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FOREWORD

This work was part of the in-house research of the Electronic and Magnetic Materials Section, Physics Laboratory under Project No. 7371, "Applied Research in Electrical, Electronic and Magnetic Materials," Task No. 737103, "Applied Research on Magnetic Materials." The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Axel M. Stoffel and Karl J. Strnat were the project engineers who did the research.

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The authors wish to thank W.D. Doyle of the Franklin Institute of the State of Pennsylvania who furnished several thin film samples.

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ABSTRACT

An experimental apparatus has been built which employs the magneto-optical Kerr effect for visual observation and photographic recording of magnetic domain patterns. The main objective of this work was to familiarize the investigators with the problems of the Kerr technique and thus provide the basis for designing a more sophisticated apparatus.

This report discusses the Kerr effect and its application to the study of magnetic domains and analyzes some of the optical problems incurred in this application. It describes the experimental set-up and presents pictures of domain structures observed on a thin film of Permalloy.

This technical documentary report has been reviewed and is approved.

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INTRODUCTION

When investigating the properties of ferromagnetic materials, it is often necessary to observe the arrangement of magnetic domains on sample surfaces, the motion of domain walls under the influence of a changing external field, or the distribution of a ferromagnetic phase in a non-magnetic matrix. Various techniques have been employed for such observations. These include the use of colloidal solutions of magnetic particles, of transmission electron microscopy, of the electron mirror microscope, and of the magneto-optical Faraday and Kerr effects. The colloid method (Bitter-technique) is the oldest and best known. While much information about domain structures occurring in ferromagnets has been gained with this technique, its application to the observation of fast-changing patterns is limited by the inertia of the colloidal particles and the viscosity of the liquid. Also, it cannot be used readily on very thin films of magnetic materials because the liquid may attack the fragile film. Both disadvantages are not present with the other techniques mentioned.

We are preparing for an investigation of extremely thin ferromagnetic films. We wish to observe the domain structure of these films in the vessel in which the films are formed by vapor deposition without exposing the samples to air between formation and measurement. Attempts will be made to accomplish this by using the magneto-optical method - the Kerr and Faraday effects, respectively (refs 1, 2). These effects may superficially be described as a slight rotation of the plane of vibration of polarized light when it is either reflected from the surface of a magnetized sample (Kerr effect) or transmitted through a sufficiently thin film of a ferromagnetic material (Faraday effect). Magnitude and sign of this rotation depend on magnitude and direction of the local magnetization. This dependence can be used to make the Weiss domains visible. The following chapter is a description of the so-called longitudinal Kerr effect, the special form of the effect in which the magnetization vector lies parallel to the reflecting surface and in the plane of incidence of the light beam. This is the situation which prevailed in our experiment.

These experiments with the Kerr effect on Permalloy films were performed to gather experience with the technique, to demonstrate its applicability to our task, and to obtain design criteria for the final apparatus.

THE LONGITUDINAL KERR MAGNETO-OPTIC EFFECT*

General

When plane polarized light is reflected from the surface of a magnetized body, the plane of polarization of the reflected beam is rotated with respect to that of the incident beam. Also, the polarization becomes slightly elliptical. This is illustrated in figure 1 for the

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*Named after the Scottish physicist John Kerr who, in 1876, discovered the so-called polar Kerr effect but failed to experimentally verify the existence of the longitudinal effect described here.

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simple case where the electrical vector I of the incident light lies in the plane of incidence ($I = I_p$; $I_s = O$ . . . component parallel to the surface). The predominant component R_p of the reflected light R is also polarized in the plane determined by the incident and the reflected beam. However, if the sample surface is magnetized as indicated in the picture, there appears also a small component R_s normal to R_p, that is, parallel to the surface. R_s and R_p are out of phase by a phase angle δ.

If they were in phase, the resultant vibration would again be plane polarized with its plane of polarization rotated through an angle α with respect to the plane of incidence (see figure 2). If δ were 90°, the polarization would be elliptical with the major axis of the ellipse in the plane of incidence. The practical case lies between these two extremes: the polarization is slightly elliptical and the major axis of the ellipse is rotated from the p-plane through the so-called "Kerr angle" $\theta < \alpha$. The quantities commonly used to describe such an elliptical vibration and the mathematical relations between them are indicated in figure 2. In addition to the ones already mentioned - "amplitude ratio" α, Kerr rotation θ, and phase difference δ, - there is the "ellipticity" ϵ, the angle between the major axis of the ellipse and the line connecting the extremes of major and minor axis. It is obvious from the equations (1) on figure 2 that only two of these four parameters are independent. A description of the two plane component vibrations by means of α and δ is equivalent to a description of the ellipse in terms of θ and ϵ (ref 3). (The ellipse can be viewed as traced by the tip of the E-vector originating in any point along the reflected beam during one cycle.)

