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Short Communication

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Is the Photon a Self-Energy Flow or a Mutual-Energy Flow?

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Abstract

In classical electromagnetic theory, energy flow density is described by the Poynting vector, while in quantum mechanics, the concept of probability current exists. These flows are all generated by the source and are referred to here as self-energy flows. Traditional theories assume that sinks (e.g., receiving antennas) do not generate electromagnetic fields or that their fields are negligible. However, alternative views exist, including the Wheeler-Feynman absorber theory and Cramer's transactional interpretation of quantum mechanics, which assert that sinks emit advanced waves. The author supports this viewpoint and finds that the mutual energy flow formed by retarded and advanced waves can describe photons. This article does not derive mutual energy flow from electromagnetic theory but rather compares the possible forms of self- and mutual-energy flows to illustrate that photons should be mutual-energy flows, not self-energy flows. Furthermore, it is shown that Maxwell's electromagnetic theory has a flaw that necessitates a correction to the phase of the far-field magnetic field. After the correction, the electromagnetic wave represents reactive power and thus does not transfer energy. Instead, the mutual-energy flow carries energy and can be regarded as the photon. The mutual-energy flow is generated at the source and annihilated at the sink, unlike the self-energy flow, which is only generated and not annihilated. Moreover, the generation and annihilation mentioned here refer to spatial generation at the source and spatial annihilation at the sink, which is different from the creation and annihilation operators in quantum field theory, where entire plane waves are created or annihilated. This paper presents six possible forms of self- and mutual-energy flows and concludes that the sixth is the most reasonable. This state requires the electric and magnetic fields of electromagnetic waves to maintain a 90-degree phase difference, making the wave purely reactive with no energy transport. All energy is instead carried by the mutual-energy flow, which is the photon. The idea is also applicable to quantum mechanics.

Keywords: Poynting's Theorem, Poynting Vector, Reciprocity Theorem, Photon, Electron, Electric Field, Magnetic Field, Electromagnetic Field, Electromagnetic Wave, Quantum, Probability Current, Maxwell's Equations, Retarded Wave, Advanced Wave, Retarded Potential, Advanced Potential, Mutual Energy Flow

1. Introduction

1.1. The Problem of Wave-Particle Duality

Whether electromagnetic waves are generated solely by the source or jointly by the source and the sink has long puzzled scientists. The term "source" refers to the transmitting antenna, the light source of a laser, or the primary coil of a transformer. The term "sink" refers to the receiving antenna, the screen that absorbs the laser, or the secondary coil of a transformer.

Traditional electromagnetic field theory has always considered the energy flow to be a self-energy flow. The so-called self-energy flow refers to the energy flow produced solely by the source itself. In electromagnetic field theory, it corresponds to the Poynting vector; in quantum mechanics, the self-energy flow corresponds to the energy flow associated with the probability current. Traditional electromagnetic field theory and quantum theory assume that the sink does not generate any field. The sink is merely a passive receiver of the field. However, a number of scientists have argued that the sink emits advanced waves, as opposed to the retarded waves emitted by the source. Notable among these are the action-at-a-distance theories by Schwarzschild and others [1-3], Wheeler and Feynman's absorber theory [4,5], Cramer's transactional interpretation of quantum mechanics, and Stephenson's advanced wave theory [6]. The author also supports this view [7].

Even if one accepts the role of the sink, there are still two possibilities: one is that the source generates its own self-energy flow and the sink generates its own self-energy flow – Cramer's transactional interpretation falls into this category. Only the author advocates that energy is transmitted by mutual energy flow [7], which is jointly generated by the retarded wave from the source and the advanced wave from the sink.

This paper does not approach mutual or self-energy flow from the perspective of electromagnetic theory itself, but rather investigates the possibility of using mutual energy flow to replace self-energy flow, focusing on the interchangeability of their respective energy flow densities.

1.2. Reciprocity Theorem, Mutual-Energy Theorem, Mutual-Energy Flow Theorem, and Energy Conservation Law

Consider the Poynting vector $\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$, which satisfies the time-integrated Poynting theorem[8],

$$\int_{t=-\infty}^{\infty} dt \left(\int_V \boldsymbol{E} \cdot \boldsymbol{J} \, dV + \oiint_\Gamma (\boldsymbol{E} \times \boldsymbol{H}) \cdot \hat{n} \, d\Gamma \right) = 0 \tag{1}$$

By the superposition principle:

$$\boldsymbol{J} = \sum_{i=1}^{2} \boldsymbol{J}_i, \quad \boldsymbol{E} = \sum_{i=1}^{2} \boldsymbol{E}_i, \quad \boldsymbol{H} = \sum_{i=1}^{2} \boldsymbol{H}_i$$

we obtain:

$$\int_{t=-\infty}^{\infty} dt \sum_{i=1}^{2} \sum_{j=1}^{2} \left(\int_V \boldsymbol{E}_i \cdot \boldsymbol{J}_j \, dV + \oiint_\Gamma (\boldsymbol{E}_i \times \boldsymbol{H}_j) \cdot \hat{n} \, d\Gamma \right) = 0 \tag{2}$$

