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Observation of the Inverse Cotton-Mouton Effect

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We report the investigation of the Inverse Cotton-Mouton Effect (ICME) i.e. the magnetization induced in a medium by light propagating in the presence of a transverse magnetic field. We present a detailed study of the ICME in a TGG crystal showing the dependence of the measured effect on the laser power density and polarization, and on the static external magnetic field. We finally derive a relation between the Cotton-Mouton and Inverse Cotton-Mouton effects which is experimentally confirmed. © 2010 Optical Society of America

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The Inverse Cotton-Mouton Effect (ICME) is a magnetization induced in a medium by a non resonant linearly polarized laser beam propagating in the presence of a transverse magnetic field. This magnetization is proportional to the value of the magnetic field, and to the energy density of the propagating electromagnetic waves [1]. The ICME was predicted for atomic and molecular systems [2] and for the quantum vacuum [3]. A complete experimental proof of the existence of this effect has not been reported yet. In 1987 Zon *et al.* reported the measurement of a magnetization of a magnetic film induced by a laser beam in the presence of a static magnetic field parallel to the direction of light propagation [4]. This laser-magnetic field geometry is called Faraday configuration and it is usually associated to the Inverse Faraday Effect, not to the ICME as the authors of ref. [4] did. The measured magnetization depended on the magnetic field value but not linearly as expected for an ICME. The reported effect did not depend on the laser polarization which is also unexpected.

We present here a detailed study of the ICME in a terbium gallium garnet (TGG) crystal showing the dependence of the measured effect on the laser energy and polarization, and on the external magnetic field.

The laser source was a Q-switched Nd:YAG laser ($\lambda = 1064\text{nm}$) providing 10 ns light pulses of about 0.5 J/pulse. The laser beam passed through two polarizers. The second one fixed the laser beam polarization, while the first one was used to change the laser power delivered to the TGG crystal. A $\lambda/2$ waveplate was placed behind the polarizers to rotate the laser polarization when needed. Folding mirrors and a lens allowed to deliver and focus the laser beam a few centimeters behind the TGG crystal. The index of refraction n of TGG at $\lambda = 1064\text{nm}$ is $n \approx 2$. Crystal dimensions were 2 mm x 2 mm x 2 mm. It was subject to a magnetic field paral-

lel to the $[0,0,1]$ direction provided by an electromagnet. The field values were in the range 0 - 2,5 T. The \mathbf{k} vector of light was parallel to the $[1,0,0]$ direction, while the polarization of laser light was parallel to the external magnetic field i.e. parallel to the $[0,0,1]$ direction or perpendicular to the external magnetic field i.e. parallel to the $[0,1,0]$ direction. In the following a subscript \parallel indicates a quantity measured with the light polarization parallel to the external field, and a subscript \perp indicates a quantity measured with the light polarization perpendicular to the external field.

Changes in the crystal magnetization have been measured using a probe constituted by a double pickup coil, a compensating coil and a signal coil. In Fig. 1 we show a sketch of the detection zone of the experimental apparatus. The signal coil is put in contact with the crystal while the other one is away from the crystal. The double coil is designed so that in such a configuration any signal not coming from the crystal is reduced to zero. Each coil is 2 mm x 2 mm and the distance between the centers of the two coils is 5 mm. Each coil has been calibrated by measuring the signal obtained in a known modulated magnetic field. The output signal of the coil is amplified by a low noise fast amplifier and filtered by a 100 kHz high pass filter. We used two of this type of probes, one for the upper side of the crystal and the other one for the lower side of the crystal.

In Fig. 2 are plotted a typical laser pulse together with the corresponding signal detected by one of the two signal coils. Both signals were recorded on a fast digital oscilloscope with 1 GS/s.

The laser pulse is monitored by extracting a small fraction of the beam injected in the crystal with a beam splitter and detecting it with a fast photodiode. The photodiode has been calibrated with respect to an energy meter measuring the pulse energy incident on the crystal. The

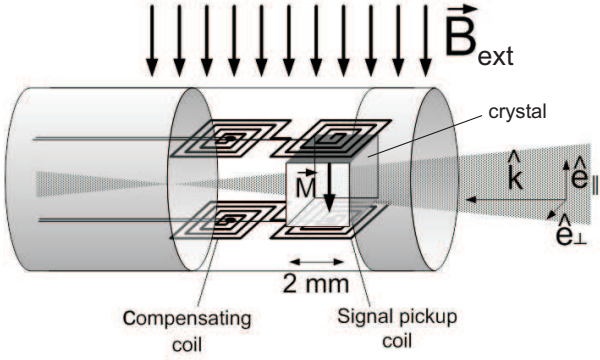


Fig. 1. Detection apparatus: a laser beam crosses the crystal transversal to an applied magnetic field B_{ext} . Two sets of pickup-compensating coils monitor the induced crystal magnetization M .

