{4\pi R} dx' dy' dz' \quad (225)$$

Considering:

$$\mathbf{J}(\mathbf{r}') = \begin{cases} I_0 \delta(x') \delta(y') \hat{z} & \Delta z/2 < z' < \Delta z/2 \\ 0 & \text{else where} \end{cases} \quad (226)$$

Thus:

$$\begin{aligned}
 \mathbf{A} &= \hat{z}\mu_0 I_0 \int_{-\infty}^{\infty} \delta(x') dx' \int_{-\infty}^{\infty} \delta(y') dy' \int_{-\Delta x/2}^{\Delta x/2} \frac{\exp(-jkR)}{4\pi R} dz' \\
 &= \hat{z}\mu_0 I_0 \int_{-\Delta x/2}^{\Delta x/2} \frac{\exp(-jkR)}{4\pi R} dz' \\
 &= \frac{\mu_0 I_0 \exp(-jkR)}{4\pi R} \Delta x \hat{z}
 \end{aligned} \tag{227}$$

$$R = |x - x'|, \quad r = |x| \tag{228}$$

Since x' is very close to the origin:

$$R \simeq r \tag{229}$$

$$\mathbf{A} = \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \hat{z} \tag{230}$$

$$\mathbf{H} = \frac{1}{\mu_0} \nabla \times \mathbf{A} = \frac{1}{\mu_0} \nabla \times A_z \hat{z} \tag{231}$$

Considering spherical coordinates:

$$A_r = \mathbf{A} \cdot \hat{r} = A_z \hat{z} \cdot \hat{r} = A_z \cos \theta = \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \cos \theta \tag{232}$$

$$A_\theta = A_z \hat{z} \cdot \hat{\theta} = -A_z \sin \theta = -\frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \sin \theta \tag{233}$$

$$A_\phi = A_z \hat{z} \cdot \hat{\phi} = 0 \tag{234}$$

$$\begin{aligned}
 \nabla \times \mathbf{A} &= \frac{1}{r^2 \sin \theta} \begin{vmatrix} \hat{r}, & r\hat{\theta}, & r\sin\theta\hat{\phi} \\ \frac{\partial}{\partial r}, & \frac{\partial}{\partial \theta}, & \frac{\partial}{\partial \phi} \\ A_r, & rA_\theta, & r\sin\theta A_\phi \end{vmatrix} \\
 &= \frac{1}{r^2 \sin \theta} \cdot
 \end{aligned}$$

$$\begin{vmatrix} \hat{r}, & r\hat{\theta}, & r\sin\theta\hat{\phi} \\ \frac{\partial}{\partial r}, & \frac{\partial}{\partial \theta}, & \frac{\partial}{\partial \phi} \\ \frac{\mu_0 I_0 \exp(-jkr)}{4\pi R} \Delta x \cos \theta, & -r \frac{\mu_0 I_0 \exp(-jkr)}{4\pi R} \Delta x \sin \theta, & 0 \end{vmatrix}$$

$$= \frac{1}{r^2 \sin \theta} \left\{ \hat{r} \left[\frac{\partial}{\partial \theta} 0 + \frac{\partial}{\partial \phi} r \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \cos \theta \right] \right.$$

$$\left. + r\hat{\theta} \left[\frac{\partial}{\partial \phi} \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \cos \theta - \frac{\partial}{\partial r} 0 \right] + r\sin\theta\hat{\phi} \right.$$

$$\begin{aligned}
& \cdot \left[\frac{\partial}{\partial r} \left(-r \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \sin \theta \right) - \frac{\partial}{\partial \theta} \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \cos \theta \right] \} \\
& = \frac{r \sin \theta \hat{\phi}}{r^2 \sin \theta} \left[-\frac{\partial}{\partial r} \frac{\mu_0 I_0 \exp(-jkr)}{4\pi} \Delta x \sin \theta - \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \sin \theta \right] \\
& = \frac{1}{r} \hat{\phi} \left[jk \frac{\mu_0 I_0 \exp(-jkr)}{4\pi} \Delta x \sin \theta - \frac{\mu_0 I_0 \exp(-jkr)}{4\pi r} \Delta x \sin \theta \right] \\
& = \frac{\mu_0 I_0 \exp(-jkr)}{4\pi} \sin \theta \Delta x \left(\frac{jk}{r} - \frac{1}{r^2} \right) \hat{\phi}
\end{aligned} \tag{235}$$

