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By Dr. Raymond B. Yarbrough and Frank S. Greene, Jr.

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INTRODUCTION

This report describes a study sponsored by the National Aeronautics and Space Administration's Ames Research Center to investigate the feasibility of a magnetometer sensor to measure low magnetic fields exploiting the magneto-optic effects in thin ferromagnetic films.

This report covers the entire contract period and describes the theoretical aspects of various magneto-optic effects which are potentially useful for measuring magnetic fields on the order of 0.1 nanotesla or less.

SUMMARY

The most promising materials for magneto-optic measurement of magnetic fields are thin films of iron, nickel and cobalt. The investigation indicates little difference between the potential use of the Faraday and longitudinal Kerr effect, that both methods should prove useful. The choice between the two effects should be made on the basis of experimental results.

The galium arsenide junction lasers appear to provide inexpensive and compact light sources which should be adequate for the proposed system for measurement. Commercially available photodiodes and phototransistors are useful detectors.

A method of cross-field excitation of thin films in conjunction with the optical apparatus provides a theoretically sensitive field detection scheme.

The system is expected to be operable in the normal range of temperatures around 300°K, with deterministic variation of performance based on the temperature characteristics of the light source, light detector and the magnetic film.

NOMENCLATURE

A - Light spot area

b - Light power density

F - Faraday rotation coefficient

F_0 - Maximum value of faraday coefficient

f - Frequency

H - Magnetic field intensity

H_K - Anisotropy field for hard direction saturation

H_L - Easy axis field

I_f - Change in light intensity-watts

I_0 - Incident light energy

I_s - Photodetector signal current

K - Boltzman constant

ℓ - Film thickness

M_L - Easy axis magnetization

M_0 - Saturation magnetization

n_e - Index of refraction for left hand polarized light

n_r - Index of refraction for right hand polarized light

P - Photodetector conversion coefficient

R - Resistance

T - Kelvin temperature

t - Path length

V - Verdet constant

v_n - Thermal noise voltage

W_0 - Reflected light power from magnetic medium

α - Attenuation constant

Θ - Rotation

λ_0 - Wavelength of incident light

μ_L - Longitudinal permeability

ϕ - Kerr effect angle

MAGNETO-OPTIC EFFECTS

Light is an electromagnetic phenomenon as may be demonstrated by a number of magneto-optic and electro-optic effects. Magnetic field measurements are theoretically possible by using the various magneto-optic effects, but the effects are too weak in most materials except for very large fields. However in ferromagnetic materials the effects are greatly enhanced by the intrinsic magnetization, so that at least two of the magneto-optic effects are of practical value in detecting and measuring small to medium magnetic fields. These two are the Faraday Effect and the Longitudinal Kerr Magneto-optic Effect.

The Faraday effect, discovered by Michael Faraday in 1845, involves a rotation of the plane of polarization of light when traveling through a substance subjected to a magnetic field. The rotation occurs in the direction that a solenoidal current would flow if it were the cause of the magnetic field. The amount of rotation is proportional to the path length and the magnetic field intensity. The constant of proportionality is called the Verdet constant (V):

$$\theta = VH\ell \tag{1}$$

For nonmagnetic substances the Verdet constant is on the order of .01 to 0.1 minutes of arc per oersted per centimeter for visible light. Thin magnetic films were shown[1,2*] to give rise to much larger rotations,

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[1] Kundt, A., Wied. Ann. 27, 191, 1886

[2] DuBois, H.E.J.G., Wied. Ann. 31, 941, 1887

[*] Full titles of references after 1950 are listed in the appendices.

proportional to the magnetization. Saturated iron yields a rotation on the order of 3×10^5 degrees per centimeter[3], which would require an equivalent Verdet constant on the order of 100 degrees / gauss / cm, considering the saturation magnetization of iron.

The Faraday effect is widely used in microwave applications for isolators, switches and circulators.

The longitudinal Kerr magneto-optic effect involves the rotation of a polarized light wave by reflection from a magnetic material. The existence of rotation of light by a magnetic pole face was first reported by Kerr[4], however this effect is the polar Kerr magneto-optic effect where the magnetization is normal to the surface. In the longitudinal effect the magnetization is in the plane of the surface. The light is polarized in the plane of incidence, and the component of the incident light in the direction of magnetization is rotated to the left or right depending on whether magnetization is positive or negative. The longitudinal Kerr rotation is much smaller than the Faraday effect, being typically a few minutes of arc. The small rotation angle is not disqualifying for the use of the Kerr effect, as optical means of detection of such angles are readily available.