From Eq. (1), using only $\boldsymbol{E}_i$, we get:

$$\int_{t=-\infty}^{\infty} dt \left(\int_V \boldsymbol{E}_i \cdot \boldsymbol{J}_i \, dV + \oiint_\Gamma (\boldsymbol{E}_i \times \boldsymbol{H}_i) \cdot \hat{n} \, d\Gamma \right) = 0 \tag{3}$$

Subtracting Eq. (3) for $i = 1$ and $i = 2$ from Eq. (2), we get:

$$\int_{t=-\infty}^{\infty} dt \sum_{i=1}^{2} \sum_{j=1, j\neq i}^{2} \left(\int_V \boldsymbol{E}_i \cdot \boldsymbol{J}_j \, dV + \oiint_\Gamma (\boldsymbol{E}_i \times \boldsymbol{H}_j) \cdot \hat{n} \, d\Gamma \right) = 0 \tag{4}$$

Or:

$$-\int_{t=-\infty}^{\infty} dt \oiint_\Gamma (\boldsymbol{E}_1 \times \boldsymbol{H}_2 + \boldsymbol{E}_2 \times \boldsymbol{H}_1) \cdot \hat{n} \, d\Gamma = \int_{t=-\infty}^{\infty} dt \int_V (\boldsymbol{E}_1 \cdot \boldsymbol{J}_2 + \boldsymbol{E}_2 \cdot \boldsymbol{J}_1) \, dV \tag{5}$$

The above equation is Welch's reciprocity theorem [9]. After applying the Fourier transform, it becomes

$$-\oiint_\Gamma (\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \cdot \hat{n} d\Gamma = \int_V (\boldsymbol{E}_1 \cdot \boldsymbol{J}_2^* + \boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV \tag{6}$$

This is the mutual energy theorem [10, 11], where both current sources $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$ are contained within the region V and Γ is the boundary surface of V. If the surface of integration is taken as a sphere of infinite radius, the surface integral vanishes. In the frequency domain, the vanishing of the surface integral in equation (6) is due to the Silver–Müller radiation condition. In the time domain version of the formula (5), the surface integral vanishes because one field is a retarded wave and the other is an advanced wave; they reach the surface at different times, one is in the furture and another is in the past, and thus do not contribute simultaneously. Therefore,

$$\int_V (\boldsymbol{E}_1 \cdot \boldsymbol{J}_2^* + \boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV = 0 \tag{7}$$

or

$$-\int_{V_1} (\boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV = \int_{V_2} (\boldsymbol{E}_1 \cdot \boldsymbol{J}_2^*) dV \tag{8}$$

If the current $\boldsymbol{J}_2$ is moved outside the region V, from equation (6) we obtain

$$\oiint_\Gamma (\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \cdot \hat{n} d\Gamma = -\int_{V_1} (\boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV \tag{9}$$

Combining the two equations above, we get

$$\int_{V_2} (\boldsymbol{E}_1 \cdot \boldsymbol{J}_2^*) dV = \oiint_\Gamma (\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \cdot \hat{n} d\Gamma = -\int_{V_1} (\boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV \tag{10}$$

Let $\boldsymbol{J}_2 = \delta(\boldsymbol{x}' - \boldsymbol{x})\hat{z}$,

$$E_{1z}(\boldsymbol{x}) = \oiint_{\Gamma} (\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \cdot \hat{n} d\Gamma = -\int_V (\boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV \quad (11)$$

This is the Huygens' principle, where the surface Γ can be any surface that separates the currents $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$. The above form of Huygens' principle was introduced by the author in 1989 [12]. Equation (10) is the mutual energy flow theorem. Mathematically, the mutual energy theorem is simply an intermediate step in deriving Huygens' principle and differs little from it. However, the physical interpretation is different. In the mutual energy theorem, $-\int_V (\boldsymbol{E}_2^*. \boldsymbol{J}_1)dV$ represents the work done by the current $\boldsymbol{J}_1$ against the reaction field $\boldsymbol{E}_2$ of the sink; this energy is injected from the transmitting antenna into space V. Then energy propagates through the mutual energy flow $\oiint_{\Gamma} (\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \cdot \hat{n} d\Gamma$ and is subsequently extracted by the receiving antenna as $\int_{V_2} (\boldsymbol{E}_1 . \boldsymbol{J}_2^*)dV$. Thus, equation (10) represents the mutual energy flow theorem, which was introduced by the author in 2017 to explain photons via mutual energy flow [13].