$$\begin{aligned}
\mathbf{H} &= \frac{1}{\mu_0} \nabla \times \mathbf{H} = \frac{I_0 \Delta x}{4\pi} \left(\frac{jk}{r} - \frac{1}{r^2} \right) \exp(-jkr) \sin \theta \hat{\phi} \\
&= \frac{I_0 \Delta x}{4\pi} jk \left(1 - \frac{1}{jkr^2} \right) \frac{\exp(-jkr)}{r} \sin \theta \hat{\phi}
\end{aligned} \tag{236}$$

We know:

$$\mathbf{E} = \frac{1}{j\omega\epsilon} \nabla \times \mathbf{H} \tag{237}$$

$$\nabla \times \mathbf{H} = \frac{1}{r^2 \sin \theta}$$

$$\cdot \begin{vmatrix} \hat{r}, & r\hat{\theta}, & r\sin\theta\hat{\phi} \\ \frac{\partial}{\partial r}, & \frac{\partial}{\partial \theta}, & \frac{\partial}{\partial \phi} \\ 0, & 0, & r\sin\theta \frac{\mu_0 I_0 \exp(-jkr)}{4\pi} \sin\theta \Delta x \left(\frac{jk}{r} - \frac{1}{r^2} \right) \end{vmatrix} \tag{238}$$

Thus:

$$E_r = \frac{I_0 \Delta z}{2\pi} \eta \left(\frac{1}{r} - \frac{1}{kr^2} \right) \frac{1}{r} \cos \theta \tag{239}$$

$$E_\theta = \frac{I_0 \Delta z j\omega\mu_0}{4\pi} \left[1 + \frac{1}{jkr} - \frac{1}{(jkr)^2} \right] \frac{\exp(-jkr)}{r} \sin \theta \tag{240}$$

So:

$$\mathbf{E}_{ff} = \frac{I_0 \Delta z j\omega\mu_0}{4\pi} \frac{\exp(-jkr)}{r} \sin \theta \hat{\theta} \tag{241}$$

$$\mathbf{H}_{ff} = \frac{I_0 \exp(-jkr)}{4\pi} \sin \theta \Delta z \frac{jk}{r} \hat{\phi} \tag{242}$$

The first subscript f denotes far, the second f denotes field.

$$\mathbf{S}_{\text{Maxwell}}$$

$$\begin{aligned}
&= \frac{I_0 \Delta z j \omega \mu_0}{4\pi} \frac{\exp(-jkr)}{r} \sin\theta \hat{\theta} \times \left(\frac{I_0 \exp(-jkr)}{4\pi} \sin\theta \Delta z \frac{jk}{r} \hat{\phi} \right)^* \\
&= \frac{I_0^2 \Delta z^2 k \omega \mu_0}{(4\pi r)^2} \sin^2\theta \hat{r} \\
&= \frac{I_0^2 \Delta z^2 k^2}{(4\pi r)^2} \eta \sin^2\theta \hat{r}
\end{aligned} \tag{243}$$

Considering:

$$k\omega\mu_0 = k\omega\sqrt{\mu_0\epsilon_0} \frac{\mu_0}{\sqrt{\mu_0\epsilon_0}} = k^2 \sqrt{\frac{\mu_0}{\epsilon_0}} = k^2\eta \tag{244}$$

We find:

$$\mathbf{S}_{1Maxwell} \sim \frac{1}{r^2} \sin^2\theta \tag{245}$$

Compared with formula (214), the pattern obtained from Maxwell's theory is completely consistent. Thus, the radiation Poynting vector $\mathbf{S}_{1Maxwell}$ calculated according to Maxwell's theory is actually the same as the author's $\mathbf{S}'_m$. The difference is that $\mathbf{S}_{1Maxwell}$ is calculated considering the Silver-Müller boundary condition, while $\mathbf{S}'_m$ is calculated by adding absorber current elements $\mathbf{J}_2$ at the infinite boundary. Another difference is that $\mathbf{S}'_m$ is generated at the source $\mathbf{J}_1$ and annihilated at the sink $\mathbf{J}_2$, but $\mathbf{S}_{1Maxwell}$ never annihilates once generated.