The longitudinal Kerr magneto-optic effect (hereafter referred to as the Kerr Effect[5]) has been extensively used to determine the state of magnetization of magnetic thin films, and has an extensive technology available.

---

[3] Argyres, P.N., Phys. Rev., 97 #2, 334, 1955

[4] Kerr, J., Rep. Brit. Assoc. 85, 1876

[5] Jenkins, F.A. and White, H.E., Fundamentals of Optics, 3rd Edition, McGraw-Hill, Chapter 29, 1957.

THEORY OF MAGNETO-OPTIC ROTATION

The Faraday Effect can be explained from the index of refraction point of view or more completely using quantum theory. The phenomenon is due to interaction of the light wave with the magnetic electrons of the media. In nonmagnetic materials the Faraday effect can be directly related to another magneto-optic effect, the Zeeman effect.[5]

The Faraday rotation of a plane polarized wave involves different indices of refraction for right hand circularly polarized waves (n_r) and left hand circularly polarized waves (n_ℓ). The plane polarized wave is considered to be made up from two equal circularly polarized waves, one rotating to the right as it propagates and one rotating to the left. The presence of a magnetic field within the material causes the index of refraction for the L.H. rotating wave to differ from the R.H. rotating wave. The result is that the two waves propagate at different velocities through the material. When they emerge on the other side there is a phase difference between the RH and LH components, which appears as a rotation of the plane polarized light made up of the two hypothetical circularly polarized components. The differences in the indices of refraction may then be related to the Verdet constant:

$$n_r - n_\ell = \frac{\lambda_o}{\pi} VH\cdot N \qquad (2)$$

where N is the direction of propagation of the light. A positive Verdet constant corresponds to rotation in the direction of a solenoidal current

---

[5] Jenkins, F.A., and White, H.E., Fundamentals of Optics, 3rd Edition, McGraw-Hill, Chapter 29, 1957.

giving rise to the field H.

It has been shown experimentally that magneto-optic effects in magnetic materials are proportional to the net magnetization of the sample, and not to the applied field. The physical origin of the difference in indices of refraction for right- and left-hand circularly polarized waves is not adequately explained without quantum theory.

Argyres[6] used the band theory of metals to explain the use of normal incidence magneto-optic effects. This includes the Faraday effect for the transmitted light and the magneto-optic polar Kerr effect. The spin-orbit interaction cause asymmetry to the electron wave functions so that the magnetic electrons produce an average current perpendicular to the plane of polarization of the incident light. This current accounts for both the Faraday rotation and the magneto-optic polar Kerr Effect.

Robinson[7] used Argyres' development to explain the cases of oblique incidence, which include the Faraday effects (polar, transverse and longitudinal) for bulk material and thin films, and the magneto-optic Kerr effects.

CROSS-FIELD SCHEME FOR FIELD DETECTION

To make use of magneto-optic rotation in the detection of small fields it is necessary to use some method of dynamic excitation of the magnetic material, as the magnitudes of the fields to be measured are well below the threshold coercive force of magnetic materials.

---

[6] Argyres, P.N., Phys. Rev. 97, #2, 334, 1955

[7] Robinson, C.C., J. Opt. Soc. of American, 54, #10, 1220, 1964

The most promising scheme appears to be one where the material is dynamically excited by a field perpendicular to measured field, and the magnetization in the direction of the measured field is then detected. This is mechanically similar to the scheme used by West et al[8]. Then the first requirement on the magnetic material is that it have only one easy axis of magnetization, a uniaxial material.

In the uniaxial material, the magnetization is driven by a field perpendicular to the easy axis to saturation in a hard axis direction. When the hard axis field is removed domains will form with the magnetization in the easy axis directions. In the absence of an ambient field in the easy axis direction there will be zero net magnetization, because there will be the same amount of domains oriented in both the positive and negative easy axis directions. The reason for such behavior is that there is a uniform dispersion of local easy axes about the average easy axis direction. In the presence of an ambient easy axis field more domain volume favoring the ambient field direction will form when the hard axis field is relaxed. Thus there will be a net magnetization in the direction of the ambient field. In general, it may be predicted that the sensitivity of the net magnetization to the ambient field will be inversely proportional to the dispersion of local easy axis directions.