Later, the author discovered that the mutual energy theorem is not just an energy transfer statement, but also an energy conservation law. Furthermore, this conservation law cannot be derived from Maxwell's equations directly; rather, it requires a modification of the solutions of Maxwell's equations, specifically a phase correction to the magnetic field [7]

$$\boldsymbol{H}_f^{(r)} = (-j)\boldsymbol{H}_{Mf}^{(r)}, \quad \boldsymbol{H}_f^{(a)} = (j)\boldsymbol{H}_{Mf}^{(a)} \quad (12)$$

where the superscript (r) denotes a retarded field, (a) denotes an advanced field, the subscript f denotes the far-field, and M indicates the magnetic field obtained from Maxwell's equations.

$$\boldsymbol{H}_M^{(r)} = \nabla \times \boldsymbol{A}^{(r)}, \quad \boldsymbol{H}_M^{(a)} = \nabla \times \boldsymbol{A}^{(a)} \quad (13)$$

The author does not consider the magnetic fields obtained from Maxwell's equations to be correct and therefore applies a phase correction. In addition, the mutual energy flow must be halved to account for the fact that the current generates half retarded and half advanced waves:

$$\int_{V_2} (\boldsymbol{E}_1 \cdot \boldsymbol{J}_2^*) dV = \frac{1}{2} \oiint_{\Gamma} (\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \cdot \hat{n} d\Gamma = -\int_{V_1} (\boldsymbol{E}_2^* \cdot \boldsymbol{J}_1) dV \quad (14)$$

Moreover, the author requires that radiation does not escape the universe:

$$\oiint_{\Gamma} (\boldsymbol{E}_1 \times \boldsymbol{H}_1^*) \cdot \hat{n} d\Gamma = \oiint_{\Gamma} (\boldsymbol{E}_2 \times \boldsymbol{H}_2^*) \cdot \hat{n} d\Gamma = 0 \quad (15)$$

Equation (12) ensures that the above conditions are satisfied. These energy conservation conditions cannot be derived from classical Maxwell theory [7].

1.3. Focus of This Paper

This paper no longer investigates mutual energy flow from the perspective of electromagnetic fields. Instead, it analyzes the problem from the perspective of the Poynting vector and the mixed Poynting vector. We assume the author does not know whether energy is transmitted by mutual energy flow or self-energy flow but attempts to replace self-energy flow with mutual energy flow to explore what consequences may result.

2. Poynting Vector and Mixed Poynting Vector

Consider the Poynting vector:

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H} = (\boldsymbol{E}_1 + \boldsymbol{E}_2) \times (\boldsymbol{H}_1 + \boldsymbol{H}_2)$$

It can be expanded as:

$$\boldsymbol{S} = \boldsymbol{E}_1 \times \boldsymbol{H}_1 + \boldsymbol{E}_2 \times \boldsymbol{H}_2 + \boldsymbol{E}_1 \times \boldsymbol{H}_2 + \boldsymbol{E}_2 \times \boldsymbol{H}_1 = \boldsymbol{S}_1 + \boldsymbol{S}_2 + \boldsymbol{S}_m \quad (16)$$

Here, $\xi_1 = [\boldsymbol{E}_1, \boldsymbol{H}_1]^T$ is generated by current $\boldsymbol{J}_1$ and $\xi_2 = [\boldsymbol{E}_2, \boldsymbol{H}_2]^T$ is generated by $\boldsymbol{J}_2$. Assume $\boldsymbol{J}_1$ is the source and $\boldsymbol{J}_2$ is the sink. The author assumes the source emits a retarded field and the sink emits an advanced field. This contrasts with traditional electromagnetic theory and quantum mechanics.

Thus, we define:

$$\boldsymbol{S}_1 = \boldsymbol{E}_1 \times \boldsymbol{H}_1^*, \quad \boldsymbol{S}_2 = \boldsymbol{E}_2 \times \boldsymbol{H}_2^*, \quad \boldsymbol{S}_m = \boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1 \quad (17)$$

Here, the asterisk denotes complex conjugation, indicating a time or ensemble average. For simplicity, we use the same notation.

2.1. Traditional Electromagnetic Field Theory

Traditional theory asserts that only self-energy flows carry energy. Thus, $\boldsymbol{S}_1 = \boldsymbol{E}_1 \times \boldsymbol{H}_1^*$ does the work, while $\boldsymbol{S}_2$ from the sink is negligible or ignored. In quantum theory, the EM wave ($\boldsymbol{E}_1$, $\boldsymbol{H}_1$) is emitted as a spherical wave, gradually collapsing into a plane wave (photon) directed toward the sink.

2.2. Advanced Waves from the Sink

By symmetry, energy might also be carried by the sink's advanced wave $\boldsymbol{S}_2 = \boldsymbol{E}_2 \times \boldsymbol{H}_2^*$. Initially spherical, it collapses toward the source.

