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# THE EXPERIMENTALLY OBSERVED OPTICAL COTTON–MOUTON EFFECT: EVIDENCE FOR THE PHOTON'S LONGITUDINAL MAGNETIC FIELD, $\mathbf{B}^{(3)}$

M. W. EVANS
*Department of Physics, University of North Carolina,*
*Charlotte, NC 28223, USA*

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The recent experimental observation of the optical Cotton–Mouton effect is consistent with the induction of magnetization by the longitudinal component of the photon's magnetic field, whose classical counterpart is the equivalent flux density $\mathbf{B}^{(3)}$. In the optical Cotton–Mouton effect observed by Zon *et al.*,[16] the field $\mathbf{B}^{(3)}$ acts at second order and is independent of the polarization of the inducing laser beam propagating parallel to a permanent magnetic field. The optical Cotton–Mouton effect is therefore proportional to the laser intensity as observed.[16]

## 1. Introduction

The well-known inverse Faraday effect (IFE) was first observed by van der Ziel *et al.*[1,2] and was among the first magneto–optic effect to be reported, i.e. an effect in which light magnetizes material with which it interacts. Since then, there have been several reports of the ability of light to act as a magnet.[13–15] An inverse (i.e. optical) Cotton–Mouton effect has recently been reported by Zon *et al.*[16] in a magnetically ordered crystal film grown by epitaxy. A linearly polarized beam from a neodymium laser with a pulse length of about 20 ns and a beam diameter of 1.3 mm was normally incident[16] on the surface of the sample immersed in an external permanent magnetic field parallel to the beam. A change in the magnetization of the sample was detected[16] by a planar three-turn coil on the surface of the sample. The electric signal from this coil was fed to a broad-band, low-noise amplifier and then to an oscilloscope, and detected as a rise transient over about 3 ns. It was found[16] that the emf was proportional to the intensity of the laser beam and was independent of the polarization of the laser, which was adjusted with a quarter wave plate. The results were interpreted as a magnetization (Eq. (2) of Zon *et al.*[16]) proportional to the permanent magnetic field multiplied by the product of $\mathbf{E}(t)$ and $\mathbf{E}^*(t)$, which are the electric field strength of the electromagnetic laser field and its complex conjugate respectively.

In this letter, these results are interpreted in terms of the equivalent longitudinal magnetic field $\mathbf{B}^{(3)}$ of a laser beam. The data of Zon *et al.*[16] provide unequivocal evidence for $\mathbf{B}^{(3)}$, which is the fundamental property of light responsible for magnetic effects in materials. Section 2 is a brief review of theory, Sec. 3 is an application to data in Ref. 16. This is followed by a discussion and suggestions for further work.

## 2. Theory of the Optical Cotton–Mouton Effect

The original Cotton–Mouton effect is well-known to be linear birefringence induced at second order in static magnetic flux density. The effect is usually described[17] as the development of a phase difference in the two coherent resolved components of the probe, linearly polarized parallel and perpendicular, respectively, to the direction $Z$ of the applied magnetic field. The phase difference is

$$\delta = \frac{\omega}{c} l(n_{11} - n_1) , \tag{1}$$

where $l$ is the sample length, $\omega$ the probe angular frequency, $c$ the velocity of light, and $n_{11}$ and $n_1$ the refractive indices for light linearly polarized parallel and perpendicular to $Z$. The resulting ellipticity is $\eta$ and it is proportional to the scalar $B^{(3)2}$. Symmetry arguments show that there is no Cotton–Mouton effect linear in $\mathbf{B}^{(3)}$. All this is well-known when $\mathbf{B}^{(3)}$ is a conventionally generated magnetic field. However, the results of Zon *et al.*[16] show that there is a Cotton–Mouton effect due to light, an effect which is linear in the laser intensity and independent of the laser polarization (linear or circular). The optical Cotton–Mouton (OCM) effect is therefore fundamentally different from the inverse Faraday effect (IFE), which occurs only in circular polarization. We show in this section that these results can be explained in terms of the novel field $\mathbf{B}^{(3)}$ of light.[17–22]

It is important to realize that $\mathbf{B}^{(3)}$ does not contribute to the electromagnetic energy density because it does not contribute[1,2] to the Poynting vector. This is clear from its definition in terms of the conjugate product used by Pershan[1,2] in the original IFE theory:

$$\mathbf{E}^{(1)} \times \mathbf{E}^{(2)} = iE_0^2\mathbf{k} = ic^2B_0^2\mathbf{k} \equiv ic^2B_0\mathbf{B}^{(3)} . \tag{2}$$