Materials for Magneto-Optic Field Detection

The choice of magneto-optic schemes of reading the magnetization depends on the properties of materials available. The Faraday effect

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[8] F.G. West, W.J. Odom, J.A. Rice, T.C. Penn, JAP, p 1163, 1964.

is preferable because of its relatively large magnitude, however the absorbtion of light in transmitting through a material becomes an important consideration. In choosing a material for magneto-optic rotation the first requirement is uniaxial anisotropy. In evaluating its use for Faraday or Kerr rotation the direction of the easy axis, the anisotropy, the temperature characteristics and the coefficients of absorbtion and reflection must be considered. Magnetic films provide the most adaptable material because of their natural tendency to uniaxial anisotropy, usually lying in the plane of the film.

Some of the transparent magnetic materials, such as Gadolinium Iron Garnet, can be deposited so that the easy axis is normal to the surface, which makes them readily adaptable to use in Faraday rotation. However the coercive force of such materials is necessarily high, in order to maintain normal magnetization in the face of high demagnetizing fields. In general, the anisotropy field is of the same order of magnitude as the coercive force for configurations with low demagnetization factors, so that the cross-field necessary for garnets will be larger than the coercive force, by as much as an order of magnitude. The coercive force field for Gadolinium Iron Garnet is on the order of 100 oersteds at room temperature, so that cross-field requirements for such materials appear to be a disqualifying feature. In addition the garnets only exhibit the high coercive force necessary to allow easy axis normal to the surface near the compensation temperature, and Gadolinium is the only available garnet with a compensation temperature near room temperature. Then it appears that for this application at the present state of technology, the transparent magnetic materials are not adaptable. The best materials for measuring low to medium fields then appear to be magnetic thin films. As metalic films are transparent to light for only thicknesses up to a few hundred angstroms, calculations were made to compare the use of Faraday rotation and the Kerr effect for thin metalic magnetic films.

ANALYSIS OF KERR SENSITIVITY

An analysis was carried out to determine the sensitivity of the Kerr magneto-optic effect in the detection of magnetic fields. The parameter which is sensitive to the magnetic field intensity is the residual magnetization of a uniaxial magnetic thin film which is pulsed in the hard direction by a field greater than the equivalent anisotropy field H_k. The measurement of the remnant magnetization is by the use of the Longitudinal Kerr magneto-optic effect, detected by a phototransistor.

An estimate of the magneto-optic signal obtainable for a field of $.1\gamma(10^{-6}$ oe) was made using a permalloy thin film as the detector and the longitudinal Kerr effect for readout. The operation of the film is similar to that described by F. West et al,[9] where fields on the order 10^{-6} oe. were detected.

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[9] F. West, W. Odom, Jr Rice, T. Penn, JAP 34:1163, April 1963.

Magnetic Film Operation

A magnetic film is driven by an ac field greater than H_k in the hard direction and a ac plus dc field in the easy direction. A perfect film with no dispersion of the easy axis would orient in the direction of the total easy axis field as the hard direction ac field decreased below H_k. A longitudinal permeability can be defined that indicates the amplitude of easy axis magnetization per unit easy axis field. In a perfect film only an infinitesimal easy axis field would be required to orient all of the magnetization in the easy direction, so the longitudinal permeability of a perfect film approaches infinity. Torok and White[10] define the longitudinal permeability as μ_L where

$$\mu_L = \frac{H_K}{M_0} \left(\frac{M_L}{H_L}\right)$$

H_K = anisotropy field for hard direction saturation

= 5 oe. for permalloy

M_0 = saturation magnetization = 10^4 gauss for permalloy

ΔM_L = net magnetization in easy direction

ΔH_L = easy direction field .

Practical films have $\mu_L = 10$ due to dispersion of the easy axis and the anisotropy constant in various regions of the film.[11]

The hard direction ac field raises the film to an energy threshold so that it is very sensitive to small easy axis fields. A small easy axis ac field helps to overcome the adverse effects of dispersion.[12]

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[10] Torok and White, JAP, 34:1064, April 1963

[11] C.E. Frank, Report 65-4, AF-AFOSR - 139-63, January 1965

[12] F. West, W. Odom, J. Rich, T. Penn, JAP 34:1163, Ap. 1963

The field to be measured is applied along the easy axis.