2.3. Coexistence of Retarded and Advanced Waves

According to Cramer's transactional interpretation, the source emits a retarded wave and the sink emits an advanced wave. Their handshake creates a photon. Between source and sink, the superposition yields destructive interference outside the region, forming:

$$\psi = \frac{1}{2}\begin{cases}\psi_1 e^{i\pi} + \psi_2, & x < 0 \\ \psi_1 + \psi_2, & 0 \le x \le L \\ \psi_1 + \psi_2 e^{i\pi}, & x > L\end{cases} = \psi_1 \begin{cases}0, & x < 0 \\ 1, & 0 \le x \le L \\ 0, & x > L\end{cases} \tag{18}$$

In this case, energy is transmitted by self-flows:

$$S_1 = \frac{1}{2}\boldsymbol{E}_1 \times \boldsymbol{H}_1^*, \quad S_2 = \frac{1}{2}\boldsymbol{E}_2 \times \boldsymbol{H}_2^* \tag{19}$$

The factor ½ arises because both self-flows contribute equally. Even Cramer did not clear mensioned the factor ½. This factor is really required.

2.4. Concurrent Self- and Mutual-Energy Transfer

Alternatively, if both self- and mutual-flows transfer energy, then four contributions arise, requiring a normalization factor:

$$S_1 = \frac{1}{4}\boldsymbol{E}_1 \times \boldsymbol{H}_1^*, \quad S_2 = \frac{1}{4}\boldsymbol{E}_2 \times \boldsymbol{H}_2^*, \quad \boldsymbol{S}_m = \frac{1}{4}(\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) \tag{20}$$

2.5. Mutual-Energy Transfer Only

In the most compelling scenario, only the mutual-flow transmits energy and self-flows collapse. Then:

$$\boldsymbol{S}_m = \frac{1}{2}(\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) = \frac{\hat{x}}{2}(E_1 H_2^* + E_2^* H_1) \tag{21}$$

Here, 1/2 accounts for splitting into retarded and advanced parts. Reactive (non-transporting) self-flows and energy is transfored by mutual energy alone require:

$$\boldsymbol{E}_1 \times \boldsymbol{H}_2^* \in \mathbb{R}, \quad \boldsymbol{E}_2^* \times \boldsymbol{H}_1 \in \mathbb{R} \tag{22}$$

The author das not think the magnetic field and electric field of the electromagnetic waves are in phase as Maxwell's theory. The above requires phase alignments:

$$E_1 \sim H_2, \quad E_2 \sim H_1 \tag{23}$$

Here the symbol ~ means "proportional to". This symbol is insensitive to magnitude but sensitive to phase. Assuming:

$$E_1 \sim e^{j\phi_1} H_1, \quad E_2 \sim e^{j\phi_2} H_2 \tag{24}$$

And for cross consistency, consider the above two formula, we have

$$H_2 \sim e^{j\phi_1} H_1 \tag{25}$$

Therefore:

$$E_1 H_2^* \sim (\exp(j\phi_1) H_1)(\exp(j\phi_1) H_1)^* \sim H_1 H_1^* \in \mathbb{R} \tag{26}$$

$$E_2^* H_1 = (\exp(j\phi_2) H_2)^* H_1 = (\exp(j\phi_2)\exp(j\phi_1) H_1)^* H_1$$

$$= (\exp(j\phi_2)\exp(j\phi_1))^* H_1 H_1^* \tag{27}$$

if the above formula is real ($\in \mathbb{R}$), we need,

$$(\exp(j\phi_2)\exp(j\phi_1))^* = (\exp(j(\phi_2+\phi_1)))^* = 1 \quad (28)$$

or

$$\phi_2 + \phi_1 = 0 \quad (29)$$

or

$$\phi_2 = -\phi_1 \quad (30)$$

One possible case is

$$\phi_1 = 0, \quad \phi_2 = 0 \quad (31)$$

In this case, all electric and magnetic fields remain in phase:

$$E_1 \sim H_1 \sim E_2 \sim H_2 \quad (32)$$

Another situation:

$$\phi_1 = \frac{\pi}{2} \quad (33)$$

$$E_1 \sim \exp(j\frac{\pi}{2})H_1 = jH_1, \quad H_1 \sim (-j)E_1 \quad (34)$$

$$\phi_2 = -\phi_1 = -\frac{\pi}{2} \quad (35)$$

$$E_2 = \exp(-\frac{\pi}{2})H_2 = -jH_2, \quad H_2 = (j)E_2 \quad (36)$$

$$E_1H_2^* + E_2^*H_1 \sim (jH_1)(H_2)^* + (-jH_2)^*(H_1)$$

$$= (jH_1)(jH_1)^* + (-j(jH_1))^*(H_1)$$

$$= H_1{H_1}^* + H_1^*H_1 \quad (37)$$

In this case, mutual energy flow carries energy,

$$\boldsymbol{S}_m = \frac{1}{2}(\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_2) \in \mathbb{R} \quad (38)$$