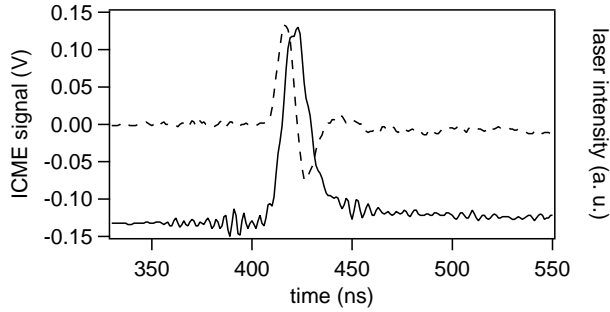


Fig. 2. Magnetization signal (dashed line) and laser pulse (line) as a function of time. The induced signal is the time derivative of the laser intensity.

ICME signal $V(t)$ is proportional to the time derivative of the magnetic flux in the pickup coil and can be written as:

$$V(t) = -gA_e \frac{dB_p(t)}{dt}, \quad (1)$$

where g is the gain of the low noise pickup coil amplifier, $A_e = 10 \text{ mm}^2$ is the calibrated effective area of the signal coil and B_p the magnetic flux density through the pickup coil area produced by the crystal magnetization M . B_p can be written as:

$$\frac{dB_p(t)}{dt} = bB_{\text{ext}} \frac{dP_d(t)}{dt}, \quad (2)$$

where P_d is the laser power density, B_{ext} is the external static transverse magnetic field, and b is a proportionality factor characterizing the ICME. This factor depends on the medium properties and on the pickup coil position with respect to the region of the medium which is illuminated by the laser beam and thus magnetized. Finally, Eq. (1) becomes:

$$V(t) = -gA_e b B_{\text{ext}} \frac{dP_d(t)}{dt}. \quad (3)$$

Therefore, the ICME signal is proportional to the time derivative of the laser pulse intensity as clearly observed

in Fig. 2. We checked that the integrated signal reproduced well the shape of the laser pulse detected by the fast photodiode. This observation, plus the observed polarization dependence described below guarantee that we are not hindered by thermo-optic effects.

In Fig. 3 we show the ICME magnetic flux density at a fixed value of the magnetic field (2.5 T) changing the laser pulse energy from 0 to 0.250 J. Data have been taken in two different configurations of the laser polarization: parallel to the external magnetic field corresponding to the measured magnetic flux density $B_{p\parallel}$ or perpendicular to the external field corresponding to $B_{p\perp}$. The diameter of the laser spot in the crystal was around 1.2 mm, corresponding to a laser power density P_d ranging between 0 and $2.2 \times 10^{13} \text{ W/m}^2$. Fig. 3 shows that the magnetic flux density depends linearly on the laser power density as expected. A 12% statistical error was estimated for the vertical axis and 5% for the horizontal axis due to pulse to pulse variations in laser energy and uncertainty in laser energy measurement as well as electromagnetic noise induced by Q-switching.

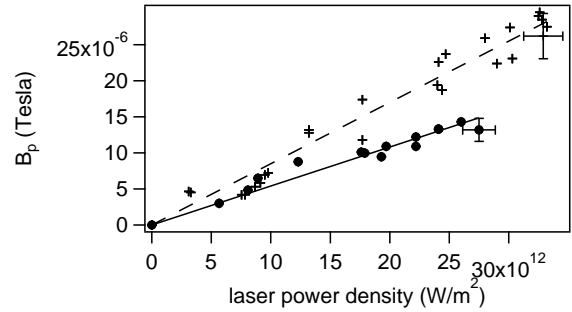


Fig. 3. Magnetic flux density B_p in the pickup coils versus laser power density P_d for two light polarizations: parallel (+) and perpendicular (•) to the applied magnetic field. Data are fitted by a linear equation. Error bars represent the typical statistical error.

In Fig. 4 is plotted the complete set of ICME data taken at different values of laser power density and external magnetic field. The measured magnetic flux density amplitude is shown as a function of the product of the laser power density and the external static magnetic field amplitude.

We also show in Fig. 3 and in Fig. 4 the best linear fit superimposed to the data. The measured magnetic flux density $B_{p\parallel}$ and $B_{p\perp}$ depend linearly on the product of the laser power density and the external magnetic field value B_{ext} as expected, with a proportional factor of $b_{\parallel} = (3.36 \pm 0.04) \times 10^{-19} \text{ m}^2 \text{ W}^{-1}$, and $b_{\perp} = (2.07 \pm 0.05) \times 10^{-19} \text{ m}^2 \text{ W}^{-1}$. During data acquisition we have changed the external magnetic field polarity and we have observed that the ICME signal also changed sign. The positive sign of the b constant which means that B_p is always parallel to B_{ext} has been verified explicitly.