A relatively simple situation similar to the one just depicted prevails also when the electrical vector of the incident light is parallel to the metal surface ($I = I_s$, $I_p = O$). However, for any arbitrary orientation of the plane of polarization between these two cases, the conditions are considerably more complex. The Kerr component will have an azimuth different from the one shown and an ordinary metallic reflection component will appear in the s-direction. The latter will, in general, be much larger than the Kerr component and therefore tend to mask it. For these reasons, we employed the simple case $I_s = O$ in the apparatus for observing magnetic domains.

Application for Viewing Magnetic Domains

The magneto-optic method of making magnetic surface domains visible was first described by Fowler and Fryer (refs 7-9). Envision two adjacent regions on the metal surface magnetized to the same magnetization value M_s (spontaneous magnetization), but in opposite directions. Let them be illuminated with plane polarized light under the conditions outlined above and illustrated in figure 3A. The plane of polarization (major axis of the ellipse) will be rotated clockwise for light reflected off the one domain (D1), counterclockwise for light reflected by the other domain (D2). The absolute value of the Kerr rotation θ, will be the same for both (see figure 3B). We will now put an analyzer (for example, a Nicol prism) in the path of the reflected light between metal surface and observer. If the "pass"-direction of the analyzer lies in the plane of incidence (p) or perpendicular to it (s), the two domains will appear equally bright (much brighter in the first case than in the latter). For any other orientation of the analyzer, the domains differ in brightness. However, the relative difference is so small that it is practically impossible to distinguish the domains unless one operates near the point of optimum contrast. The highest contrast is obtained when the analyzer is set under the Kerr angle away from the position in which it would be "crossed" with the polarizer. It is then normal to the major axis of the elliptically polarized light coming from the one domain (R^{D2} in figure 3B).

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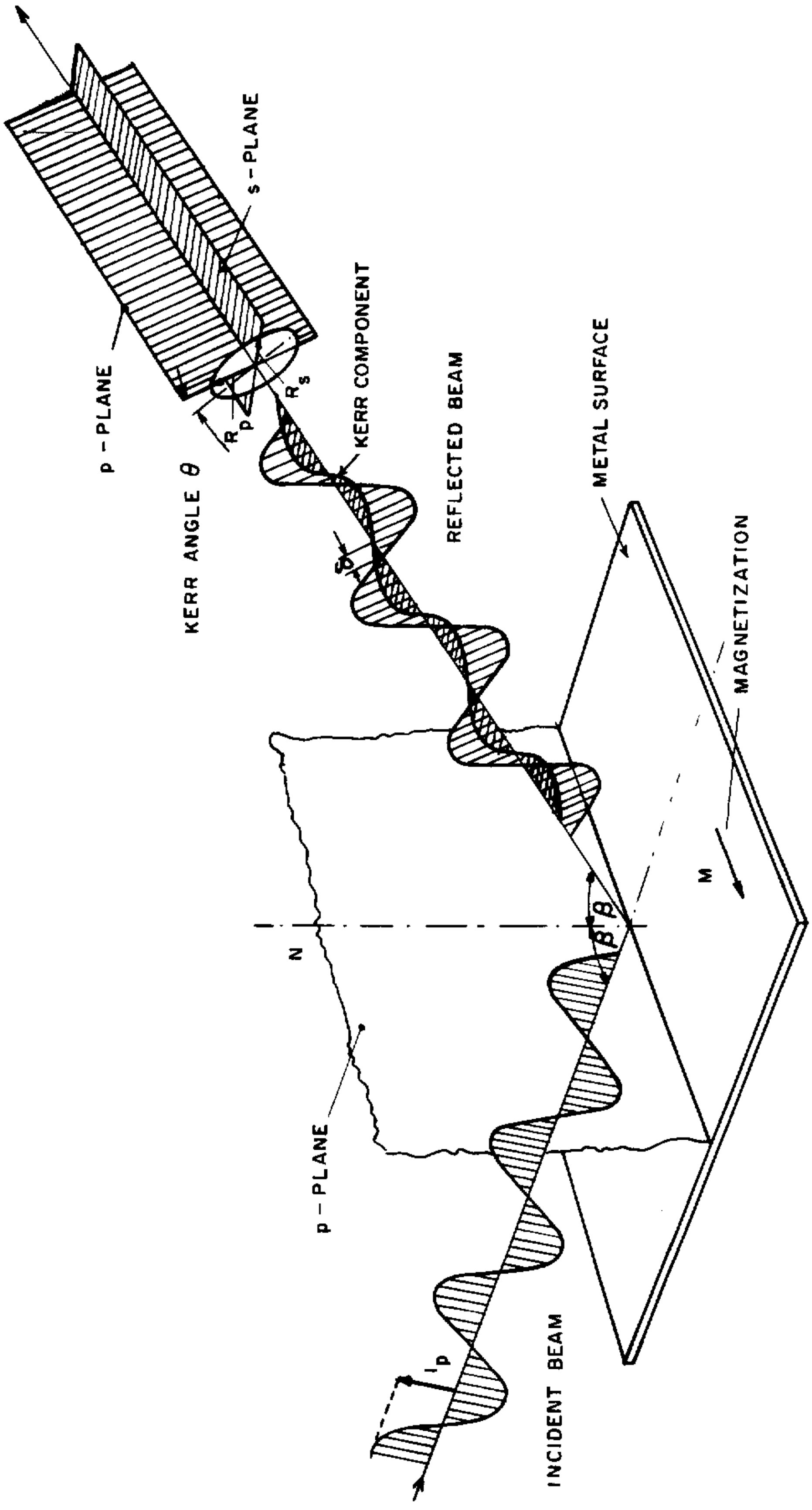