However, the self-energy flow is reactive power,

$$\mathrm{Re}(\boldsymbol{E}_1 \times \boldsymbol{H}_1^*) = \mathrm{Re}(\boldsymbol{E}_2 \times \boldsymbol{H}_2^*) = 0 \quad (39)$$

2.6. Comparison

	Transfer	ϕ_1	ϕ_2	Collapse	Self-Energy	MEF	Factor	Generation	Annihilation
1	S_1	0	0	S_1	$S_1 > 0, S_2 = 0$	$S_m = 0$	1	Yes	No
2	S_2	0	0	S_2	$S_1 = 0, S_2 > 0$	$S_m = 0$	1	No	Yes
3	$S_1 + S_2$	0	0	S_1S_2	$S_1 > 0, S_2 > 0$	$S_m = 0$	1/2	Yes	Yes
4	$S_1 + S_2 + S_m$	0	0	S_1S_2	$S_1 > 0, S_2 > 0$	$S_m > 0$	1/4	No	No
5	S_m	0	0	S_1S_2 reverse	$S_1 = 0, S_2 = 0$	$S_m > 0$	1/2	Yes	Yes
6	S_m	$\frac{\pi}{2}$	$-\frac{\pi}{2}$	S_1S_2 reactive	$S_1 = 0, S_2 = 0$	$S_m > 0$	1/2	Yes	Yes

In the table "Transfer" means the energy transfer by which type of energy flow; ϕ_1 and ϕ_1 are the phase difference between electric field and magnetic field; "Collapse" tells which energy flow shoud collapse; "Self-Energy" means self energy flow; "MEF" means the mutual energy flow; "factor" is the compress factor of the energy flow; "Gerneration" tells whether this energy flow generates from a source; "Annihilation" tells whether this energy flow annihilates at a sink.

Method 1 corresponds to classical electromagnetic theory and quantum mechanics, where energy transfer is achieved by $\boldsymbol{S}_1$ only. $\boldsymbol{S}_1$ results in generation but no annihilation. Methods 2 and 4 have not been proposed by others; the author includes them here to illustrate alternative possibilities. Method 3 is the transactional interpretation of quantum mechanics proposed by Cramer in 1986 [14,15]. This interpretation allows for sources and sinks, as well as retarded and advanced waves. However, it does not compute mutual energy flow.

Method 5 was proposed by the author in 2017 [13]. It does not modify the magnetic field obtained from Maxwell's equations but instead adds a time-reversed electromagnetic wave to classical theory. The main drawback of this method is that one must introduce a time-reversed Maxwell's equations.

The first four cases all require wave collapse. The fifth involves reverse wave collapse. Only the sixth does not require any wave collapse! Wave collapse is a physical process, yet there is no established equation describing it. On the other hand, reverse collapse can be described by an equation. If wave collapse could also be described by an equation, it would imply a modification of Maxwell's electromagnetic theory.

Hence, all these methods inherently involve some correction to Maxwell's theory. However, only the sixth case explicitly modifies the magnetic field. Moreover, mutual energy flow requires a normalization factor of 1/2 to transfer energy. This normalization factor is not derivable from Maxwell's equations; it originates from the idea of half-retarded and half-advanced waves [4,5], which again constitutes a correction to Maxwell's theory.

3. Examples

3.1. Transformer

The energy flow in a transformer cannot be due to self-energy flow. This example relates to the so-called Maxwell-Lodge effect. In fact, the Aharonov-Bohm (AB) effect in quantum mechanics is also connected to this issue [16,17].

Assume a primary coil that is infinitely long, with its magnetic field completely confined inside the coil. The secondary coil is wound outside the primary coil at radius r=R_2, as shown in Figure 1.

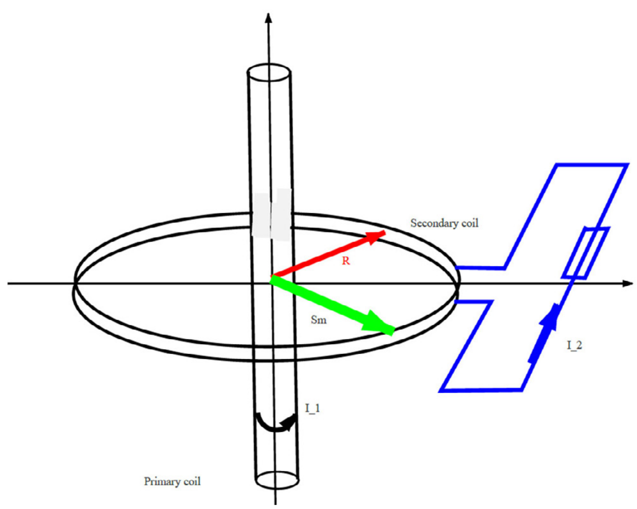

Figure 1: The primary is an infinitely long coil with radius $r = R_1$; its magnetic field is confined inside the coil. The secondary coil is placed outside at $r = R_2$, where the magnetic field $\boldsymbol{B}_1 = 0$, hence the Poynting vector $\boldsymbol{E}_1 \times \boldsymbol{B}_1^* = 0$.

