Electric-field induced magnetization in YIG observed by Faraday rotation

K Fujimoto¹, T Hasunuma¹ and T Kohmoto¹,²

¹ Graduate School of Science, Kobe University, Kobe 657-8501, Japan
² Molecular Photoscience Research Center, Kobe University, Kobe 657-8501, Japan

E-mail: kohmoto@kobe-u.ac.jp

Abstract. We studied the electric-field induced magnetization caused by the magnetoelectric effect in YIG. The magnetization was observed as the Faraday rotation of a transmitted continuous-wave probe light. From the observed dependence of the Faraday-rotation amplitude on the electric and magnetic fields, it was found that the two components linear and quadratic in the electric field coexist at low temperatures.

1. Introduction

Yttrium iron garnet (YIG, Y₃Fe₅O₁₂) is a ferrimagnetic material with a Curie temperature of 560 K and is known to show a large Faraday effect. YIG is also known to show the magnetoelectric (ME) effect. The second-order ME effect (magnetic-field induced electric polarization) at room temperature [1] and the first-order ME effect (electric-field induced magnetization) below 125 K [2,3] have been reported. Recently, the magnetocapacitance effect and the magnetic-field induced electric polarization in YIG were investigated in detail [4,5]. In the present report, we studied the electric-field induced magnetization caused by the magnetoelectric effect in a YIG single crystal by using the Faraday rotation of a probe light.

2. Experiment

A single crystal of YIG, which has a (001) plane of 5 × 5 mm² and a thickness of 0.3 mm, was set in a temperature-controlled cryostat. The magnetic and electric fields were applied along the [001] direction. The sample was sandwiched between a transparent electrode and a metal mirror, and a square-wave electric field pulse, whose period is 20 ms, was applied between them. A continuous-wave probe light, whose wavelength is 1064 nm, goes through the electrode and the sample, is reflected by the metal mirror, and goes back through the sample and the electrode. The magnetization induced by the electric field was detected by a polarimeter as the Faraday rotation of the transmitted probe light. The change of the Faraday rotation angle induced by the electric field was obtained as the Faraday-rotation amplitude. Before the measurement, the temperature was decreased to 7 K in an electric field $E$ of 3.3 MV/m and a magnetic field $B$ of 1 T (field cooling).

3. Results and Discussion

3.1. Electric-field dependence

The electric-field dependence of the Faraday-rotation amplitude observed at 50 K and 175 K in the magnetic field of +1 T is shown in figure 1. The observed amplitude can be considered to be a sum of
two components linear and quadratic in the electric field. At low temperatures, the amplitude of the linear component is larger than that of the quadratic component, and the inversion of the electric-field direction reverses the sign of the Faraday-rotation signal. The relative amplitude of the quadratic component increases at higher temperatures, and the sign of the signal amplitude at $E = \pm 3.3 \text{ MV/m}$ is the same.

The solid curves in figure 1 are the best fit to the observed data using the function of equation (1).

$$S(E) = \alpha E + \beta E^2 \quad (B = +1 \text{ T}),$$  

where $S$ is the Faraday-rotation amplitude, and $\alpha$ and $\beta$ are the coefficients for the linear and quadratic components. From this fitting, the coefficients $\alpha$ and $\beta$ can be evaluated.

### 3.2. Magnetic-field dependence

The magnetic-field dependence of the Faraday-rotation amplitude observed for $E = \pm 3.3 \text{ MV/m}$ at 7 K are shown in figure 2. The magnetic field was swept up and down between $\pm 1 \text{ T}$ for $E = +3.3$ and $-3.3 \text{ MV/m}$. The inversion of the magnetic-field direction reverses the sign of the Faraday-rotation signal. The absolute value of the amplitude is the same for $B = \pm 1 \text{ T}$. The large amplitude change in the magnetic field between $\pm 0.2 \text{ T}$ is considered to be caused by the saturation of magnetization in YIG.

