Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 September 2022 doi:10.20944/preprints202209.0396.v1

The electromagnetic wave without a magnetic component: a thought experiment

Sherif Abdulkader Tawfik[1, 2, *]
[1] *Institute for Frontier Materials, Deakin University, Geelong, Victoria 3216, Australia.*
[2] *ARC Centre of Excellence in Exciton Science, School of Science, RMIT University, Melbourne, VIC 3001 Australia.*

The well-known coupling between the magnetic and electric fields in electromagnetic radiation is revisited in light of the recent introduction of a microscopic theory for the Ørsted magnetic field induction. I argue that, if the Ørsted magnetic field induction does indeed have a microscopic origin rather than the continuum solution offered by the Maxwell-Ampere equation, the "electromagnetic wave" propagating in vacuum will not have a magnetic component.

I. INTRODUCTION

According the Maxwell-Ampere equation, the onset of the Ørsted magnetic field is directly related to the presence of a current density in a given volume. The success of the equation in predicting the magnitude and direction of the Ørsted magnetic field in currying-carrying wires has enabled physicists to draw conclusions from the equation at a more fundamental level; the equation relates between the magnetic field and the electric field. That is: a temporal perturbation of the electric field in vacuum will be accompanied by a magnetic field induction. This has been the crux of Maxwell's theory of electromagnetic radiation, and the foundation of the modern of picture of light waves, whereby light is seen as an electric field perturbation accompanied by a magnetic field perturbation along the direction of propagation of radiation.

Despite of how fundamental that equation is, the Maxwell-Ampere equation is essentially a *phenomenological continuum*, not a microscopic, theory of magnetic induction. Born as an integral force equation by Ampere in 1820 until it obtained its modified differential form by Maxwell, the equation evolved before an understanding of electrons as particles has crystallized. Microscopic theories of macroscopic phenomena followed the development of the microscopic theory of matter. For example, after the first observations of superconductivity, London developed a phenomenological model to describe the magnetic field decay due to the Meissner effect. However, a deeper understanding of superconductivity was gained in the form of the Bardeen–Cooper–Schrieffer theory. This was after quantum theory was widely endorsed by the physics community. I believe that the Ørsted magnetic field induction phenomenon is over-due for a microscopic theory. It is for this reason that I proposed the *current magnetization hypothesis* [4, 6] to envisage a microscopic origin for the Ørsted phenomenon.

Here I will conduct a thought experiment to examine *what happens to the established picture of electromagnetic radiation if one adopts a microscopic theory of the Ørsted magnetic field induction.* A microscopic theory for the Ørsted magnetic field induction will provide a derivation for the induced magnetic field based on claimed mechanisms in which atoms and conduction electrons interact in certain ways. For example, according to the current magnetization hypothesis, the Ørsted magnetic field phenomenon can be derived from the interaction between the conduction electrons and the wire material in a current-carrying wire. That is, the Ørsted magnetic field is not induced by the temporal change in the electric field alone, but by a microscopic mechanism that involves the particles in the wire. Even though this microscopic theory is able to provide a deeper insight into the nature of the phenomenon, it raises a warning sign: if the occurrence of the Ørsted magnetic field is tied to particle interactions, then it might be irrational to assume that the magnetic field is induced by pure electric field fluctuations. Thus, the equation $\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$, which was constructed by Maxwell with no experimental evidence, might not hold. In this paper, I shall examine the controversial argument that the electromagnetic radiation does not possess a transverse magnetic field.

II. THE TRANSVERSE MAGNETIC FIELD COMPONENT IN ELECTROMAGNETIC RADIATION

Before continuing the thought experiment, I will review the well-known classical theory of electromagnetic radiation. This radiation possesses two field components: the electric field and the magnetic field. Those two components are themselves waves that are propagating in directions transverse to the direction of propagation; if the radiation propagates along the z-axis, then it will be accompanied by an electric field that is polarized along the y-axis, and

* sherif.tawfic@gmail.com

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 September 2022 doi:10.20944/preprints202209.0396.v1

likewise a magnetic field polarized along the x-axis. This picture of the electromagnetic radiation is an idealization that follows from the solution of Maxwell's equations in vacuum. Needless to say, such idealized picture of electromagnetic radiation lies very deeply in the physics pedagogy. The very term "electromagnetic" was introduced by Ørsted to describe the coupling between the two fields [1]. The electromagnetic radiation is a massless propagating energy field, whether visible to the eye, in which case it is called light, or invisible, such as radio waves, ultraviolet, etc. This radiation was described by Maxwell in terms of the set of equations that he compiled and curated, the Maxwell equations. This set of equations tightly couples the electric and magnetic fields via the Maxwell-Faraday equation, Eq. 1a and the Maxwell-Ampere equation, Eq. 1b,

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}, \tag{1a}$$
$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \partial_t \mathbf{E} + \mu_0 \mathbf{j}, \tag{1b}$$
$$\nabla \cdot \mathbf{B} = 0, \tag{1c}$$
$$\nabla \cdot \mathbf{E} = 0, \tag{1d}$$

Applying both Eq. 1a and Eq. 1b yields the coupling between the electric and magnetic fields in electromagnetic radiation, as derived in standard textbooks [2, 3] and illustrated in Fig. 1(a). However, the statement that such coupling exists is not merely a mathematical corollary. It is a statement about the nature of radiation, and hence is a falsifiable statement that should be experimentally verified. *Is it possible to test whether the so-called "electromagnetic" radiation is indeed composed of both an electric and magnetic field fluctuations?* Note that such test must distinguish between the influence of the particular field component of radiation, and the energy delivered by the radiation. To achieve such distinction, one should test the influence of the wave as a function of the wave polarization, rather than the source field strength, because the latter is directly related to the wavelength i.e. the energy of the radiation, whereas the former is not.

