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MAGNETO-OPTICAL HYSTERESIS MEASUREMENTS AND CALCULATIONS OF ORTHOFERRITES

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The aim of this work is to provide a better understanding of the non-linear magneto-optical behavior of orthoferrite-crystals. By means of an optical method it is possible to measure the hysteresis loop containing the characteristics of the ferromagnetic material. The magnetization of a single plate of yttrium orthoferrite ($YFeO_3$) reaches values up to 8.36 kA/m within magnetization curves up to fields of 400 kA/m. The measured loops will be compared with the results of different methods of calculations of the magnetization curves.

Keywords: orthoferrites, transparent ferromagnets, hysteresis, domain size

1 INTRODUCTION

Orthoferrites show a variety of properties, for instance good transparency and therefore a high magneto-optical figure of merit, high mobility of domain walls, the highest limit of the domain wall velocity, high Neel temperatures and interesting phase transitions, which provide the opportunity to create a large family of various sensors as well as devices for optical communications and data processing [1]. But there is still a need of basic research.

The present investigation of the hysteresis behavior, the measurement and the calculation of the magnetization curves of an orthoferrite plate were done to provide a better understanding of the underlying physics.

2 MEASUREMENT

The sample with a thickness of 120 μm was a single crystal plate of yttrium orthoferrite cut perpendicular to an optical axis. The optical axes of $YFeO_3$ lie in the *bc* plane and – at a wavelength of 0.63 μm – form angles of ±52° with the axis of weak ferromagnetism (the cristallographic *c* axis). The specific Faraday rotation at this wavelength equals –2900°/cm [2]. Perpendicular to the surfaces of the sample the adjustable homogeneous magnetic field H was applied as shown in Fig. 1.

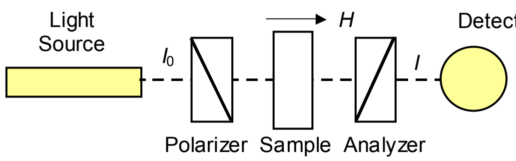

Fig. 1. Measuring arrangement, simplified schematic representation.

Red light emerging from the light source, *eg* laser with intensity I_0, is linearly polarized using a polarizing filter or prism (short: polarizer) and passing the sample. The analyzing polarization filter (short: analyzer) transforms the magnetization dependent Faraday rotation of the light polarization plane into intensity modulations, which are converted into electrical signals by a photodetector.

The linear dependence of the domain wall position upon the amplitude of the applied magnetic field is illustrated in Fig. 2 by an orthoferrite crystal consisting of only two domains, from which the upper one appears transparent due to the angular position of the analyzer with respect to the polarizer. This two-domain structure is produced by applying an additional inhomogeneous DC field [3]. A rectangular signal at a frequency of 100 kHz causes a motion of the domain wall within the gray colored area. The width of this area corresponds to the respective amplitude of the magnetic field.

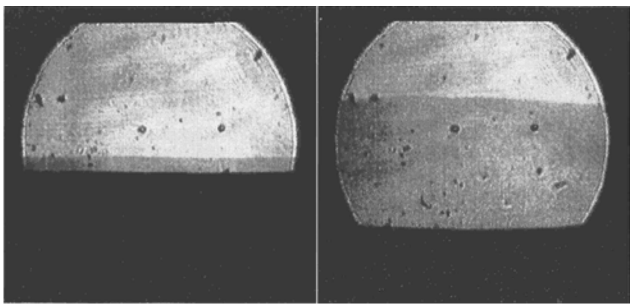

Fig. 2. Domain wall position in linear dependence of the amplitude of the magnetic field (rectangular signal, 100 kHz): $YFeO_3$ crystal, two domains; left: H = 100 A/m, right: H = 1000 A/m.

When there are many domains in a crystal, it looks rather like the thulium orthoferrite in Fig. 3, which shows more than 50 domains. Under the influence of a magnetic field some of them grow together and the domain walls are moving irreversibly. This is the origin of the observed macroscopic hysteresis.

To detect the current position of domain walls respectively the resulting magnetization of the sample, a chopped red-light laser beam was sent through the sample in the direction of the applied field, passed a polarization filter and a converging lens and was absorbed by a photocell connected to an oscilloscope.

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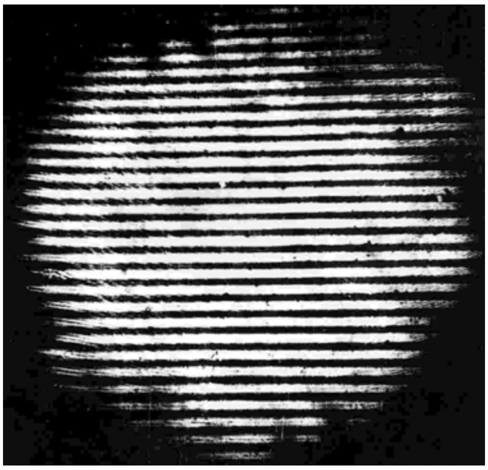

Fig. 3. Multi-domain structure in thulium orthoferrite at a temperature of 100 K [4].