$$\boldsymbol{H}_1(r = R_2) = 0 \tag{40}$$

$$\boldsymbol{S}_1 = \boldsymbol{E}_1(r = R_2) \times \boldsymbol{H}_1(r = R_2) = 0 \tag{41}$$

Traditional electromagnetic theory addresses this type of problem by considering:

$$\boldsymbol{A}_1(r = R_2) \neq 0 \tag{42}$$

$$\boldsymbol{E}_1(r = R_2) = -\frac{\partial}{\partial t}\boldsymbol{A}_1(r = R_2) \neq 0 \tag{43}$$

The induced electromotive force (EMF) in the secondary coil is:

$$\mathcal{E}_{1\to 2} = \oint_{C_2} \boldsymbol{E}_1(r = R_2) \cdot d\boldsymbol{l} \neq 0 \tag{44}$$

The current in the secondary coil is:

$$I_2 = \frac{\mathcal{E}_{1\to2}}{R+j\omega L_2} \simeq \frac{\mathcal{E}_{1\to2}}{R} \sim \mathcal{E}_{1\to2} \sim E_1(r = R_2) \quad (45)$$

The power on the secondary coil is:

$$P_2 \sim \mathcal{E}_{1\to2} I_2^* \sim E_1 E_1^* > 0 \quad (46)$$

Thus, the secondary coil receives power, but this power transfer is not explained using the Poynting vector. This indicates that the energy transfer from the primary to the secondary coil in a transformer cannot be explained by the Poynting theorem. The author believes that the energy flow from the primary to the secondary is a mutual energy flow. Consider:

$$\boldsymbol{S}_m(r = R_2) = \boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1 = \boldsymbol{E}_1(r = R_2) \times \boldsymbol{H}_2^*(r = R_2) \neq 0 \quad (47)$$

In the above, we assume $\boldsymbol{H}_1$ $(r = R_2) = 0$. But since $\boldsymbol{H}_2$ $(r = \boldsymbol{R}_2) \neq 0$, energy transfer is ensured.

3.2. Dipole Antenna Pair

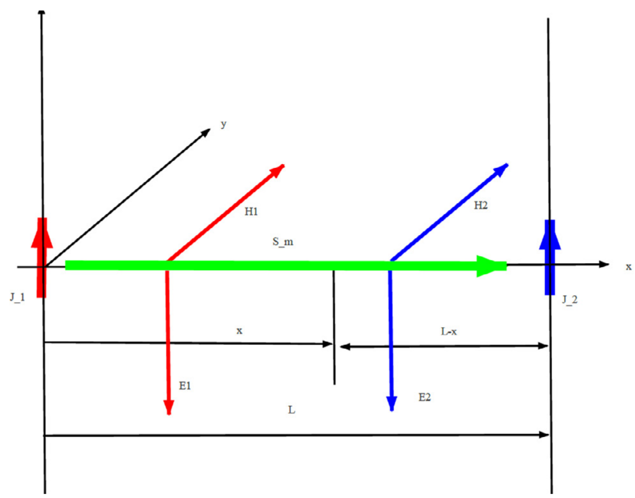

Figure 2: The transmitting antenna is a dipole, and the receiving antenna is also a dipole. The electric field is in the -$\hat{z}$ direction, the magnetic field is in the $\hat{y}$ direction and the energy flows in the $\hat{x}$ direction.

The transmitting antenna is $\boldsymbol{J}_1 = \hat{z}\, I_1\, l\delta\,(x)$ and the receiving antenna is $\boldsymbol{J}_2 = \hat{z}\, I_2\, l\delta\,(x\text{-}L)$, where $l \ll \lambda$ is the length of the dipole and λ is the wavelength. $\boldsymbol{J}_1$ generates electromagnetic fields $\boldsymbol{E}_1$, $\boldsymbol{H}_1$ and $\boldsymbol{J}_2$ generates $\boldsymbol{E}_2$, $\boldsymbol{H}_2$, as shown in Figure 2. We now describe the energy flow of a photon from the transmitting to the receiving dipole antenna. Using mutual energy flow density, we calculate:

$$\boldsymbol{S}_m = \frac{1}{2}(\boldsymbol{E}_1 \times \boldsymbol{H}_2^* + \boldsymbol{E}_2^* \times \boldsymbol{H}_1) = \frac{\hat{x}}{2}(E_1 H_2^* + E_2^* H_1) \quad (48)$$

We assume that the source initially emits retarded spherical waves randomly in all directions, and the sink also emits advanced waves in all directions. Suppose the retarded wave from the source and the advanced wave from the sink are synchronized. This means when the electromagnetic wave from the source reaches the sink, the sink emits an advanced wave. Once synchronized, the advanced wave becomes a guiding wave for the retarded wave and vice versa. Due to the interference effect, both waves become quasi-plane waves directed from the source to the sink. This is equivalent to the collapse of both into plane waves.

