Dynamics of the electric-field induced magnetization in antiferromagnetic chromium oxide observed by Faraday rotation

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Abstract. We observed the dynamics of the electric-field induced magnetization in antiferromagnetic chromium oxide (Cr₂O₃) by the Faraday-rotation measurement using a continuous-wave probe light in the millisecond region and a pulse probe light in the nanosecond region. It was found that the Faraday-rotation amplitude linearly depends on the electric field, decreases with increasing temperature, and disappears above the Néel temperature. In the nanosecond region, nanosecond rise of the electric-field induced Faraday-rotation signal was observed.

1. Introduction
In recent years, various types of multiferroic materials, in which ferroelectric and magnetic orders coexist, have been found. Many of them are antiferromagnets which have spin structures of spiral type, and their giant magnetoelectric effect has been attracting attention.

Antiferromagnetic chromium oxide (Cr₂O₃) is not multiferroic, but is known to show the linear magnetoelectric effect, in which the electric polarization is induced in proportion to the applied magnetic field and the magnetization is induced in proportion to the applied electric field. Cr₂O₃ is a material in which magnetoelectric effect was first observed a half century ago [1]. Since the linear magnetoelectric effect was discovered, Cr₂O₃ has attracted interest in the magnetoelectric effect and the magneto-optical effect in the experiments of the nonreciprocal rotation of the polarization plane [2] and the second harmonic generation [3]. Recently, the details of the room-temperature linear magnetoelectric effect was reported [4].

The electric-field induced magnetization has been observed as the response to the applied alternating electric field. The electromotive force in a pickup coil [1,4-7] or Faraday rotation of a probe light [8-10] was detected as the magnetization signal, where the alternating frequency of 10⁵-10⁶ Hz was used. However, the dynamics of electric-field induced magnetization in the time regions shorter than microseconds has not been reported so far. In the present study, we pay attention to the magnetization induced by the electric field in the magnetoelectric effect. We studied the dynamics of the electric-field induced magnetization in Cr₂O₃ using a Faraday-rotation measurement in the millisecond and nanosecond regions.

2. Sample and Experiment
We use a single crystal of Cr₂O₃ as the sample, whose thickness is 0.25 mm. Cr₂O₃, which has a corundum structure with a threefold symmetry axis (c-axis), is an antiferromagnet with the Néel
temperature $T_N = 307$ K. Cr$^{3+}$ ions align along the $c$-axis and are surrounded by distorted octahedra of O$^2$ ions. Below $T_N$, the spins of Cr$^{3+}$ ions align antiferromagnetically along the $c$-axis, and Cr$_2$O$_3$ shows the linear magnetoelectric effect.

The linearly-polarized probe light enters the sample parallel to the $c$-axis, and the Faraday-rotation signal of the transmitted light is detected by a polarimeter. The sample is sandwiched between a transparent electrode (ITO) and a metal mirror, and an electric field is applied between them. Since the Faraday-rotation signal is proportional to the magnetization, the electric-field induced magnetization can be observed by Faraday rotation. In this study, the Faraday-rotation signal was observed in the millisecond and nanosecond regions. In the millisecond region, a continuous-wave (cw) probe light (1064 nm) and a square-wave electric field are used, and the waveform of the Faraday-rotation signal from the polarimeter is averaged on an oscilloscope. In the nanosecond region, a pulse probe light (800 nm) and a pulsed electric field, whose rise time is 4 ns and decay time is ~50 ns, are used. The delay between the probe pulse and the rise of the electric field is swept, and the change in the Faraday-rotation signal for the on/off of the electric-field pulse is lock-in detected.

3. Results and Discussion

3.1 Measurement in the millisecond region by cw probe

The electric-field induced Faraday-rotation signals observed in the millisecond region in the square-wave electric field of +4.0, +1.6, -1.6, and -4.0 MV/m at 290 K is shown in figure 1. The electric field is switched on/off in a period of 2 ms. The rise and fall time of the Faraday-rotation signal is determined by the electric-field pulse. Figure 2 shows the electric-field dependence of the Faraday-rotation amplitude obtained from the millisecond signal at 290 K. The Faraday-rotation amplitude linearly depends on the electric field. This result suggests the linear magnetoelectric effect.

![Figure 1](image_url)

*Figure 1.* Electric-field dependence of the Faraday-rotation signals observed in the square-wave electric field of +4.0, +1.6, -1.6, and -4.0 MV/m at 290 K.
3.2. Measurement in the nanosecond region by pulse probe

The change of the electric-field induced Faraday-rotation signals observed in the nanosecond region at 280 K and 320 K is shown in figure 3, where the electric field is switched from -2.8 MV/m to +2.8 MV/m at $t = 0$. The rise time of the Faraday-rotation signal was observed to be $\sim 5$ ns. This time is considered to be determined by the rise time of the electric-field pulse. The Faraday-rotation signals are found below $T_N$, but are not found above $T_N$. Figure 4 shows the temperature dependence of the Faraday-rotation amplitude. It decreases with increasing temperature and disappears above $T_N$.

![Figure 3](image.png)

**Figure 3.** Faraday-rotation signals observed at (a) 280 K and (b) 320 K. The electric field is switched from -2.8 MV/m to +2.8 MV/m at $t = 0$.

![Figure 4](image.png)

**Figure 4.** Temperature dependence of the Faraday-rotation amplitude.
The influence of the electric field on the magnetization in the sample can manifest itself differently in various regimes. The electric-field induced magnetization signal may be caused by the change in the magnetization within individual domain and/or the motion of domain walls in the electric field [11]. Figure 3(a) suggests that there is no domain-wall motion in the nanosecond region after the electric-field switching.

Figure 5 shows the electric-field dependence of the Faraday-rotation amplitude obtained from the nanosecond signal at 290 K. It linearly depends on the electric field.

![Figure 5](image)

**Figure 5.** Electric-field dependence of the Faraday-rotation amplitude obtained from the nanosecond signal at 290 K.

4. **Summary**
We observed the dynamics of the electric-field induced magnetization in an antiferromagnet Cr$_2$O$_3$ by the Faraday-rotation measurement using a continuous-wave probe light in the millisecond and a pulse probe light in the nanosecond region. In the millisecond region, it was found that the Faraday-rotation amplitude linearly depends on the electric field. This result suggests the linear magnetoelectric effect. In the nanosecond region, the Faraday-rotation amplitude linearly depends on the electric field, decreases with increasing temperature, and disappears above $T_N$. In our experiment, the response time of the electric-field induced magnetization to the electric field could not be determined, but it was found that the response time is faster than 5 ns.

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