Although the calculation results for $\mathbf{S}'_m$ and $\mathbf{S}_1$ are the same, and the right-hand sides of formulas (224) and (220) are identical, the left-hand sides of the two formulas are different. From the left-hand side, we can definitively determine which method is correct.

Calculating the left-hand side of (224), $-\int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV$, consider:

$$\mathbf{E}_1 = -j\omega\mathbf{A}_1 = -j\omega \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}_1}{r} \exp(-jkr) dV \tag{246}$$

Consider:

$$\mathbf{J}_1 = J_{10} \delta(\mathbf{x}) \Delta z \hat{z} \tag{247}$$

Consider:

$$\begin{aligned}
\mathbf{E}_1 &= -j\omega \frac{\mu_0}{4\pi} \int_V \frac{J_{10} \delta(\mathbf{x}) \Delta z \hat{z}}{r} \exp(-jkr) dV \\
&= -j\omega \frac{\mu_0}{4\pi} \frac{J_{10} \Delta z \hat{z}}{r} \exp(-jkr)
\end{aligned} \tag{248}$$

$$E_{1\theta}(r=R) = \mathbf{E}_1 \cdot \hat{\theta} = j\omega \frac{\mu_0}{4\pi} \frac{J_{10} \Delta z}{R} \exp(-jkR) \sin\theta \tag{249}$$

Considering:

$$\hat{z} \cdot \hat{\theta} = -\cos\left(\frac{\pi}{2} - \theta\right) = -\sin\theta \tag{250}$$

Also consider:

$$J_2 \sim E_{1\theta}(r = R) \sim j\omega \frac{\mu_0}{4\pi} \frac{J_{10}\Delta z}{R} \exp(-jkR) \sin\theta \quad (251)$$

The θ -component of the electric field generated by J_2 is:

$$J_2 = J_2 \delta(\mathbf{x} - \mathbf{x}_2) \Delta z \hat{\theta} \quad (252)$$

$\mathbf{x}_2$ is a point on the sphere $\mathbf{x}_2 = (R, \theta, \phi)$, hence,

$$\begin{aligned} \mathbf{E}_{\theta 2} &= -j\omega \frac{\mu_0}{4\pi} \int_V \frac{J_2}{r} \exp(-jk(r - R)) dV \\ &= -j\omega \frac{\mu_0}{4\pi} \int_V \frac{J_2 \delta(\mathbf{x} - \mathbf{x}_2) \Delta z \hat{\theta}}{r} (-jk(r - R)) dV \\ &= -j\omega \frac{\mu_0}{4\pi} \frac{J_2 \Delta z \hat{\theta}}{r} \exp(-jk(r - R)) dV \\ &\sim \frac{-j\omega \mu_0}{4\pi} (j\omega \frac{\mu_0}{4\pi} \frac{J_{10} \Delta z}{R} \exp(-jkR) \sin\theta) \frac{\Delta z \hat{\theta}}{R} \exp(-jk(r - R)) \\ &\sim \omega^2 \left(\frac{\mu_0}{4\pi}\right)^2 J_{10} \frac{\Delta z^2}{R^2} \exp(-jkr) \sin\theta \hat{\theta} \end{aligned} \quad (253)$$

Consider:

$$E_{z2} = \mathbf{E}_{\theta} \cdot \hat{z} \quad (254)$$

Consider:

$$\hat{\theta} \cdot \hat{z} = -\sin\theta \quad (255)$$

$$E_{z2} = -\omega^2 \left(\frac{\mu_0}{4\pi}\right)^2 \frac{\Delta z^2}{R^2} \exp(-jkr) \sin^2\theta \quad (256)$$