Since the sink is to the right of the source, we assume the right side of each current emits retarded waves, and the left side emits advanced waves. At the current elements, the wave types flip. Thus, to the right of both currents, we have retarded waves, and to the left, advanced waves. Therefore:

$$\boldsymbol{H}_1 \sim \begin{cases} -\frac{1}{2} I_1 \exp(-jkx)\hat{y}, & x < 0 \\ \frac{1}{2} I_1 \exp(-jkx)\hat{y}, & x \geq 0 \end{cases} \tag{49}$$

The initial phase above is determined by the Ampère's circuital law. The phase factor exp(-*jkx*) represents the retarded wave on the right and the advanced wave exp(+*jk*|*x*|)=exp(-*jkx*) on the left. The electric field is:

$$\boldsymbol{E}_1 \sim j\eta \frac{1}{2} I_1 \exp(-jkx)(-\hat{z}) \tag{50}$$

The initial phase is based on the quasi-static Faraday's law $\boldsymbol{E}_1 = -\frac{\partial}{\partial t}\boldsymbol{A} \sim -jI_1\hat{z}$, plus the retardation/advance factor exp(-*jkx*). Then,

$$I_2 \sim -E_1(x = L) = -j\eta \frac{1}{2} I_1 \exp(-jkL) \tag{51}$$

We assume the impedance of the receiving antenna is purely resistive, so the current I_2 should be in phase with $\boldsymbol{E}_1$. Therefore,

$$\boldsymbol{E}_2 \sim j\eta \frac{1}{2} I_2 \exp(+jk|x-L|)(-\hat{z}) = j\eta \frac{1}{2} I_2 \exp(-jk(x-L))(-\hat{z})$$

$$= j\eta \frac{1}{2}(-j\eta \frac{1}{2} I_1 \exp(-jkL))\exp(-jk(x-L))(-\hat{z})$$

$$= -jj\frac{\eta^2}{4} I_1 \exp(-jkx)(-\hat{z}) \tag{52}$$

Since $\boldsymbol{E}_2$ is an advanced wave, it uses the factor exp(+*jk*|*x-L*|). The field remains continuous at the current $\boldsymbol{J}_2$, so this expression holds for $x>L$.

Now let us caculate $\boldsymbol{H}_2$, For $x \leq L$, we get:

$$\boldsymbol{H}_2 \sim \frac{1}{2} I_2 \exp(+jk|x-L|)(-\hat{y}) = \frac{1}{2} I_2 \exp(-jk(x-L))(-\hat{y})$$

$$= \frac{1}{2}(-j\eta \frac{1}{2} I_1 \exp(-jkL))\exp(-jk(x-L))(-\hat{y})$$

$$= \frac{1}{4}(j\eta I_1)\exp(-jkx)\hat{y} \tag{53}$$

Considering the sign change of magnetic field across the current,

$$\boldsymbol{H}_2 = \frac{1}{4}(j\eta I_1)\exp(-jkx)\hat{y} \begin{cases} 1 & x \leq L \\ -1 & x > L \end{cases} \tag{54}$$

So for $0 \leq x \leq L$, the mutual energy density is:

$$\boldsymbol{S}_m = \frac{\hat{x}}{2}(E_1 H_2^* + E_2^* H_1)$$

$$\sim \frac{\hat{x}}{2}((j\eta \frac{1}{2} I_1 \exp(-jkx))(\frac{1}{4}(j\eta I_1)\exp(-jkx))^*$$

$$+(-jj\frac{\eta^2}{4} I_1 \exp(-jkx))^*(\frac{1}{2} I_1 \exp(-jkx)))$$

$$= \frac{\hat{x}}{2} \cdot \frac{1}{8}\eta^2 I_1 I_1^*((j)(j)^* + (-jj)^*) = \frac{\hat{x}}{8}\eta^2 I_1 I_1^* \tag{55}$$

For $x < 0$, $\boldsymbol{H}_1$ changes sign, and the two terms in mutual energy cancel out. For $x > L$, $\boldsymbol{H}_2$ changes sign, and cancellation also occurs. Thus,

$$\boldsymbol{S}_m \sim \hat{x} \begin{cases} 0 & x < 0 \\ 1 & 0 \leq x \leq L \\ 0 & x > L \end{cases} \tag{56}$$

The sign changes of $\boldsymbol{H}_1$ and $\boldsymbol{H}_2$ can be explained either by Ampère's law or by the wave-type inversion across the current – that is, the switch between retarded and advanced waves, as described by Eq. (12). For $\boldsymbol{E}_1$, $\boldsymbol{H}_1$, the wave is advanced for $x < 0$ and becomes retarded for $x > 0$. For $\boldsymbol{E}_2$, $\boldsymbol{H}_2$, it is advanced for $x < L$ and retarded for $x > L$. This way, the mutual energy flow density $\boldsymbol{S}_m$ is generated at the source ($x = 0$) and annihilated at the sink ($x = L$), accurately describing photon creation and annihilation. This example corresponds exactly to Case 6 in the comparison table.

