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THE LONGITUDINAL PHOTOMAGNETON OF ELECTROMAGNETIC RADIATION: ON THE ABSENCE OF FARADAY INDUCTION IN VACUO

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The recently proposed free space photomagneton, $\hat{B}^{(3)}$, of electromagnetic radiation produces no intrinsic Faraday induction in a vacuum, but in matter produces phase free magnetization in the inverse Faraday effect.

Key words: photomagneton, induction, electrodynamics.

1. INTRODUCTION

In this note it is shown that the recently proposed [1–5] free space photomagneton $\hat{B}^{(3)}$ of electromagnetic radiation produces no intrinsic Faraday induction in vacuo. The reason for this result is that the Maxwell equations in vacuo are invariant under Lorentz transformations, and the expectation value of $\hat{B}^{(3)}$, the classical ghost field $\boldsymbol{B}^{(3)} = \langle \hat{B}^{(3)} \rangle$, remains solenoidal, divergenceless and phase-free in all Lorentz frames. An experiment designed to detect the effect of $\hat{B}^{(3)}$ by intrinsic Faraday induction in free space will therefore produce a null result. However, the effect of $\hat{B}^{(3)}$ can be detected in phase-free magnetization of matter, the inverse Faraday effect [6–8]. The latter occurs through the interaction of $\hat{B}^{(3)}$ with a material property tensor, in first order a susceptibility, in second order a hyperpolarizability [5].

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2. DESCRIPTION OF $B^{(3)}$ IN THE MAXWELL EQUATIONS

In quantum field theory the photomagneton $\hat{B}^{(3)}$ is generated directly [1–5] by the intrinsic (or spin) angular momentum of the photon,

$$\hat{B}^{(3)} = B^{(0)}\frac{\hat{J}}{\hbar}, \tag{1}$$

where $B^{(0)}$ is the scalar amplitude of magnetic flux density in free space and $\hbar$ is the reduced Planck constant. The classical equivalent of Eq. (1) is,

$$\boldsymbol{B}^{(3)} = \langle\hat{B}^{(3)}\rangle = B^{(0)}\boldsymbol{k}, \tag{2}$$

which is a relativistically invariant axial vector. This means that the axial unit vector $\boldsymbol{k}$ is the same in all Lorentz frames of reference in vacuo, $B^{(0)}$ being a frame invariant scalar quantity. It has been shown [1–5] that $\boldsymbol{B}^{(3)}$ is part of the cyclically symmetric set

$$\boldsymbol{B}^{(1)} \times \boldsymbol{B}^{(2)} = iB^{(0)}\boldsymbol{B}^{(3)*}, \tag{3}$$

and cyclic permutations of superscripts 1, 2, and 3. Here $\boldsymbol{B}^{(1)} = \boldsymbol{B}^{(2)*}$ is the usual magnetic part of the plane wave in vacuo, $\boldsymbol{B}^{(2)}$ being the complex conjugate of $\boldsymbol{B}^{(1)}$ [1–5]. Equation (3) re-expresses the nonlinear conjugate product $\boldsymbol{B}^{(1)} \times \boldsymbol{B}^{(2)}$ in terms of the ghost field $\boldsymbol{B}^{(3)} = \boldsymbol{B}^{(3)*}$, a pure real, physical, magnetic flux density. The inverse Faraday effect then becomes [5], to second order in $B^{(0)}$,

$$\boldsymbol{M}^{(3)} = AB^{(0)}\boldsymbol{B}^{(3)} = -iA\boldsymbol{B}^{(1)} \times \boldsymbol{B}^{(2)}, \tag{4}$$

where $\boldsymbol{M}^{(3)}$ is observable [6], phase-free ("static") magnetization and A is an averaged molecular property tensor. Since $\boldsymbol{B}^{(3)}$ in Eq. (1) is independent of wave frequency, it generates no Planck energy and $\boldsymbol{B}^{(3)}$ contributes nothing to the Poynting theorem [4].

The classical Maxwellian description of $\boldsymbol{B}^{(3)}$ is, in free space,

$$\nabla \cdot \boldsymbol{B}^{(3)} = 0, \qquad \nabla \times \boldsymbol{B}^{(3)} = -\frac{\partial \boldsymbol{B}^{(3)}}{\partial t} = \mathbf{0}, \tag{5}$$

and there is no Faraday induction due to the ghost field in a vacuum. For example, if a circularly polarized laser beam is pulsed through an induction coil, no signal will be seen due to any type of intrinsic Faraday induction from the elementary $\boldsymbol{B}^{(3)}$. This result will remain true in all Lorentz frames because, in special relativity, Maxwell's equations in vacuo are invariant to Lorentz transformation. (This is equivalent to the result that the Lorentz rotation in spacetime of a null four-vector produces a null four-vector; and, in special relativity, Maxwell's equations in vacuo are $b_\mu \equiv \partial F_{\mu\nu}/\partial x_\nu = 0$. Here $F_{\mu\nu}$ is the electromagnetic four-tensor [9] and $x_\mu \equiv (X, Y, Z, ict)$. Applying the Lorentz transformation from frame K to K' produces $a_{\lambda\mu} b_\mu = 0$ [10] and since $a_{\lambda\mu} \neq 0$ by definition, $b_\mu = 0$ in frame K' as well as in frame K. Zero subjected to the Lorentz rotation $a_{\lambda\mu}$ in Minkowski spacetime is still zero.)