Figure 1. The Longitudinal Kerr Effect

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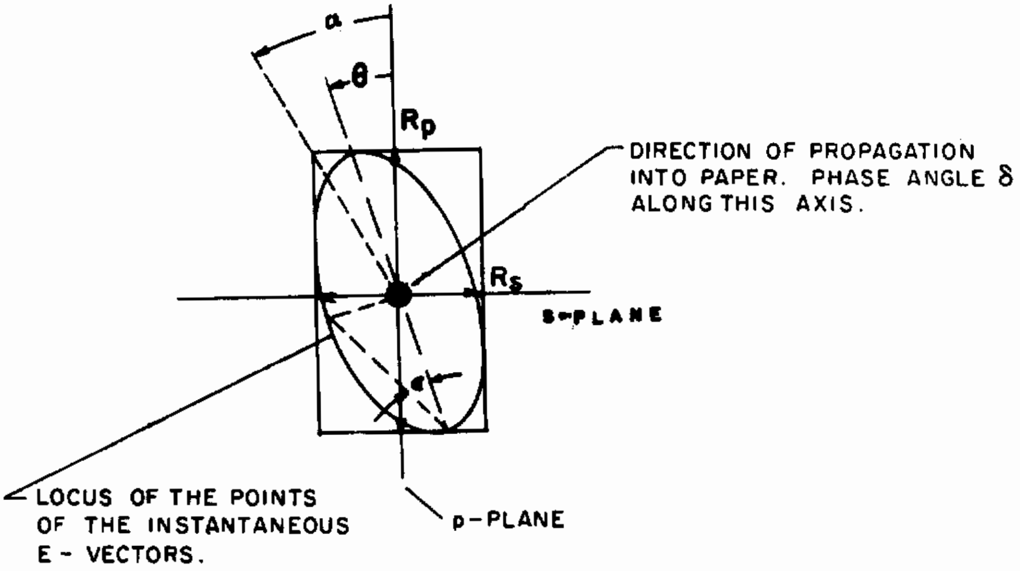

(1)

$$\tan \alpha = \frac{R_s}{R_p}$$

$$\tan 2\theta = \tan 2\alpha \cos \delta$$

$$\tan 2\epsilon = \sin 2\alpha \sin \delta$$

$$\tan \epsilon = \frac{\text{minor axis of the ellipse}}{\text{major axis of the ellipse}}$$

(2)