Magneto-optic Signal

If $\mu_L = 10$, $H_k = 5$ oe., $M_0 = 10^4$ gauss, $\Delta H_L = 10^{-6}$ oe., then

$$\Delta M_L = \mu_L \frac{M_0}{H_K} (\Delta H_L) = 10 \frac{10^4 \times 10^{-6}}{5}$$

$$\Delta M_L = 2 \times 10^{-2} \text{ gauss,}$$

the net magnetization parallel to the plane of incidence for a 10^{-6} oe. easy axis field.

The amplitude of ΔM_L, which is directly proportional to ΔH_L (field to be measured), will be read out using the longitudinal Kerr effect[13]. The plane of polarization of incident plane polarized light is rotated on reflection from the magnetized film surface. The amount of rotation is directly proportional to the amplitude of the magnetization parallel to the plane of incidence.

The photo detector signal current is given as

$$I_S = PW_0\phi \sin 2$$

P = photo detector conversion coefficient - amp/watt-light power

W_0 = reflected light power from magnetic medium-watts

ϕ = Kerr effect angle

θ = angle of rotation of analysis from its portion of minimum transmittance.

---

[13] C. Fowler and E. Fryer, Phys. Rev., 94:52, 1954.

For $\Delta M_L = 10^4$ gauss, $\phi = 10^{-3}$ rad[14], so for $\Delta M_L = 2 \times 10^{-2}$ gauss $\phi = 2 \times 10^{-9}$ rad, $P \quad 50$ for a photo transistor or diode the reflected light power is

$$W_0 = A\ b$$

A = light spot area

b = power density = watts/cm^2

for $A = 10^{-2}$cm and $b = 25$ watts/cm^2, $W_0 = 25 \times 10^{-2}$watts $\doteq \frac{1}{4}$ watt. This assumes approximately a 1 watt laser as there is a 50% transmission loss through the Glan-Thompson polarizer. The signal current I_S is

$$I_S = 50\ (\tfrac{1}{4})\ (2 \times 10^{-9}) = 25 \times 10^{-9} = 25 \text{ nanoamps.}$$

The photo transistor would be used as a diode as shown in the circuit in Figure 1 with a 10 K emitter resistor. The signal voltage into the operational amplifier is 250 μvolts.

The thermal noise voltage generated by the 10 K emitter resistor would be predominate noise source since the transistor is operated as a diode with low leakage current. The noise voltage is

$$\bar{\nu}_n^{\,2} = 4k\ TR\ \ \Delta f \qquad\qquad \Delta f = 10^2\text{cps}$$