The peak-to-peak value of the recorded alternating voltage is proportional to the magnetization of the sample versus the magnetic field. Magnetization curves up to fields of 400 kA/m were measured, as shown in Fig. 4 and 5. The saturation magnetization of the sample is 8.36 kA/m.

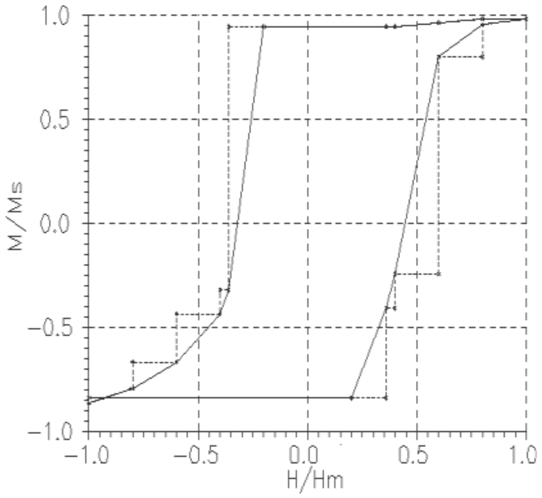

Fig. 4. Measured hysteresis loop of the $YFeO_3$ sample (solid line); actual behavior (jumps) between measured values (dotted line): $H_m = 4000$ A/m; $M_s = 8.36$ kA/m.

Some characteristic hysteresis data – spontaneous magnetization M_s (equivalent to the saturation magnetization), coercivity H_c, initial susceptibility χ_0 and remanence magnetization M_r – , their measured and their calculated values are shown in Table 1.

Table 1. Some characteristic hysteresis data.

	measured:	calculated (EM):
M_s		8.36 kA/m
H_c	1600 A/m	1534 A/m
χ_0	0.21	0.26
M_r	7.52 kA/m	7.90 kA/m

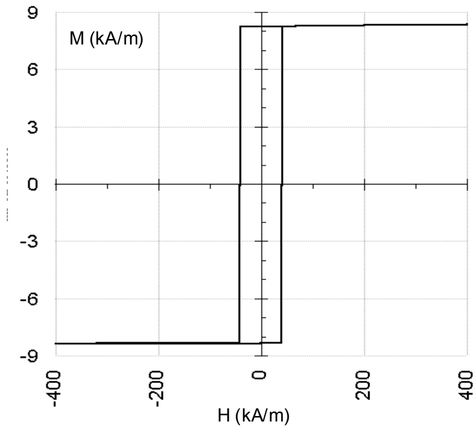

Fig. 5. Measured hysteresis loop of the $YFeO_3$ sample: $H_m = 400$ kA/m; $M_s = 8.36$ kA/m.

3 CALCULATION AND RESULTS

3.1 THE ENERGETIC MODEL

The energetic model of ferromagnetic hysteresis (EM) is an appropriate tool for the prediction of the magnetic behavior. It has already been applied for various kinds of magnetization processes and materials, also for yttrium orthoferrite [5].

The main idea of the EM is the interpretation of the magnetization process as a process of order, which is determined by an elementary probability function, based on Newton's probability formula [6].

The sgn(x) and $|x|$ functions provide the correct four quadrant calculation with

$$M = m M_s , \tag{1}$$

where m and M_s are the reduced or spontaneous magnetization respectively, and with

$$H = -H_d + \mathrm{sign}(m) H_r + \mathrm{sign}(m - m_o) H_1 , \tag{2}$$

which is divided into the demagnetizing field

$$H_d = -N_d m M_s , \tag{3}$$

where N_d is the average demagnetizing factor, a fictitious reversible field

$$H_r = h\left[\left((1+m)^{1+m}(1-m)^{1-m}\right)^{g/2} - 1\right] \tag{4}$$

and a fictitious irreversible field

$$H_1 = \left(\frac{k}{\mu_0 M_s} + c_r H_r\right)\left[1 - \kappa \exp\left(-\frac{q}{\kappa}|m - m_o|\right)\right] \tag{5}$$

with the function

$$\kappa = 2 - \kappa_o \exp\left[-\frac{q}{\kappa_o}|m - m_o|\right], \tag{6}$$

which describes the influence of the total magnetic state at points of magnetization reversal [7]. m_o is the starting value of m at the last field reversal and κ_o is the old value of κ. This function is the most simple reversal under the conditions of continuity and the similarity of χ_0 with the incremental susceptibility at coercivity.

The calculation always starts with the initial magnetization curve ($m = m_o = 0$, $\kappa = \kappa_o = 1$) and m is increased stepwise (the stepwidth determines the desired resolution of the calculation), which gives the corresponding field by equation (2). At a point of field reversal κ_n is calculated by equation (6) and m_o is set to the actual value of m at this point. Then m is decreased stepwise until the next reversal point, etc. Fig. 6 shows the calculation with parameters g = 10.18442, h = 0.5499751, k = 16.10642, q = 26.85174 and the domain geometry ratio c_r = 4.17.