Given that there is a clear mathematical form for both field fluctuations (electric and magnetic) that accompany electromagnetic radiation, say a ray of light, it should in principle be possible to test whether such ray of light could influence the magnetic and/or electronic properties of its surroundings. Once such influence can be measured, the existence of the field can be established. And indeed, the influence of the radiation field on the electronic properties of materials is already established: as a naive illustration, the photoelectric effect directly demonstrates that.

III. THE DIRECTION OF CAUSALITY

Consider the traditional derivation of the electromagnetic wave equation. This derivation requires both the Maxwell-Faraday and the Maxwell-Ampere equations, in addition to $\nabla \cdot \mathbf{E} = 0$ and $\nabla \cdot \mathbf{B} = 0$, to arrive at the two wave equations, $\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \ddot{\vec{\mathbf{E}}}$ and $\nabla^2 \mathbf{B} = \mu_0 \epsilon_0 \ddot{\vec{\mathbf{B}}}$. Then, applying the Maxwell-Faraday equation to the plane wave solutions for $\mathbf{E}$ and $\mathbf{B}$, we find that the induced magnetic field is perpendicular to the electric field in the directions transverse to the propagation direction.

An important aspect of Maxwell's equations, Eq. 1, is the causality between the electric and magnetic fields. Faraday's law implies that a time-changing magnetic field will induce a non-constant electric field. This causality I shall label as $\mathbf{B} \rightarrow \mathbf{E}$. The corresponding causality in Maxwell-Ampere's law, Eq. 1b, is $\mathbf{E} \rightarrow \mathbf{B}$. Hence is the symbol $\mathbf{B} \rightleftarrows \mathbf{E}$ in Fig. 1. Griffiths [3] asserted that Faraday's law alone can be used to establish that $\mathbf{E} \rightarrow \mathbf{B}$. That is, the equality sign "=" in Eq. 1 is assumed to interpreted as a *bidirectional causation* relationship: the right-hand side implies the occurrence of the left-hand side, and vice versa.

This is problematic. Let us refer to Eq. 1a. It implies that a time-changing magnetic field will result in a spatially non-constant electric field ($\mathbf{B} \rightarrow \mathbf{E}$). This can be directly derived from Faraday's experiments, where the spatially non-constant electric field is associated with the presence of an electric current in a wire. Reading the equation the other way around (that is, the $\mathbf{E} \rightarrow \mathbf{B}$ causality): the existence of a static spatially non-uniform electric field will be associated with a time-varying magnetic field. Consider a piece of metal: there is no magnetic field surrounding it, let alone a time-dependent one, although the metal itself imposes a spatially non-uniform electric field. Thus, we cannot reason that $\mathbf{E} \rightarrow \mathbf{B}$ follows from Faraday's law.

I have recently demonstrated [4] that the Maxwell-Ampere equation, Eq. 1b, might not hold microscopically. I suggested, instead, an alternative microscopic model that explains the Ørsted magnetic field induction phenomenon (also known as the *right-hand rule*) at the atomic scale. That alternative model could explain the recently reported measurements of Ørsted magnetic field in conducting nanosheets [5]. The model I suggested, which I called the generalized spin-orbit interaction in Ref. [4], and the "current magnetization hypothesis" (CMH) in Ref. [6] (and I certainly prefer the latter name for the theory), agrees with the form of Eq. 1b at the macroscopic limit.

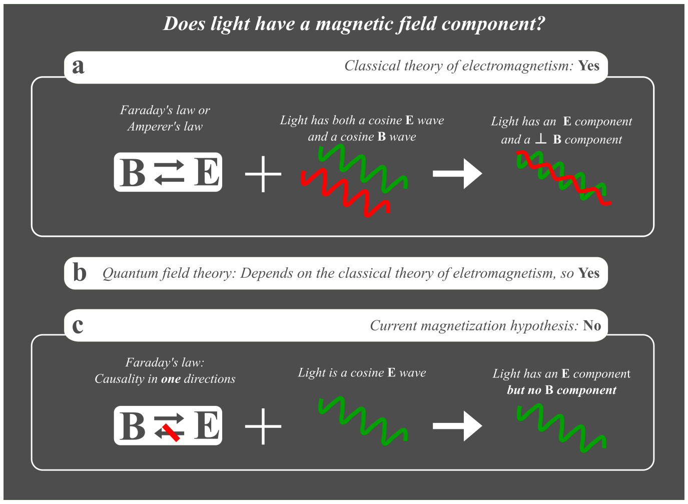

FIG. 1. A schematic illustration of the direction of causality between the electric (**E**) and magnetic (**B**) fields. The symbol $\mathbf{B} \rightarrow \mathbf{E}$ indicates that the presence of a **B** field, under the particular conditions dictated by an equation, will "induce" the **E** field. That is, **B** *causes* **E**. In (a), the causality implied by the classical Maxwell equations is illustrated. (b) shows that this causality stays the same in modern physics. (c) shows that the causality $\mathbf{E} \rightarrow \mathbf{B}$ is broken if we were to accept the current magnetization hypothesis.