$$\bar{\nu}_n = \sqrt{4k\ TR\ \Delta f} \qquad\qquad T = 300°K$$

$$\bar{\nu}_n = .5\mu \text{ volt rms}$$

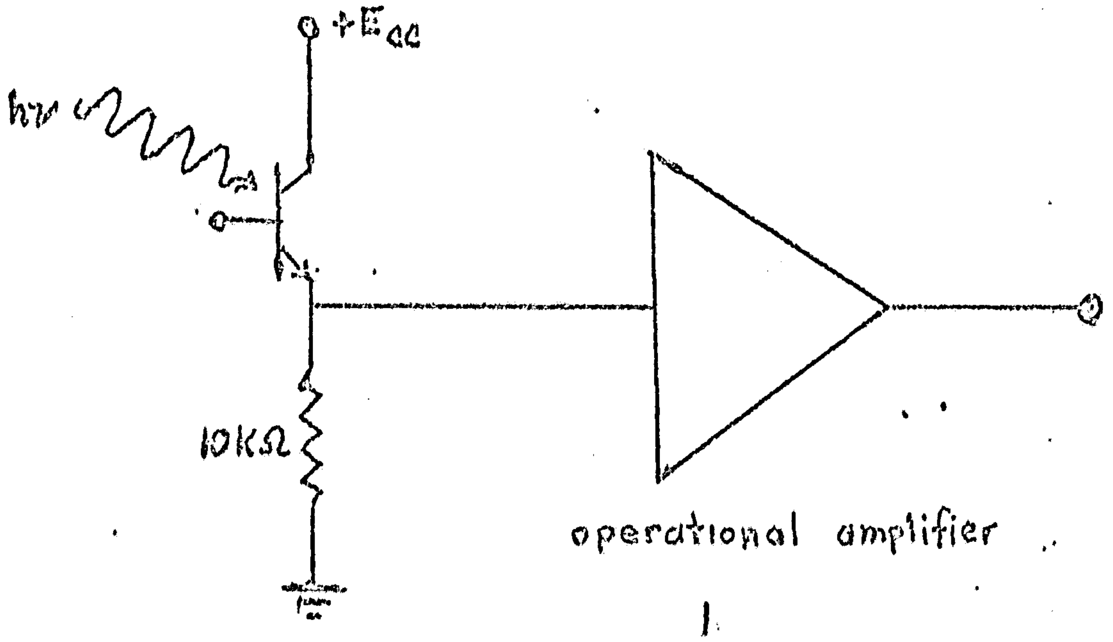


Figure 1
Photo transistor circuit

FARADAY EFFECT MAGNETO-OPTIC SIGNAL

The Faraday magneto-optic effect can also be used for readout provided the magnetic material is "thin" enough. Since the meaning of "thin" varies with material, no definition will be given except to say thin for permalloy (80-20 NiFe) is less than 300°A.

The intensity change is plane polarized light passing through a sample that reverses its magnetization by M_s is given by

$$I_f = I_o e^{-\alpha t} [\sin^2(\theta + 2Ft) - \sin^2 \theta] \tag{3}$$ [15,16]

where

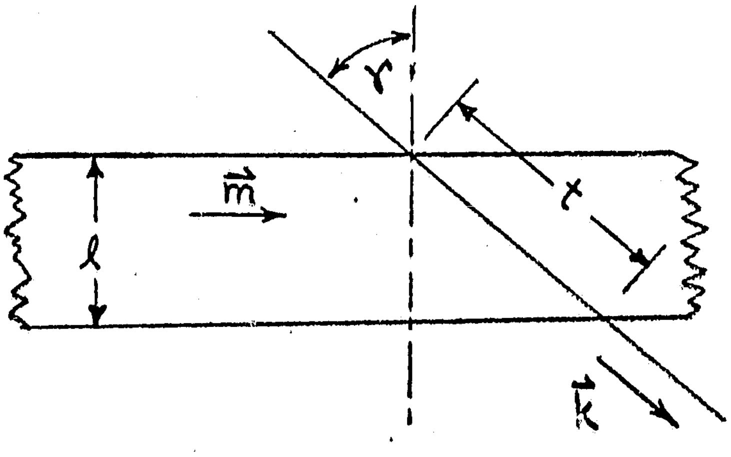
I_o	incident light energy-watts
F	Faraday rotation coefficient for saturated material - deg/cm
α	attenuation constant - cm^{-1}
t	path length through material - cm
θ	angular deviation of analyzer from position of minimum transmission

Also

$$F = F_o \vec{m} \cdot \vec{k}$$

where $\vec{m}$ and $\vec{k}$ are the magnetization and light propagation unit vectors respectively and F_o the maximum value of the Faraday rotation coefficient.

The geometry of the light and film arrangement is shown on the following page with an angle of incidence γ .



ℓ = film thickness

$t = \dfrac{\ell}{\cos \gamma}$

$\vec{m} \cdot \vec{k} = \sin \gamma$

---

[15] C.D. Mee and G.J. Fan, IEEE Mag. Trans, 3:72, March 1967

[16] D. Treves, JAP 38:1192, March 1967

Expanding equation (3) and using the fact $2Ft << 1°$ gives

$$I_f = I_o e^{-\alpha \ell / \cos \gamma} \; 2F_o \frac{\sin \gamma}{\cos \gamma} \sin 2\theta \qquad (4)$$

Differentiating I_f to find the maximum light transmission point gives

$$\frac{\partial I_f}{\partial \ell} = 0; \qquad \ell = \frac{\cos \gamma}{\alpha}$$

Using this value for ℓ in equation (4) yields

$$I_f = I_o e^{-1} \; \frac{2F_o}{\alpha} \; \sin 2\theta$$

Table One gives values of γ and ℓ for NiFe where $\frac{1}{\alpha} = 147 \; 10^{-8}$cm and $F = 10^5$ deg/cm.