To calculate the magnetization of the TGG from the

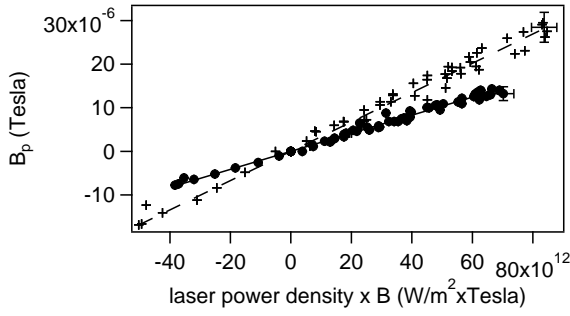


Fig. 4. Magnetic flux density versus the product of laser power density by the applied magnetic field for two light polarizations: parallel (+) and perpendicular (•) to B_{ext} . Data are fitted by linear equation. Error bars represent the typical statistical error.

measured value of the magnetic flux density, one has to evaluate the fraction of magnetic flux outgoing from the optically magnetized region of the crystal passing through the pick-up coil. Assuming a homogeneous transverse magnetization in a cylindrical region with a diameter of 1.2 mm, we have calculated the magnetic flux perpendicular to the pick-up coil for our experimental setup, using a finite element magnetic modeler [5]. For a magnetization M of 1 A/m, we found a magnetic flux density B_p of about 4×10^{-8} T at the position where our signal coil was placed i.e. at about 2.5 mm from the center of the laser spot. The conversion factor between magnetic flux density B_p and the crystal magnetization M is therefore about 2.5×10^7 (A/m)T $^{-1}$.

The ICME magnetization of the TGG can be defined as:

$$M = C_{\text{ICM}} P_d B_{\text{ext}} \quad (4)$$

where C_{ICM} depends only on the medium properties and that one can call the Inverse Cotton-Mouton constant. Our data indicates therefore that for our TGG crystal $C_{\text{ICM}\parallel} = 8.4 \times 10^{-12}$ (A.m)(W.T) $^{-1}$ and $C_{\text{ICM}\perp} = 5.2 \times 10^{-12}$ (A.m)(W.T) $^{-1}$.

As far as we know, no theoretical prediction of the value of the ICME in a TGG crystal exists. As shown in ref. [3] the Inverse Cotton-Mouton effect can be calculated starting from the term in the expansion of the electromagnetic energy of the medium U which is quadratic in the electric and in the magnetic field. Let's write it as:

$$U = -\frac{1}{4} \frac{\epsilon_0}{\mu_0} \chi_{\alpha\beta\gamma\delta} f_\alpha f_\beta E_\alpha E_\beta B_\gamma B_\delta \quad (5)$$

where ϵ_0 is the vacuum permittivity, μ_0 the vacuum permeability, $\chi_{\alpha\beta\gamma\delta}$ is the second order magnetic and electric susceptibility, f_α, f_β the local electric field factors, E the electric field and B the magnetic field. In the following we will assume Kleinman symmetry [1].

The medium magnetization can be calculated using the relation $M = -\frac{\partial U}{\partial B}$. Since $f_\alpha = f_\beta = f$ in our case,

$\Delta M \equiv M_{\parallel} - M_{\perp}$ can be expressed as:

$$\Delta M = \frac{1}{2} \frac{\epsilon_0}{\mu_0} (\chi_{\parallel} - \chi_{\perp}) f^2 E^2 B_{\text{ext}}. \quad (6)$$

On the other hand, the Cotton-Mouton effect is related to the variation of the index of refraction induced by the transverse magnetic field $\Delta n_{\text{CM}} \equiv n_{\parallel} - n_{\perp}$ [6]. Following the quantum theory developed for media with $n \neq 1$ [8], one can write:

$$\Delta n_{\text{CM}} = \frac{1}{4\mu_0 n} (\chi_{\parallel} - \chi_{\perp}) f^2 B_{\text{ext}}^2, \quad (7)$$

where n is the index of refraction without magnetic field.

Eqs. (6) and (7) show that a simple relation exists between Δn_{CM} and $\Delta C_{\text{ICM}} \equiv C_{\text{ICM}\parallel} - C_{\text{ICM}\perp}$:

$$\frac{\Delta n_{\text{CM}}}{\Delta C_{\text{ICM}}} = \frac{B_{\text{ext}}^2}{2\epsilon_0 n}. \quad (8)$$

We can therefore estimate the value of the Cotton-Mouton effect for our TGG crystal from our ICME measurement: $\Delta n_{\text{CM}} \approx 10^{-4}$ T $^{-2}$. This value is compatible with the values reported in ref. [7] for a different laser wavelength ($\lambda = 0.63 \mu\text{m}$) and different configuration for the \mathbf{k} vector of light.

Our observation of the ICME in a crystal of TGG opens a new field of investigations of electromagnetic properties of matter. Cotton-Mouton effect gives only information on the difference between matter response while the Inverse Cotton-Mouton effect provides an absolute value for this response.

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