Therefore:

$$\begin{aligned} -\int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV &= -\int_V (E_{z2}^* J_{1z}) dV \\ &\sim -\int_V (J_{10} (-\omega^2 \left(\frac{\mu_0}{4\pi}\right)^2 \frac{\Delta z^2}{R^2} \exp(-jk0) \sin^2\theta)^* \delta(\mathbf{x}) J_{10} \Delta z) dV \\ &= \omega^2 \left(\frac{\mu_0}{4\pi}\right)^2 \frac{\Delta z^2}{R^2} \sin^2\theta J_{10} J_{10}^* \\ &= \text{RealPositive} \end{aligned} \quad (257)$$

We see that $-\int_V (\mathbf{E}_2^* \cdot \mathbf{J}_1) dV$ is a positive real number. This is the power contribution of the antenna to J_2 at $\mathbf{x}_2$. Therefore, the mutual energy flow law (224) can be satisfied.

On the other hand, substituting E_1 into the left-hand side of formula (220):

$$\begin{aligned}
 & - \int_V (\mathbf{E}_1^* \cdot \mathbf{J}_1) dV \\
 &= - \int_V \left(-j\omega \frac{\mu_0}{4\pi} \frac{J_{10} \Delta z \hat{z}}{r} \exp(-jkr) \right)^* \Big|_{r=0} \cdot J_{10} \delta(\mathbf{x}) \Delta z \hat{z} dV \\
 &= j\omega \frac{\mu_0}{4\pi} \frac{\Delta z^2}{r} J_{10}^* \cdot J_{10} \\
 &= \text{imaginary}
 \end{aligned} \tag{258}$$

Therefore, the calculation shows that the left-hand side of Poynting's theorem (220) is imaginary, while its right-hand side is the dipole antenna radiation, a positive real number. Thus, this formula cannot be satisfied!

This indicates that although Maxwell's electromagnetic theory remains effective in calculating the electromagnetic radiation of dipole antennas, this effectiveness is achieved through two mutually canceling errors. The first error is mistaking the mutual energy flow that transmits electromagnetic wave energy for self-energy flow. The second error is defining the magnetic field as the curl of the vector potential. This definition miscalculates the phase of the magnetic field in the far-field. The two errors coincidentally cancel each other out to some extent.

However, Maxwell's theory cannot satisfy Poynting's theorem in some case. Furthermore, the Poynting vector S_{Maxwell} cannot completely annihilate at the receiving antenna or absorbers. This still demonstrates that Maxwell's electromagnetic theory contains errors.

7. Conclusion

Conclusion: Maxwell's electromagnetic theory has fundamental flaws in its interpretation of physical essence, particularly in describing photon behavior. Photons are essentially discrete entities generated at the source and annihilated at the sink, a dynamic process that Maxwell's theory cannot characterize. Within the traditional Maxwellian framework, electromagnetic waves are mistakenly regarded as carriers of energy; however, if waves transfer energy, it contradicts the experimentally verified fact that "particles (photons) transfer energy," leading to the irreconcilable wave-particle duality paradox. This paper posits that waves essentially represent reactive power and do not participate in actual energy transport; the true carriers of energy are particles, whose physical essence is mutual energy flow.

Despite severe theoretical defects, Maxwell's theory's computational results remain effective in most engineering practices. This effectiveness stems from a remarkable mutual cancellation of two internal errors: first, mistaking mutual energy flow for self-energy flow in energy transfer; second, incorrectly calculating the phase of the magnetic field far from the radiation source. When these two deviations combine, the derived self-energy flow S_{Maxwell} numerically coincides with the mutual energy flow S'_m . However, this consistency is not universal. For instance, S_{Maxwell} lacks the physical characteristic of mutual energy flow—"starting at the source and ending at the sink"—and Poynting's theorem within the Maxwellian framework cannot be satisfied in the dipole antenna example. Additionally, the mutual energy flow calculated in Maxwell's theory is imaginary, preventing the mutual energy flow theorem from being satisfied. In contrast, the electromagnetic theory proposed in this paper self-consistently resolves the above contradictions.