$$\alpha = \frac{R_s}{R_p}$$

$$\theta = \alpha \cos \delta$$

$$\epsilon = \alpha \sin \delta$$

Figure 2. The Parameters of an Elliptical Vibration

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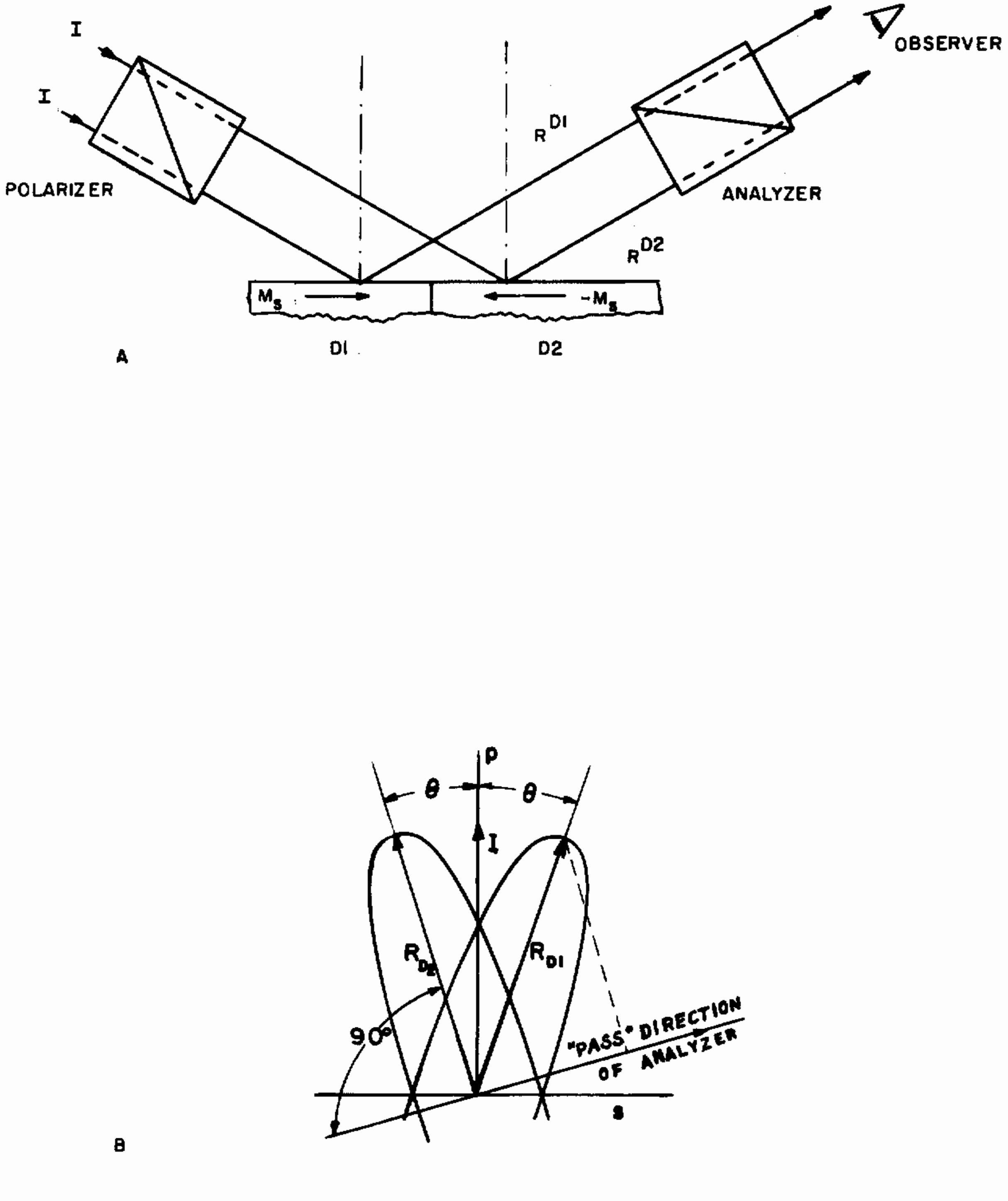

Figure 3. Rotation and Ellipticity Caused by Reflection from Oppositely Magnetized Domains

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If there were no ellipticity of this light, the domain D2 would appear completely dark. Because the reflected light is elliptically rather than plane polarized, complete extinction is impossible and the obtainable contrast is lowered.

The experiment just described can be performed with white or monochromatic light. If light of a single wavelength is used, it is possible to optimize the contrast by interposing a retardation plate of proper thickness and orientation between sample and analyzer. The situation is depicted in figure 4. Light reflected by domain D1 consists of the components R_p and R_s^{D1}; that reflected by the oppositely magnetized domain D2 has the same normal reflection component R_p and a Kerr component R_s^{D2} which is 180° out of phase with R_s^{D1} ($R_s^{D2} = -R_s^{D1}$). The phase lead of R_s^{D1} with respect to R_p is δ_1, that of R_s^{D2} consequently $\delta_2 = 180 + \delta_1$. A retardation plate with its "slow axis" in the s-direction and a thickness such that it delays each Kerr component by δ_1 will bring R_s^{D1} into phase, R_s^{D2} exactly 180° out of phase, with R_p. This will remove the ellipticity from both reflected beams and increase the Kerr angles to the maximum possible values α and $-\alpha$, respectively.

If retardation plates are used in combination with white light, it should be possible to obtain color effects. These, however, would be difficult to analyze. Enhancement of the contrast has also been achieved by coating the surface of the ferromagnetic material with a transparent dielectric layer such as zinc sulfide (refs 10, 11).