Therefore, for all $B^{(0)}$ and in all reference frames in vacuo,

$$-\frac{\partial \boldsymbol{B}^{(3)}}{\partial t} = -\left(B^{(0)} \frac{\partial \boldsymbol{k}}{\partial t} + \frac{\partial B^{(0)}}{\partial t} \boldsymbol{k} \right) = \mathbf{0}, \tag{6}$$

and it is important to realize that $\partial \boldsymbol{k}/\partial t = \mathbf{0}$ for all $B^{(0)}$ and t of any Lorentz frame. Similarly, $B^{(0)} \nabla \times \boldsymbol{k} = \mathbf{0}$ and $B^{(0)} \nabla \cdot \boldsymbol{k} = 0$. The amplitude $B^{(0)}$ for the classical equivalent of one photon is fixed by Noether's theorem and conservation of elementary charge e, and cannot be changed in free space. If it asserted that $\partial B^{(0)}/\partial t \neq 0$, and we attempt to transform from one Lorentz frame K to another, K', we obtain

$$\left(\frac{\partial B^{(0)}}{\partial t} \right)_K =? \left(\frac{\partial B^{(0)}}{\partial t'} \right)_{K'}; \tag{7}$$

and since t in frame K is not the same as t' in frame K', the only possible solution is

$$\frac{\partial B^{(0)}}{\partial t} = 0 \tag{8}$$

in both frames. The amplitude $B^{(0)}$ therefore cannot be varied with time in free space, and there can be no intrinsic Faraday induction due to $B^{(0)}$. It is of course possible to block off part or all of the $B^{(0)}$ from a detector using some mechanical device, but this will not change the magnitude of $B^{(0)}$, any more than it would change the magnitude of the charge on the electron. This is an illustration of the fact that $B^{(0)}$ is an *elementary* property of light, a constant of physics. Since there is no Faraday induction due to $B^{(0)}$ of one photon, there will be none due to two photons, and none due to N photons. Therefore increasing or decreasing the number of photons in a beam by pulsing it will not cause Faraday induction in vacuo.

It is important to note that the longitudinal *axial* vector $\boldsymbol{k}$ is relativistically invariant, does not change from one Lorentz frame to another. It must not be confused with a longitudinal *polar* vector, which is subject to Fitzgerald-Lorentz contraction.

3. THE INVERSE FARADAY EFFECT, MAGNETIZATION OF MATTER BY THE PHOTOMAGNETON

If the pulsed, circularly polarized, laser is directed at a material inside the induction coil a signal will be observed through the inverse Faraday effect [6–8], Eq. (4); signalling the existence of $\hat{B}^{(3)}$. The latter exists in vacuo, it source is photon spin (Eq. (1)), and it can be detected experimentally through its magnetization of matter. To second order in $B^{(0)}$ [1–5],

$$\hat{M}^{(3)} = AB^{(0)2}\frac{\hat{J}}{\hbar} = AB^{(0)}\hat{B}^{(3)}, \tag{9}$$

a phenomenon which is due to the *elastic* transfer of photon angular momentum $\hat{J}/\hbar$ from light to matter. There is no necessity for direct transfer of light *energy* to matter in the inverse Faraday effect, which can therefore occur far from any optical resonance, as observed experimentally [6–8]. In other words, there is no necessity for the absorption of a light quantum $\hbar\omega$ in the inverse Faraday effect. There is, however, always a transfer of photon angular momentum $\hat{J}/\hbar$. The photomagneton $\hat{B}^{(3)} = B^{(0)}\hat{J}/\hbar$ therefore magnetizes matter to produce $\hat{M}^{(3)}$, whose observed expectation value is $\boldsymbol{M}^{(3)}$. Therefore the classical magnetic field $\boldsymbol{B}^{(3)}$ produces the magnetization $\boldsymbol{M}^{(3)}$. It appears that such a process can also occur in principle at first order in $B^{(0)}$ [5].

CONCLUSIONS

The elementary (i.e., fundamental) $\hat{B}^{(3)}$ photomagneton of a pulsed, circularly polarized, laser produces no signal when passed through an induction coil in a vacuum, because its magnitude per photon is fixed, in the same way that the charge on the electron is fixed. If there is material inside the coil a signal can be detected in principle through the inverse Faraday effect.

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