The limitations of Maxwell's electromagnetic theory extend not only to the classical realm but also deeply into the foundations of quantum mechanics and quantum field theory. The author has already made necessary corrections to the Schrödinger equation in quantum mechanics, including introducing and correcting the definition and mechanism of the magnetic field. The author firmly believes that quantum field theory also requires similar fundamental corrections. Due to current personal limitations and space constraints, this task is not yet fully accomplished. Therefore, the author calls upon colleagues and readers to jointly contribute to the perfection and innovation of quantum theory, completing this epoch-making disciplinary gap.

References

1. Wheeler, J. A., & Feynman, R. P. (1945). Interaction with the absorber as the mechanism of radiation. *Reviews of modern physics*, 17(2-3), 157.
2. Wheeler, J. A., & Feynman, R. P. (1949). Classical electrodynamics in terms of direct interparticle action. *Reviews of modern physics*, 21(3), 425.
3. Schwarzschild, K. (1903). *Nachr. ges. Wiss. Gottingen*, pages 128,132.

4. Tetrode, H. (1922). *Zeitschrift fuer Physik*, 10:137.
5. Fokker, A. D. (1929). Ein invarianter Variationssatz für die Bewegung mehrerer elektrischer Massenteilchen. *Zeitschrift für Physik*, 58(5), 386-393.
6. Cramer, J. (1986). The transactional interpretation of quantum mechanics. *Reviews of Modern Physics*, 58:647–688.
7. Cramer, J. G. (1988). An overview of the transactional interpretation of quantum mechanics. *International Journal of Theoretical Physics*, 27(2), 227-236.
8. Dirac, P. A. M. (1938). Classical theory of radiating electrons. Proceedings of the Royal Society of London. Series A. *Mathematical and Physical Sciences*, 167(929), 148-169.
9. Stephenson, L. M. (2000). The relevance of advanced potential solutions of maxwell's equations for special and general relativity. *Physics Essays*, 13(1), 138.
10. Lorentz, H. A. (1896). The theorem of Poynting concerning the energy in the electromagnetic field and two general propositions concerning the propagation of light. *Amsterdammer Akademie der Wetenschappen*, 4, 176.
11. Carson, J. R. (1929). Reciprocal theorems in radio communication. Proceedings of the Institute of Radio Engineers, 17(6), 952-956.
12. Carson, J. R. (1930). The reciprocal energy theorem. *Bell System Technical Journal*, 9(2), 325-331.
13. Kong, J. A. (1975). Theory of electromagnetic waves. New York. Wiley-Interscience., AA(MIT, Cambridge, Mass).
14. Zhao, S. R. (1987). The application of mutual energy theorem in expansion of radiation field in spherical waves. *ACTA Electronica Sinica, P.R. of China*, 15(3):88–93
15. Zhao, S. R. (1989). The simplification of formulas of electromagnetic fields by using mutual energy formula. 电子与信息学报, 11(1), 73-77.
16. Zhao, S. R. (1989). THE APPLICATION OF MUTUAL ENERGY FORMULA IN EXPANSION OF RADIATION FIELD IN PLANE WAVES. 电子与信息学报, 11(2), 204-208.
17. de Hoop, A. T. (1987). Time-domain reciprocity theorems for electromagnetic fields in dispersive media. *Radio science*, 22(7), 1171-1178. Zhao, S. R.
18. Welch, W. (1960). Reciprocity theorems for electromagnetic fields whose time dependence is arbitrary. *IRE Transactions on Antennas and Propagation*, 8(1), 68-73.
19. Zhao, S. R., Yang, K., Yang, K., Yang, X., & Yang, X. (2017). A new interpretation of quantum physics: Mutual energy flow interpretation. *American Journal of Modern Physics and Application*, 4(3), 12-23.
20. Zhao, S. R. (2021). Huygens principle based on mutual energy flow theorem and the comparison to the path integral. *Physics Tomorrow Letters*, 09-06.
21. Zhao, S. R. (2020). Photon can be described as the normalized mutual energy flow. *Journal of Modern Physics*, 11(5), 668-682.
22. Zhao, S. R. (2020). solution for wave-particle duality using the mutual energy principle. *Physics tomorrow letter*.
23. Zhao, S. R. (2021). Solve the Maxwell's equations and Shrodinger equation but avoiding the Sommerfeld radiation condition. *Theoretical Physics Letters*, 10(5), 2022.
24. Zhao, S. R. (2022). The theory of mutual energy flow proves that macroscopic electromagnetic waves are composed of photons. *International Journal of Physics*, 10(5), 2022.
25. Zhao, S. R. (2022). Mutual stress flow theorem of electromagnetic field and extension of newton's third law. *Theoretical Physics Letters*, 10(7).
26. Zhao, S. R. (2022). The paradox that induced electric field has energy in Maxwell's theory of classical electromagnetic field is shown and solved. *International Journal of Physics*, 10(4), 204-217.
27. Zhao, S. R. (2022). The contradictions in poynting theorem and classical electromagnetic field theory. *International Journal of Physics*, 10(5), 242-251.
28. Zhao, S. R. (2022). Energy conservation law and energy flow theorem for transformer, antenna and photon. *International Journal of Physics*, 11(2):56–66, 2023.
29. Zhao, S. R. (2023). Energy flow and photons from primary coil to secondary coil of transformer. *International Journal of Physics*, 11(1):24–39.
30. Zhao, S. (2023). Calculate the energy flow of transformers, antenna systems, and photons by redefining the radiated electromagnetic field of plane-sheet current. *International Journal of Physics*.11(3):136–152.
31. Zhao, S. R. (2023). Experiment to prove the existence of the advanced wave and experiment to prove the wrong definition of magnetic field in maxwell's theory. *International Journal of Physics*, 11(2), 73-80.
32. Zhao, S. R. (2023). Definition, measurement and calibration of magnetic field of electromagnetic wave “correct the defects of maxwell's classical electromagnetic field theory. *International Journal of Physics*, 11(3):106–135.
33. Zhao, S. R. (2023). Calculate the energy flow of transformers, antenna systems, and photons by redefining the radiated electromagnetic field of plane-sheet current. *International Journal of Physics*.11(5):261–273.
34. Zhao, S. R. (2024). The radiation of infinite current sheets considering a half retarded and half advanced field rather than potential. *Eng OA*, 2(3), 01-15.
35. Zhao, S. R. (2024). Discussion on the correction of classical electromagnetic wave theory through transmission lines. *International*