The effects to be observed are very small. For iron, nickel, and Permalloy film samples the amplitude ratio is of the order $\frac{R_s}{R_p} = \frac{1}{1000}$, corresponding to a maximal Kerr angle of $\alpha = 4$ minutes. For this reason, a very bright light source, precision polarizers and, generally, large aperture optical components are required to obtain images of the domain pattern which are sufficiently bright for visual observation and photographing, and also have good contrast and high resolution (ref 3).

THE APPARATUS

General

Figure 5 shows schematically the experimental arrangement with which we obtained our first pictures of magnetic domains. The light of a mercury arc lamp A.L. is collimated by the lens L1, polarized in the plane of incidence by the polarizer P (Nicol prism), an iris diaphragm D restricts the diameter of the beam and illuminates the thin film sample S under 60° to the normal. The films used were circular with a diameter of approximately 9 millimeters. The light reflected somewhat diffusely from the film surface is collimated again by the lens L2 for passage through the analyzer A. (Good extinction with crossed Nicols can be obtained only if the light passes them nearly parallel.) The

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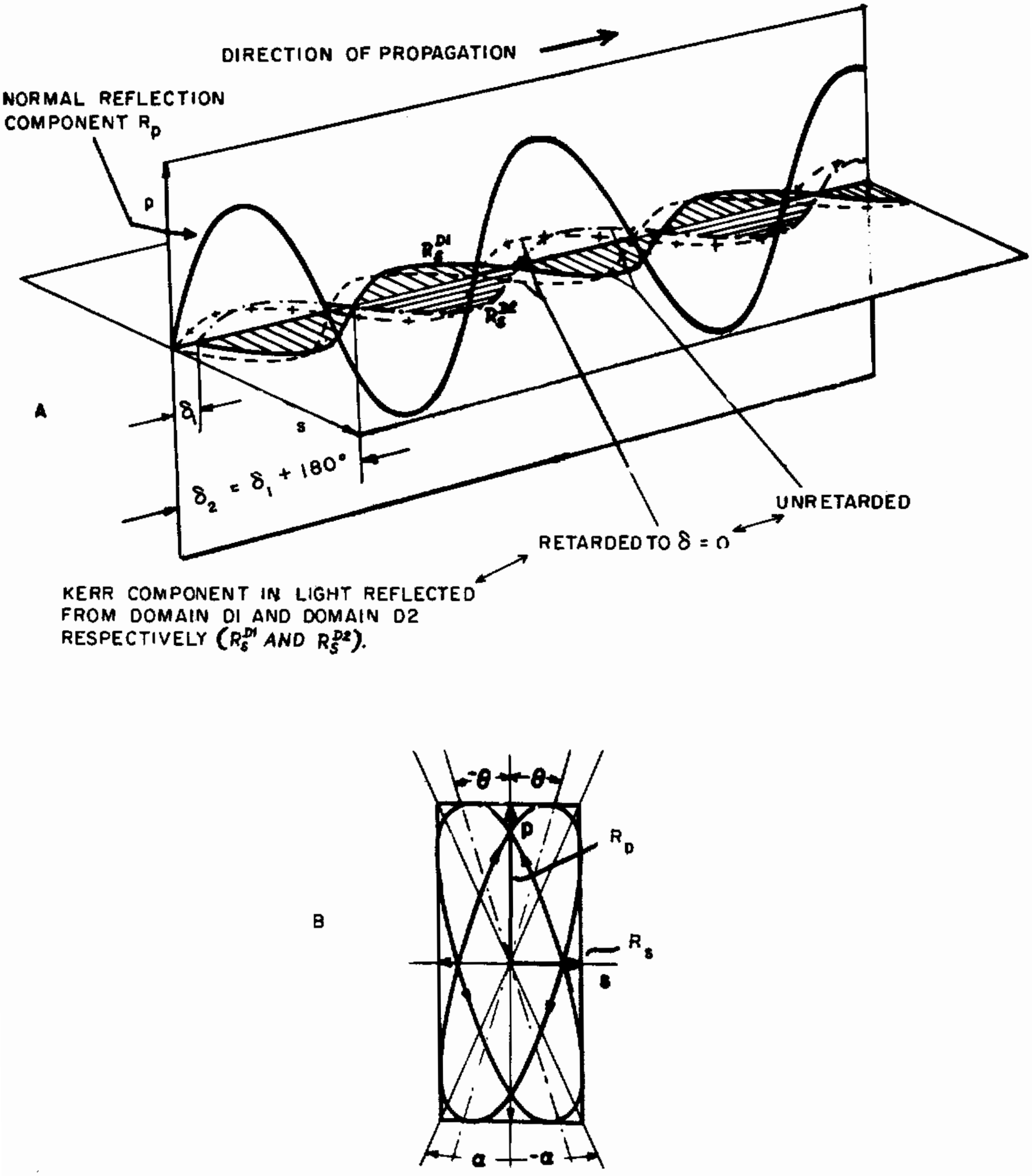