Here, $\mathbf{E}^{(1)}$ is the oscillating electric field of the laser and $\mathbf{E}^{(2)}$ its complex conjugate. The magnetic field $\mathbf{B}^{(3)}$ therefore changes sign with the sense of circular polarisation (right or left). In a linearly polarised beam, there is therefore no net $\mathbf{B}^{(3)}$, but effects in the scalar $B^{(3)2}$ exist in linear polarisation because $B^{(3)2} = (-B^{(3)})^2$. **There is an optical Cotton–Mouton effect due to B in linear polarisation and circular polarisation, and is the same in magnitude for all polarisations.** The ellipticity of the optical Cotton–Mouton effect was derived in Ref. 17 and is given by

$$\eta = \frac{1}{120}\,\omega\mu_0 c l N B^{(3)2}\zeta . \tag{3}$$

Here, $\omega$ is the frequency of the probe beam, $\mu_0$ the permeability in vacuo, $c$ the speed of light, $l$ the sample path length, $N$ the number of molecules per cubic metre, and $\zeta$ a combination of molecular property tensor elements. In this reference, it was wrongly thought that the optical Cotton–Mouton disappears in linear polarisation. It is true that the net $\mathbf{B}^{(3)}$ in linear polarization is zero, but the optical Cotton–Mouton effect is in the scalar $B^{(3)2}$, and this does NOT disappear. Linear polarisation is 50% left and 50% right circular polarisation, and there is therefore 50% $+\mathbf{B}^{(3)}$ and 50% $-\mathbf{B}^{(3)}$ present in linear polarisation. Effects in the scalar $B^{(3)2}$ therefore persist in linear polarisation. On the other hand, the IFE is an effect in the vector $ic^2 B_0 \mathbf{B}^{(3)}$ and disappears in linear polarization, being opposite for right and left circular polarization.

## 3. Applications of the $\mathbf{B}^{(3)}$ Theory to the Optical Cotton–Mouton Effect

The magnetization associated with the optical Cotton–Mouton effect can therefore be expected to be proportional to the scalar $B^{(3)2}$ in all states of polarization of the inducing light beam, and this is observed experimentally by Zon *et al.*[16] as an increase in magnetization in comparison with the steady state value in the absence of the laser light. The effect was distinguished carefully[16] from thermal and thermoelastic effects, and we note that it is distinguished from the IFE because the latter is expected[1,2] only in circular polarization. In their Fig. 3, Zon *et al.*[16] report a plot of emf amplitude against the energy of the laser pulse. This appears to be linear within the uncertainty for six experimental points, although the best fit straight line does not go through the origin, indicating a small system uncertainty. Nevertheless, these data suggest that the magnetization is proportional to light intensity (energy) and therefore to $B^{(3)2}$. As mentioned by Zon *et al.*,[16] this is the first time that linearly polarized optical radiation has been observed to magnetize.

The magnetization can be interpreted straightforwardly in terms of a material property $\xi$ of the sample:

$$\mathbf{M} = \xi B^{(3)2} \mathbf{B}_0 , \tag{4}$$

which is Eq. (2) of Zon *et al.*[16] written in a simplified way. Here, $\mathbf{B}_0$ is the permanent magnetic flux density of the magnet used by Zon *et al.*[16] We note that these authors write $B^{(3)2}$ in terms of the product $E(t)E^*(t)$ in their notation. The mediating material property $\xi$ is $\hat{T}$ and $\hat{P}$ positive, where $\hat{T}$ denotes motion reversal and $\hat{P}$ parity inversion, and therefore exists after averaging[17] in all materials. If we attempt to write a simpler expression in terms of $B^{(3)2}$ only:

$$\mathbf{M} \supseteqq \xi_1 B^{(3)2} , \tag{5}$$

we find that the mediating hyperpolarisability $\xi_1$ must be negative to motion reversal, and so disappears on averaging. Such an effect cannot therefore be observed, in contrast to the IFE, where the mediating hyperpolarisability is $\hat{P}$ and $\hat{T}$ positive, as shown by Woźniak, Evans, and Wagnière.[19]

## 4. Discussion

It is significant that Zon *et al.*[16] also report an optical Cotton–Mouton effect in Yb-doped samples of similar composition, as well as in samples doped with Lu. In Tm samples, the effect is hidden by a large thermal response. The fact that their observed magnetization can be expressed in terms of $B^{(3)2}$ means that it is indeed a Cotton–Mouton type of magnetization, corresponding with an ellipticity change which can also be expressed in terms of $B^{(3)2}$[17] as discussed already. Zon *et al.*[16] did not of course use a probe beam but measured the magnetization directly on an oscilloscope. The fact that effects due to $B^{(3)2}$ exist in linear and circular polarization suggests that the data obtained by Zon *et al.*[16] are significant evidence for the interpretation of magneto–optic effects in terms of the equivalent magnetic field $\mathbf{B}^{(3)}$, which can be written[18] as the fundamental longitudinal magnetic field of the photon. An ensemble of photons delivers a $\mathbf{B}^{(3)}$ field which causes magnetic effects when the light interacts with a sample. One of these effects is the optical Cotton–Mouton magnetization observed by Zon *et al.*[16] for the first time. Another is the inverse Faraday effect observed experimentally on several occasions in different laboratories.

There is an obvious need for a systematic study of both effects under controlled conditions in diamagnetics, paramagnetics, and ferromagnetics (for example, magnetic semiconductors). For example, it is not clear why the signal reported by Zon *et al.*[16] should be constant for all polarizations, because in circular polarization, we expect the simultaneous presence of an inverse Faraday effect. The latter would add to the OCM effect in one sense of polarization and detract from it in the other. In linear polarization, an IFE is not expected. This appears to be an experimental problem, not a theoretical one, because both the IFE and OCM effects can be explained straightforwardly with $\mathbf{B}^{(3)}$. The latter is the most fundamental property of light responsible for the magnetization of material, and to date, there are very few data in the literature on this phenomena. A thorough and systematic search is essential for an accurate determination of its properties. It is certain, however, that $\mathbf{B}^{(3)}$ is not zero, because if this were so, there would be no IFE and OCM effects.

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