36. Zhao, S. R. (2024). New law or boundary condition of electromagnetic wave theory: Radiation shall not overflow the universe. *OA J Applied Sci Technol*, 2(1):01–46.
37. Zhao, S. R. (2024). Particles are mutual energy flows and waves are reactive power without collapse. *OA J Applied Sci Technol*, 2(2):01–22.
38. Zhao, S. R. (2024). Prove that the half retarded and half advanced electromagnetic theory is equivalent to maxwells classical electromagnetic theory. *OA J Applied Sci Technol*, 2(3):01–20.
39. Zhao, S. R. (2024). Distinguish between the average magnetic field on a circular coil and the original definition of magnetic field and correct the serious loopholes in classical electromagnetic theory. *OA J Applied Sci Technol*, 2(1):01–29.
40. Zhao, S. R. (2024). Using the method of contradiction to prove that the definition of magnetic field in maxwell's theory is incorrect. *OA J Applied Sci Technol*, 2(2):01–12.
41. Maxwell, J. C. (1856). On Fraday's line of force. Transactions of the Cambridge Philosophical Society, Vol. X. part 1, Dec. 10, 1855, and Feb. 11.
42. Maxwell, J. C. (1861). On physical lines of force. *Philosophical magazine*.
43. Graneau, P., & Assis, A. K. T. (1994). Kirchhoff on the motion of electricity in conductors. *Apeiron*, 19(19-25), 3-7.
44. Frisvad, J. R., & Kragh, H. (2019). On Ludvig Lorenz and his 1890 treatise on light scattering by spheres. *The European Physical Journal H*, 44(2), 137-160.