γ deg	ℓ Å
90	0
88	5.16
85	12.7
80	25.6
70	50.0
60	73.0

Table One

Therefore a magnetic sample reserving its total magnetization M_s would produce a magneto-optic signal of

$$\frac{\Delta M_L}{M_s} = \mu_L \; \frac{\Delta H_L}{H_K} \qquad \text{as defined above.}$$

Now the expected magneto-optic signal can be calculated. Assuming an angle of incidence of 60 degrees to give a reasonable thickness film (73° Å), $I_o = .45$ watts and $\sin 2\theta \approx 1$ gives

$$I_f' = \frac{\Delta M_L}{M_s} I_f = \frac{\Delta M_L}{M_s} I_o \sin \gamma \, 1.89 \cdot 10^{-3} \sin 2\theta$$

$$= 1.47 \text{ nano watts}$$

Using a phototransistor with a conversion coefficient of 50 amps/watt gives an emitter current of 75 nano amps or 750 μvolts output from an emitter follower circuit with a 10 k ohm emitter resistor.

This is approximately three times the calculated Kerr magneto-optic signal. The noise voltages are the same in both cases so a three to one improvement in signal to noise ratio should be realized.

Conclusion

This analysis indicates that the Kerr magneto-optic effect is potentially useful in the detection of gamma level magnetic fields. The analysis indicates good performance at the present level of technological capability. An improvement in the longitudinal permeability, which appears theoretically possible, would allow even greater accuracy. The limitations of the technique appear to be in the film materials and can only be determined by experiment.

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A search of pertinent literature was carried out in two general areas: Appendix A includes magneto-optic theory and technology, magneto-optic properties of materials and properties of thin magnetic films relating to their application in measuring magnetic fields. This bibliography is as comprehensive as possible and includes virtually all the papers pertinent to the detection of magnetic fields. Appendix B is a less thorough bibliography including light emitting diodes and photo diodes. These papers are only those which give technological information, as the theory of the devices and development of new and exotic types of devices are not of direct interest in this investigation. The bibliography on light sources and detectors is brief but representative of the information necessary to this project.

A brief abstract of some of the most important papers is included in Appendix C.

APPENDIX A

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APPENDIX B

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APPENDIX C

ANNOTATIONS ON SOME IMPORTANT PAPERS

C.A. Fowler, E.M. Fryer, Phys. Rev., p 52, 1954.

Important because of historical value. One of the first to use Kerr effect for domain observation in the way it is used now. Good pictures of single crystal SiFe showing domain structure as a hard axis field is slowly reduced to zero.

P.N. Argyres, Phys. Rev., 334, 1955.

The Faraday and polar magneto-optic Kerr effects are described in terms of the semi-classical theory of radiation, with the band-theory of metals as a basis. Polarizability and conductivity tensors are developed and interpreted to explain the assymetrical effect of the magnetized ferromagnetic material on right- and left-hand circularly polarized wave. A complicated mathematical treatise which has great value in establishing a theoretical basis for magneto-optic rotation. A basic theory paper.

P.H. Lissberger, J. Optical Soc. of America, 948, 1961.
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These two papers concern the longitudinal Kerr magneto-optic effect. The first gives a very detailed description of experimental measurements of the Kerr effect for films with nonreflective coatings. The second paper develops a theory to account for the experimental results. Strong points are the consideration of dispersion of the angle of incidence and multiple reflections within the dielectric coating. Signal to noise calculations do not consider scattering by surface imperfections, but considers the shot noise of the photodetector as the primary noise source. Trevis, 1967, has demonstrated that surface noise is paramount.

D. Trevis, J.A.P., p 358, 1961.

Shows that contrast of domains using Kerr effect is limited by ellipticity caused by metalic reflection. Appendix derives ellipticity relations. A number of curves are given relating apertures and angle of incidence to contrast. This work supports the use of parallel light for maximum signal to noise ratio.

F.G. West, W.J. Odom, J.A. Rice, T.C. Penn, p 1163, JAP, 1963.

The basic idea of a thin-film magnetometer is developed, using hard axis pumping, and detecting easy axis flux with a coil pickup. Angular dispersion of the easy axis is considered. Experimental procedure and results are given. Sensitivity of 0.1 gamma is reported.

C.C. Robinson, J. Opt. Soc. of America, p 681, 1963.