Figure 4. Contrast Enhancement with a Retardation Plate

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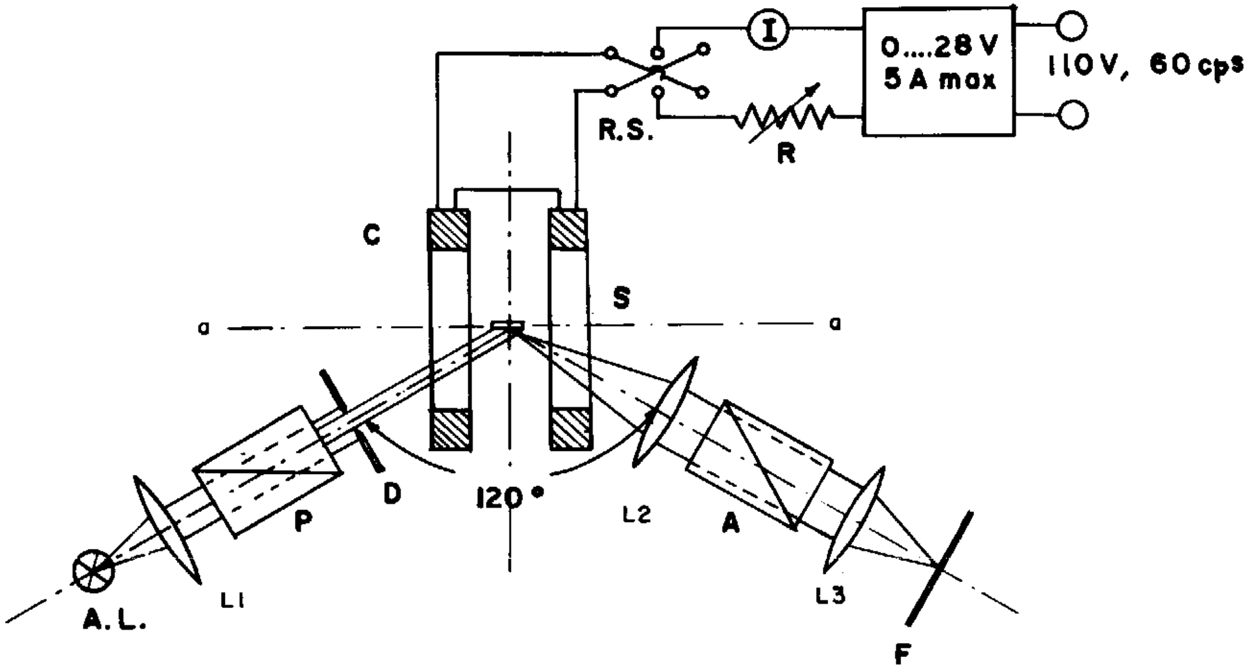

Figure 5. Experimental Arrangement, Schematic

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third lens L3 produces an image on the film F (inside a photographic camera). Alternatively, it can be visually observed through an eyepiece. The magnification obtained on the film was approximately 2 x. Attempts to obtain considerably higher magnifications with a microscope were unsuccessful.*

The glass slide carrying the film sample was placed in the center of a pair of Helmholtz coils C with the magnetic preference direction of the film in the axis a-a of the coils (direction of the magnetic field). The plane determined by a-a and the normal to the film is also the plane of incidence of the light beam. The coil current is supplied from an adjustable DC voltage power supply and measured by the ampere-meter I. The rheostat R permits fine adjustment of the current; the polarity can be reversed with the switch R.S.

The entire system was mounted on a light optical bench. Figure 6 is a photograph of the experimental set-up.