By proposing that the Ørsted magnetic field induction phenomenon emerges from an interaction between the moving charges in a wire and the wire material (being a two-body interaction, see [6]), the magnetic induction is no longer a fundamental property of the electric and magnetic fields as is understood from the Maxwell-Ampere equation. That is, the CMH proposal could split the strongly held coupling between the electric and magnetic fields in electromagnetic wave propagation. Thus, the direction of causality in the Maxwell-Ampere equation 1b, which is $\mathbf{E} \rightarrow \mathbf{B}$, will not longer hold. We are only left with the causality $\mathbf{B} \rightarrow \mathbf{E}$: a dynamic magnetic field generates an electric field. This implies that a propagating light wave is composed of a fluctuating electric field, rather than a coupled electric and magnetic field components, as is traditionally held.

Fig. 1(c) illustrates how the CMH yields an electric field-only theory of radiation. Without Eq. 1b, we cannot have a closed system of wave equations for **E** and **B**.

IV. THE MAGNETO-OPTICAL EFFECT

It might be thought that the magneto-optical (MO) effect [7] is based on the presence of the magnetic field component in radiation, because the effect emerges from applying a magnetic field to a medium in which light propagates. However, the application of the magnetic field induces these effects only by changing the dielectric matrix of the medium [9], which interacts with the electric field component of light. Thus, the magnetic field is not directly affecting the nature of the field radiation.

The MO effect is also present in magneto-plasmonic nanoantennas. These systems are composed of magnetic and non-magnetic metals, and the exposure to radiation generates plasmons in the non-magnetic metal [8]. Here, the application of an external magnetic field affects the properties of the composite material, which subsequently influences the plasmonic properties. Again, the operation of these systems does not stem from a propagating magnetic field in radiation.

V. CONCLUSION

This work examined the concept of causality in the classical electromagnetic theory: how the theory reasons for the statements "magnetism causes electricity" and "electricity causes magnetism". While the causality of the Faraday law seems to follow the experimental procedure, the Ampere law does not. Based on this, it is possible to reason that light does not constitute of a fluctuating magnetic field. Even though this statement is contrary to the established paradigm, the idea of the perpendicular magnetic field has never been established experimentally. Coupled with the proposal of a microscopic theory for magnetic induction, this work suggests that the classical theory of electrodynamics

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 September 2022 doi:10.20944/preprints202209.0396.v1

can benefit from fundamental insights that might have impact on several of the strongly-held conclusions of the theory.

---

[1] Andre Koch Torres Assis and J. P. M. C. Chaib. Ampère's Electrodynamics: Analysis of the Meaning and Evolution of Ampere's Force Between Current Elements, Together with a Complete Translation of His Masterpiece: Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience, C. Roy Keys Incorporated, 2015.
[2] John David Jackson, Classical Electrodynamics (3rd ed.). New York: Wiley (1999).
[3] David J. Griffiths, Introduction to electrodynamics. Upper Saddle River, New Jersey: Prentice Hall (1999).
[4] Sherif Abdulkader Tawfik, The generalized spin-orbit interaction: a microscopic origin of the Ørsted magnetic field, J. Mag. Mag. Mat 504, 166660 (2020).
[5] J.-P. Tetienne, N. Dontschuk, D. A. Broadway, S. E. Lillie, T. Teraji, D. A. Simpson, A. Stacey, and L. C. L. Hollenberg, Apparent delocalization of the current density in metallic wires observed with diamond nitrogen-vacancy magnetometry, Phys. Rev. B 99, 014436 (2019).
[6] Sherif Abdulkader Tawfik, The current magnetization hypothesis as a microscopic theory of the Ørsted magnetic field induction, The European Physical Journal Plus 137, 1 (2022).
[7] P. S. Pershan, Magneto-optical effects, J. Appl. Phys. 38, 1482-90 (1967).
[8] Ivan S. Maksymov, Magneto-plasmonic nanoantennas: Basics and applications, Reviews in Physics 1, 36-51 (2016).
[9] J.C. Jacquet, T. Valet, A new magneto-optical effect discovered on magnetic multilayers: The magnetorefractive effect, in: E. Marinero (Ed.), Magnetic Ultrathin Films, Multilayers and Surfaces. MRS Symposium Proceedings, Pittsburgh, vol. 384, 1995, pp. 477-490.