An excellent description of the longitudinal Kerr effect is given. The Kerr effect is explained as a rotation due to a Kerr reflection transverse to the incident light and an ellipticity due to the phase shift of the Kerr reflected light. An experimental set to independently measure the rotational and elliptical component is described. Experimental data indicates in general the elliptical component is larger than rotated component. Also an expression for the magneto-optic conductivity that relates the optical and electrical properties of the films.

C.C. Robinson, J. Opt. Soc. of America, p 1220, 1964.

The Kerr reflection and Faraday transmission relations are calculated on the basis of an electromagnetic wave incident on magnetized slab of homogeneous isotropic material. The polar, transverse, and longitudinal Kerr effects are described as well as the Faraday effect for thin films.

D.B. Dove, T.R. Long, Proc. INTERMAG Conf., p 12.5, 1964.

A Kerr apparatus is used to examine 25μ diameter film areas. The angular dispersion and H_k magnitude dispersion is measured. Also the longitudinal remanent flux versus the longitudinal bias field for an ac transverse field greater than H_k indicates a longitudinal permeability of between 34 and 170 for the sample described.

D.O. Smith, G.P. Weiss, p 962, JAP, 1965.

The uniaxial anisotropy nonmagnetostrictive films is described in terms of five components. These are (1) fast ($\leq$ 5 sec) lattice vacancy anisotropy, (2) show (5-10 min) lattice vacancy anisotropy, (3) oriented half interstitual, (4) oriented interstitutial pairs, and (5) Fe-Fe directional pairs. By various annealing processes the different components could be seperated out and measured. Oxygen seems to lock up the vacancy anisotropy processes because the annealing properties are less after the film is exposed to air.

D.B. Dove, T.R. Long, p 1068, JAP, 1965.

This is an expansion of a paper given at the Intermag Conference in 1964. A detailed description of the Kerr and Bitter pattern apparatus is given. Using a light spot of .007 inch diameter very small film regions were examined. A comparison of the measurements of small areas and the overall film shows the effect of coupling between the small areas. These coupling effects are not seen in the overall film measurements. Domain widths of approximately .001 inch for 1000 Å can be made reproducibly if the ac strong fields are cancelled.

F.G. West, C.L. Simmons, p 1283, JAP, 1966.

A series of permalloy films were made with grain sizes ranging from 150 to 550 Å. The angular dispersion, α_{50}, as measured by the Crowther method, increased with increasing grain size. The angular dispersion variation with grain size can be explained by a model proposed by Hoffman if the internal stresses increases as the grain size decreases. Composition variation within the film thickness is also suggested as possible cause of the α_{50} variation. The product of α_{50} H_k was approximately constant for grain size variation from 200 to 500 Å .

C.E. Frank, Rev. Sci. Inst., p 875, 1966.

The equilibrium energy conditions for a single domain particle are described with the "inverse asteriod" function. A new measurement technique based on the inverse asteriod function is presented for obtaining the angular and magnitude anisotropy dispersion distributions. A dipole (ferromagnetic) resonance technique is described that has been used to measure dc fields as small as 10^{-5} gauss.

V.A. Ehresman, C.D. Olson, p 1287, JAP, 1966.

A probe capable of resolving film areas of less than .1 mm (4 mils) was used to measure the local permeability. The probe operation is based on the nonlinear mixing of orthogonal drive fields to detect the local magnetization direction. The range of values of H_k is consistent with Δ_{90} measurements and are randomly distributed. However, the angular variation of the magnetization is almost entirely due to the shape demagnetizing fields.

D. Trevis, p 1192, JAP, 1967.

Various noise sources are evaluated. Techniques to minimize the noise are discussed and experimental results verify their effectiveness. An excellent paper which contains many fundamental relations. Uses space filters and differential techniques to minimize noise due to surface imperfections.

A. Yelon, p 325, JAP, 1967.

The overall anisotropy of a collection of nonparallel uniaxial regions is described in terms of a uniaxial anisotropy constant and a series of higher order anisotropy constants that are field dependent. Detailed calculations are presented for the biaxial and triaxial cases. The coupling between regions is assumed to be due to the stray fields so that it is strongest for parallel regions. The higher order anisotropies decreases as the coupling between regions increases. This implies a decrease in the higher order anisotropies as the dispersion decreases.