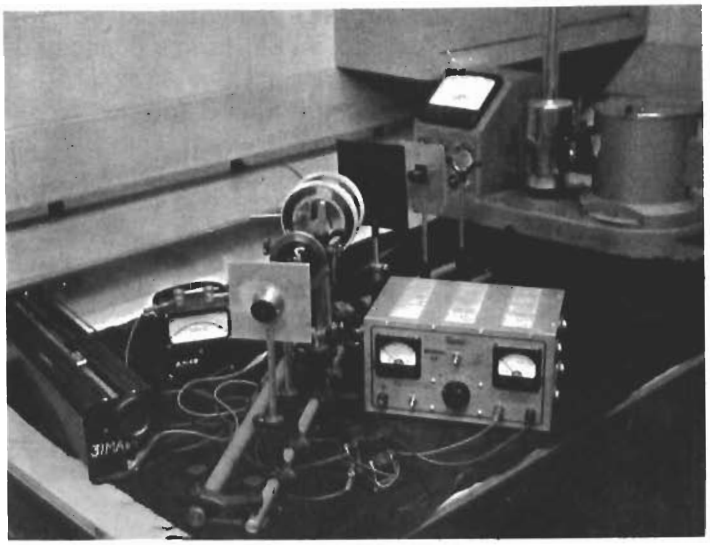

Figure 6. Photograph of the Experimental Arrangement

Component Identification and Data

Light source, A.L.: Super Pressure Arc Lamp, OSRAM HBO 200 W

Power supply for lamp: Autotransformer, Type Kerber - 200 for HBO 200 W

Polarizer P, and analyzer A: Nicol Prisms 10 x 10 mm

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*Treves (ref 12) discusses the problems encountered: The higher the microscope magnification, the more divergent the light passing the analyzer. This divergence, in turn, reduces the effectiveness of the analyzer and the contrast between domains. Also, greater divergence means more light loss for a given aperture of the analyzing prism and consequently a less bright image.

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Lenses: L1 f = 6 cm

L2 f = 12 cm

L3 f = 12 cm

Photographic camera: Plaubel. Karl Zeiss, Jena

Helmholtz coils:
(see figure 7)

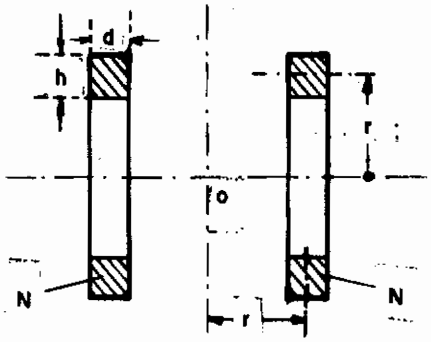

Figure 7. Helmholtz Coils

$r = 3.5''$, $h = 1''$, $d = \frac{5}{8}''$

N = 900 turns on each half-coil

25 AWG enameled copper wire, wound on Lucite coil form. Coils are connected in series.

Total resistance 25Ω

Field in the center O:

$$H^{(Oe)} = 180 \times I^{(A)}$$

Power supply for coils:

DC Power Supply, Electro
Model EF 0-28 V, 5 A max

Rheostat:

R - 0 2500 Ω

DOMAIN PATTERNS

Figure 8 (a) and (b) are examples of domain patterns photographed with this arrangement. The film* was Permalloy of the composition 83 percent nickel, 17 percent iron. It was vapor deposited under oblique incidence and had uniaxial anisotropy. Approximate film thickness d = 1000 Å, anisotropy field $H_k = 3.7$ Oe, coercive force in the easy direction $H_c = 1.4$ Oe. The circular film appears as an ellipse because it is viewed under an angle of 30° from the normal. The short axis of the ellipse is the direction of both magnetizing field and the intersect of the plane of light incidence with the film. The easy axis is under an angle of about 30° from this direction.

The film was saturated in one direction, and while the film was in this condition the analyzer was rotated to the position of minimum brightness. (Complete extinction could not be obtained.) The field was then reduced to zero, a reverse field applied and increased

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* This film was obtained from the Franklin Institute of the State of Pennysłvania, courtesy of Mr. W. Doyle. The data given were supplied with the sample.