It is evident that when calculating the mutual energy flow, the electric and magnetic fields can be derived under magneto-quasistatic conditions, then modified using the appropriate retarded or advanced phase factors. Of course, Maxwell's equations can also be used directly, but afterward, one must correct the magnetic field using Eq. (12). The electromagnetic field of a photon is a plane (or quasi-plane) wave and does not contain the static component $\boldsymbol{E}_s = -\nabla\phi$, so there is no need to apply correction to $\boldsymbol{E}_s$.

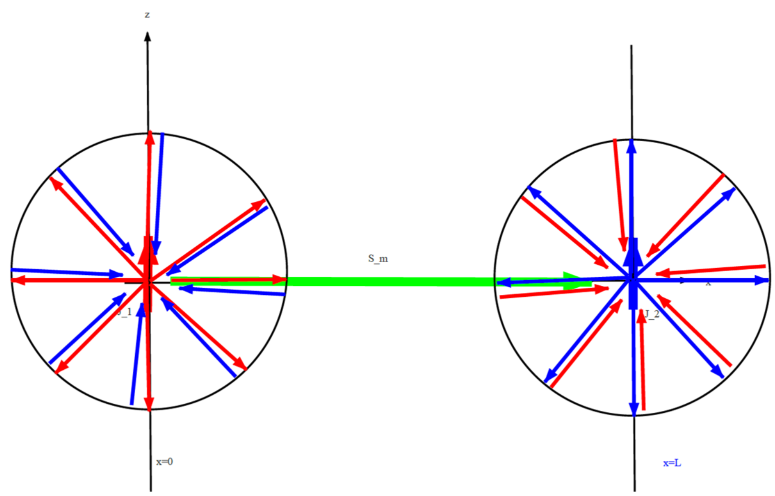

Figure 3: The transmitting and receiving antennas are both dipoles. The retarded and advanced waves are reactive powers and appear to collapse back in all directions.

Only along the source-sink line does mutual energy flow exist. In this example, the source initially emits retarded spherical waves, and the sink emits advanced spherical waves. After synchronization due to mutual interaction, both waves interfere and become quasi-plane waves directed from source to sink. This naturally explains the wave collapse. Alternatively, one can view the retarded and advanced waves as reactive power that is emitted into space and simultaneously collapses back to the source or sink. However, along the source-sink line, due to the existence of mutual energy flow, the energy of one photon is exactly transferred – see Figure 3. This figure also corresponds to Case 5 in the comparison table.

Case 5 is indeed a promising approach. However, it requires manually introducing time-reversed electromagnetic waves. Time-reversed EM waves may also generate time-reversed mutual energy flows, which might cancel the original mutual energy flow. Hence, it is not yet a perfect solution.

In Case 6, the self-energy flow formed by electric and magnetic fields is reactive power. During one oscillation cycle, the wave propagates forward for half the time and backward for the other half. On average, there is no net energy transfer. Since these waves do not transfer energy, they do not need to be interpreted probabilistically. Reactive waves and probabilistic interpretations serve similar roles. In this case, energy is fully transferred by the mutual energy flow.

4. Conclusion

If mutual energy flow is to replace self-energy flow, it must be normalized by a factor of 1/2 because it consists of two terms, which otherwise would double the energy flow. If energy is indeed transferred via mutual energy, then self-energy flow should not carry energy – otherwise, two types of photons would exist: self-energy photons and mutual-energy photons, contradicting observations. We observe only one type of photon. To prevent self-energy from carrying energy, it must either undergo reverse collapse or be constructed with a 90-degree phase difference between electric and magnetic fields. The latter requires a correction to classical Maxwell's theory: namely, a 90-degree phase adjustment to the far-field magnetic component. This adjustment allows the magnetic field's initial phase to be derived under magneto-quasistatic conditions, with the radiation field acquired by appending retarded or advanced phase factors.

The fields between a transmitting and receiving antenna, due to interference, become quasi-plane waves. The mutual energy flow calculated from them is created at the source and annihilated at the sink – precisely matching photon behavior. Thus, the mutual energy flow theory proposed herein can accurately describe photons. These ideas are also applicable to quantum mechanics.

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