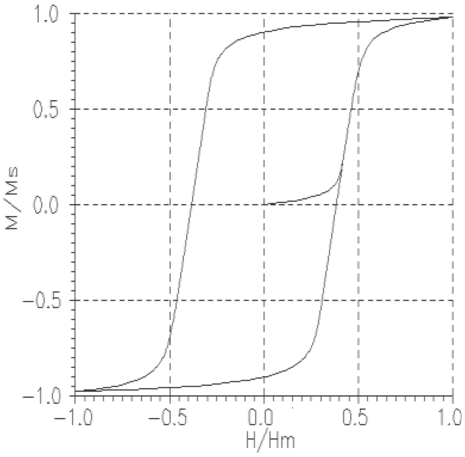

Fig. 6. Calculated hysteresis loop of $YFeO_3$: H_m = 4000 A/m; M_s = 8.36 kA/m.

3.2 THE CONSIDERATION OF LARGE SINGLE DOMAINS

The graphic representation of the measured hysteresis loop in Fig. 4 (solid line) does not correspond exactly to reality. The field H was increased or decreased until a change of magnetization M was detected. Then the reached values were recorded. The dotted line in Fig. 4 shows clearly the sudden changes of magnetization.

On the one hand we can recognize 8 distinct values of H/H_m, which are ±0.36, ±0.4, ±0.6 and ±0.8, where the jumps appear even if we run through the loop repeatedly. On the other hand the change of the magnetization M shows various amounts at those values within one cycle as well as various amounts at the same value but within different cycles.

For an explanation of this phenomenon we have to consider the fact that the domain size in the sample reaches a width of about 0.5 mm, so that we can assume a total of about 8 single domains. If we assign the sudden changes of magnetization to jumps of domain walls, we have to correlate each of the 8 values of H/H_m with an individual Barkhausen jump starting position and the various amounts of change are due to the occasional coincidence of several jumps.

An appropriate method based on our analysis supplied the hysteresis loops in Fig. 7 and Fig. 8.: Each branch was assembled out of 8 jumps of equal amount – to simplify matters – in correlation to the domain wall jumps of 8 large single domains. The position of the jumps was restricted to the above mentioned distinct values of H/H_m: 0.36, 0.4, 0.6, 0.8 (ascending branch) and −0.36, −0.4, −0.6, −0.8 (descending branch). In Fig. 7 the number of jumps at each value was chosen to supply the best conformity with Fig. 4 (dotted line). The complete sequence is 2-1-4-1 or 5-1-1-1 respectively.

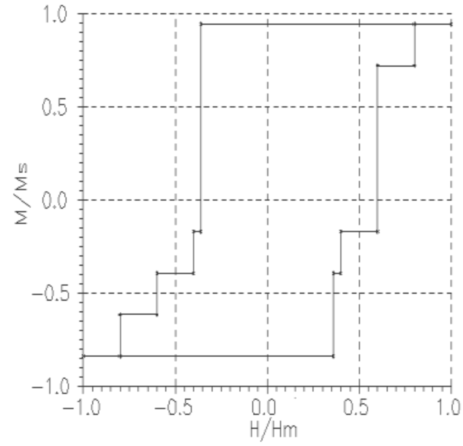

Fig. 7. Calculated hysteresis loop; solitary and coincident jumps of magnetization due to domain wall jumps of 8 large single domains (equal amount per jump): H_m = 4000 A/m; M_s = 8.36 kA/m.

The result was quite similar and in considerable accordance with further measured hysteresis loops even if these sequences were generated by random numbers, for instance 2-1-3-2 or 4-2-1-1 respectively (Fig. 8).

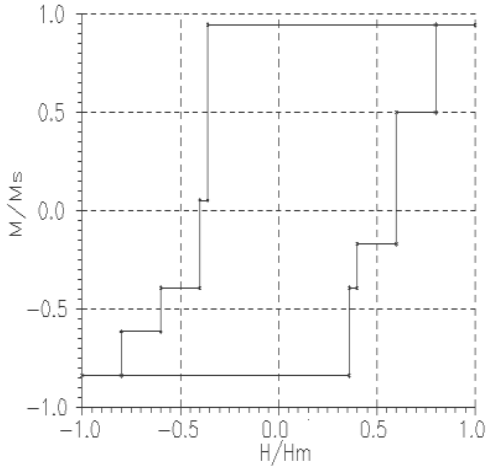

Fig. 8. Calculated hysteresis loop; solitary and coincident jumps of magnetization, allocated by random numbers (equal amount per jump): H_m = 4000 A/m; M_s = 8.36 kA/m.

4 CONCLUSIONS

In general results with satisfying correlation between the measured characteristics of the hysteresis and the calculations by means of the so-called energetic model – supposing statistical domain behavior – could be yielded. Only within the field range of H_m = ±4000 A/m it turned out to be an improvement to calculate the hysteresis jumps of single domains which are then combined to approach the characteristics of the yttrium orthoferrite plate, which has rather big domains of about 0.5 mm width.

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