Figure 2. Magnetic-field dependence of the Faraday-rotation amplitude observed at 7 K for the electric field of (a) $+3.3 \text{ MV/m}$ and (b) $-3.3 \text{ MV/m}$.
Assuming that the same relation is valid for the Faraday-rotation amplitude for $E = \pm 3.3$ MV/m and $B = +1$ T in the measurements of electric-field dependence and magnetic-field dependence, equation (1) for the observed amplitude at $B = +1$ T in the measurement of magnetic-field dependence yields

$$\begin{cases} S(+3.3 \text{ MV/m}) = \alpha(3.3 \text{ MV/m}) + \beta(3.3 \text{ MV/m})^2, \\ S(-3.3 \text{ MV/m}) = -\alpha(3.3 \text{ MV/m}) + \beta(3.3 \text{ MV/m})^2. \end{cases}$$

(2)

The value of the Faraday rotation amplitude $S(E)$ in the saturated magnetization at $B = +1$ T is expected to be $\alpha|E| + \beta E^2$ for positive $E$ and $-\alpha|E| + \beta E^2$ for negative $E$. The coefficients $\alpha$ and $\beta$ for the linear and quadratic components can be evaluated from equations (2).

3.3. Temperature dependence of $\alpha$ and $\beta$

Figure 3 shows the temperature dependence of $\alpha$, $\beta$, and $\alpha/\beta$, where both of those values evaluated from the measurements of electric-field dependence and magnetic-field dependence are plotted. The agreement of the values of $\alpha$ and $\beta$ evaluated from the two measurements is not good. In the magnetoelectric effect in YIG, oxygen vacancies were suggested to play an important role [4,5], and significant sample dependence was reported [6]. The disagreement may be because that the efficiency of the electric-field induced magnetization is not the same for different spots in the sample and/or for each field-cooling process. However, the value of ratio $\alpha/\beta$ obtained from the two measurements is in good agreement.

![Figure 3](image-url)

**Figure 3.** Temperature dependence of the values of $\alpha$, $\beta$, and $\alpha/\beta$ evaluated from the measurements of electric-field dependence (circle) and magnetic-field dependence (diamond).
Figure 3 shows the coexistence of linear and quadratic components in the electric-field induced magnetization in YIG. The value of \( \alpha/\beta \) begins to decrease at about 150 K, its sign is changed at about 180 K, and the Faraday-rotation signal disappears above 250 K. The sign change in \( \alpha/\beta \) is caused by that in \( \alpha \), which suggests the direction inversion of the induced magnetization for the linear component.

4. Summary
We observed the electric-field dependence and the magnetic-field dependence of the electric-field induced magnetization in YIG by Faraday rotation. The Faraday-rotation amplitude can be given by a sum of two components linear and quadratic in the electric field, and we evaluated the coefficients for the two components from the two measurements independently. It was found that the linear and quadratic components coexist below 250 K in the electric-field induced magnetization in YIG. The linear component is dominant below 150 K, the ratio of the linear component to the quadratic one decreases around 180 K, and the sign of its coefficient is inverted above 180 K.

References
[1] O’Dell T H 1967 *Phil. Mag.* **16** 487
[2] Ogawa H, Kita E, Mochida Y, Kohn K, Kimura S, Tasaki A and Siratori K 1987 *J. Phys. Soc. Jpn.* **56** 452
[3] Kita E, Takeno S, Tasaki A, Shiratori K, Kohn K and Kimura S 1988 *J. Appl. Phys.* **64** 5659
[4] Yamasaki Y, Kohara Y and Tokura Y 2009 *Phys. Rev. B* **80** 140412(R)
[5] Kohara Y, Yamasaki Y, Onose Y and Tokura Y 2010 *Phys. Rev. B* **82** 104419
[6] Kita E, Takano S, Kohn K, Siratori K, Kimura S and Tasaki A 1992 *J. Magn. Magn. Matter.* **104-107** 449