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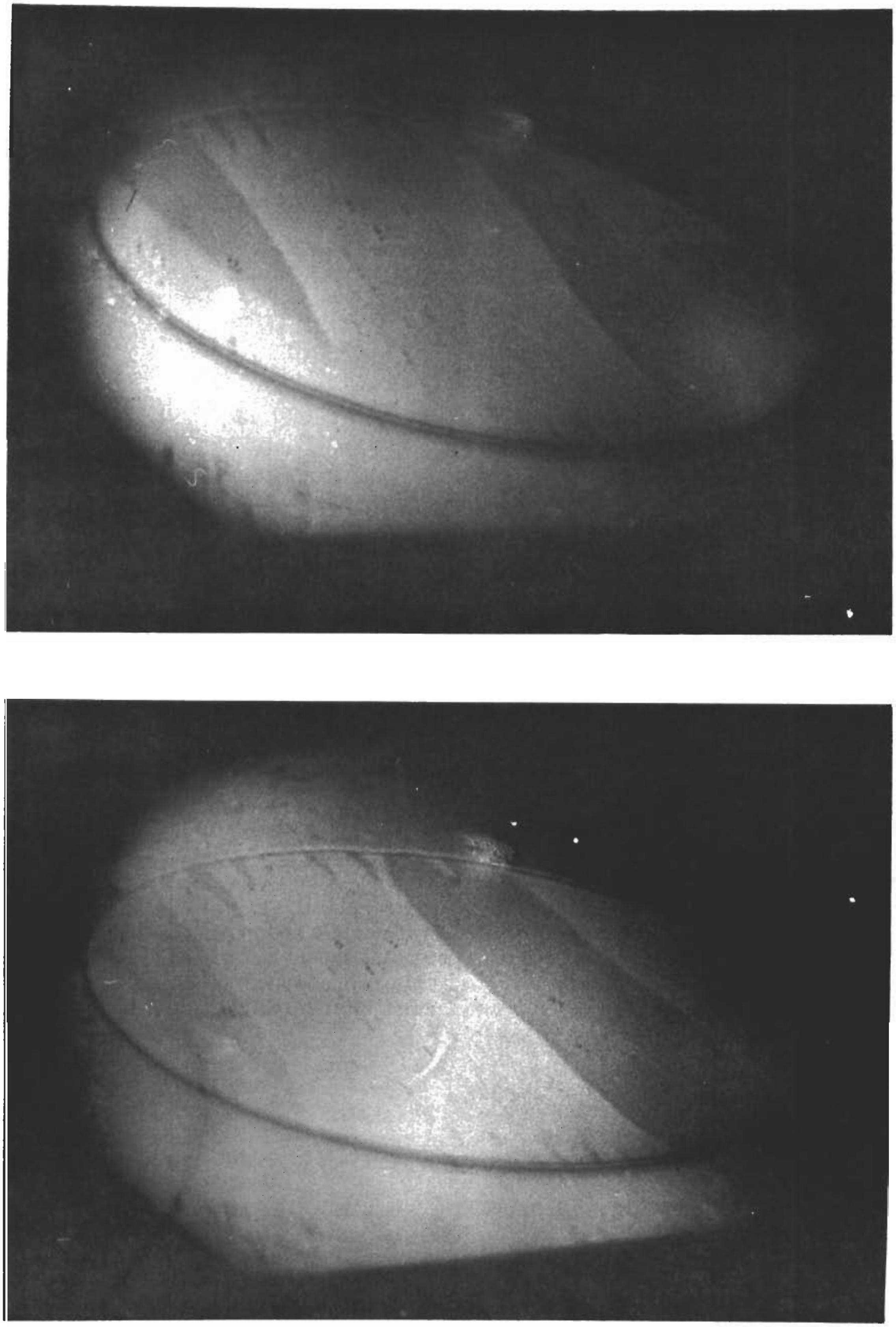

a

b

Figure 8. Domain Patterns on a Permalloy Film

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until the first large domains appeared as areas of slightly greater brightness. This happened at fields approaching H_c. The two pictures were taken at slightly different field strengths and illustrate the motion of domain walls. The walls lie approximately in the direction of the easy axis. (The angle between easy axis and field appears larger than it is due to perspective distortion.)

The contrast is very low. Visual observations must be made in a dark room and the eye has to be dark adapted to discern the domains. The use of a proper photographic emulsion enhances the contrast considerably. The film material used was Kodak Tri-X, the exposure time 1 min. with a lens opening of f:11. The total magnification of the enlargements shown is nearly 14 x.

CONCLUSIONS

It was possible to obtain pictures of magnetic domain patterns with the apparatus constructed from parts on hand in the laboratory. However, the apparatus is unsatisfactory for planned thin film research. For high-resolution domain observation and particularly for quantitative determination of the magneto-optical parameters, the following improvements must be made:

1. Monochromatic light must be used.

2. The lamp must approximate more closely a point source so that there will be better parallelism of the light in the polarizer.

3. Larger aperature high quality polarizers must be used to acquire higher magnifications combined with sufficient brightness.

4. The polarizers must have precision mounts for adjusting and measuring angles of rotation to 1 minute.

5. A sturdy optical bench must be used.

6. To obtain the maximum Kerr angle for different materials and magnetizations, a device for adjusting the phase angle of the Kerr component should be on hand. This could be a Soleil compensator or an electro-optical Kerr cell, both of which would permit continuous adjustment of the phase shift. A less satisfactory alternative is a set of retardation plates in $\pi/8$ intervals.

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