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OPTICAL INFORMATION HANDLING WITH THIN MAGNETIC FILMS[a]

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Abstract.—This paper considers an optical method for extracting stored information from thin magnetic films based on the Kerr magneto-optic effect.[1] The effect may be described as the rotation of the plane of polarization of plane polarized light upon reflection from a magnetized surface. The direction of this rotation depends upon the magnetic polarity of the reflecting surface. Thus, the state of a thin magnetic film, which is represented by its magnetic polarity, may be detected optically in a nondestructive manner. However, the effect is rather small, and as such, is not particularly useful. This paper describes attempts to increase the effect, and in fact, shows that it can easily be increased by a factor somewhat greater than 5. The theory indicates that this factor can be further increased, and suggestions for future research along these lines are indicated.

Several possible applications of the Kerr effect are described. These include computer display schemes and logic operations.

I. INTRODUCTION

Thin ferromagnetic films show exciting promise as a substitute for ferrite cores as the storage medium in high-speed digital computer memories.[1,2] Kittel has shown that for Permalloy (83 percent nickel—17 percent iron alloy) films with a maximum thickness of 3000 Angstrom units, the preferred configuration (on a least free energy argument) will be that of a single domain. Theoretically, only a few millimicroseconds should be required to switch such an element. In such an application, these thin films offer the advantages of higher speed and simpler assembly than ferrite cores.

Electrical readout, as with cores, is still possible. However, the high surface to volume ratio of thin films introduces the possibility of an alternate readout method using this characteristic.

II. OPTICAL READOUT

Magneto-Optic Effect

One intriguing approach is the application of the magneto-optic effect discovered in 1877 by Kerr.[3] It is important not to confuse the Kerr magneto-optic effect which is to be discussed here, with the more widely known Kerr electro-optic effect. The latter occurs in certain materials which become doubly refracting under the influence of an electric field.

The Kerr magneto-optic effect is the rotation of the plane of polarization of plane polarized light on reflection from a magnetized surface. The direction of rotation depends on the magnetic polarity of the reflecting surface.

A similar effect was observed and reported by Michael Faraday in 1845.[4] He noted that when plane polarized light is sent through glass in a direction parallel to an applied magnetic field, the plane of vibration is rotated, i.e., the glass becomes optically active.

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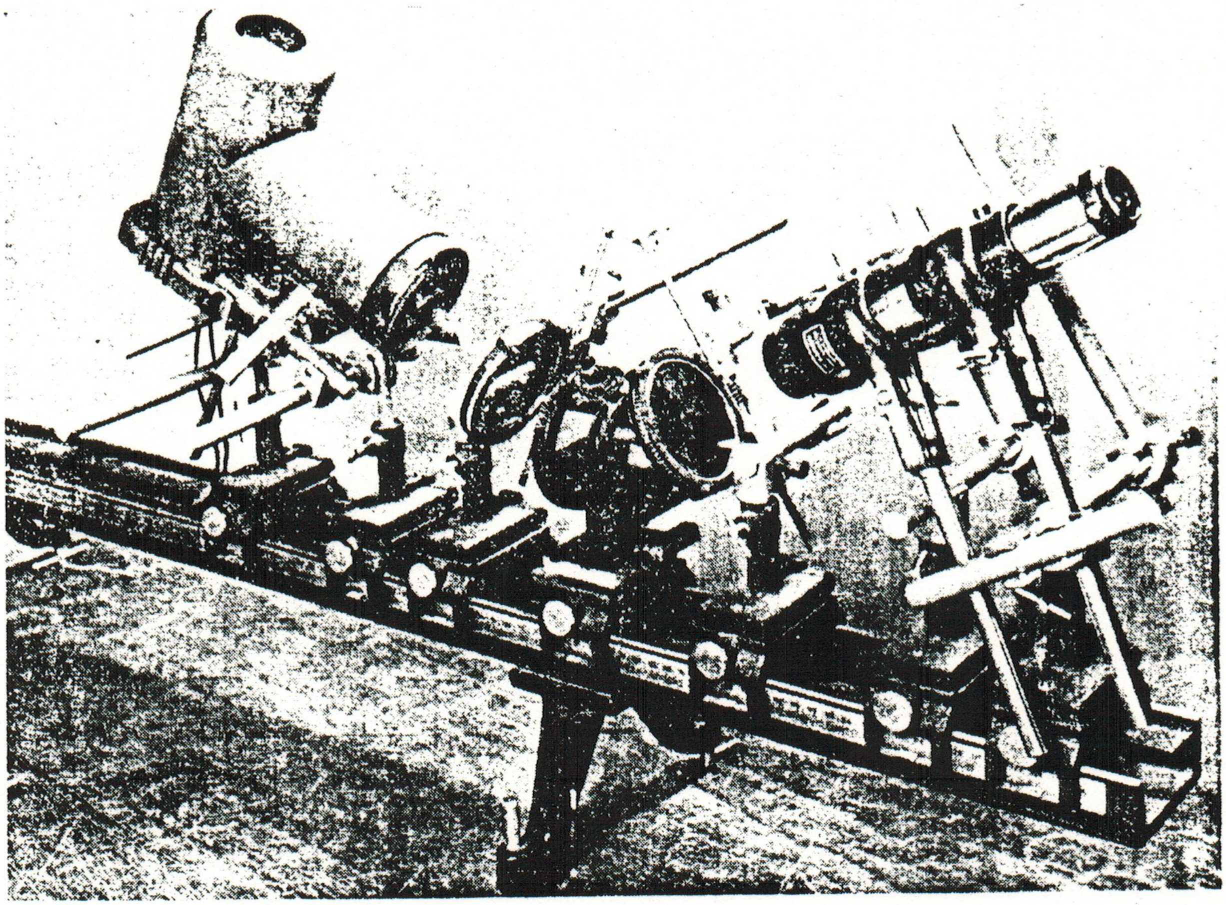

Fig. 1—Optical bench for observation of Kerr effect.

It seemed likely that these two effects would find their explanations in theories not too different from each other, and indeed this is so. However, it was not until recently that a satisfactory theory was developed to explain these phenomena. An excellent paper on the "Theory of the Faraday and Kerr Effects in Ferromagnetics"[5] has been prepared by Argyres (1955) in which the effects are treated using the band theory of metals. His results for the case where the magnetic polarity is normal to the specimen surface, yield an expression for the angle of rotation of the plane of polarization as shown in (1).

$$\theta_k = - \mathcal{I}_m \left[(-4\pi) \frac{(O_1/w) + j\,a_1}{(n - jk)\,[(n - jk)^2 - 1]} \right] \quad (1)$$

where O_1 is the conductivity, w is the frequency of the incident light, a_1 is the polarizability, $(n-jk)$ is the complex index of refraction and $\mathcal{I}_m$ means the imaginary part of the expression in brackets.

The Kerr effect was visually observed with the apparatus shown in Fig. 1 and is explained diagrammatically in Fig. 2. Light from a tungsten source is collimated by lens L and passed through polarizer 1 before impinging on the magnetic film. In order to minimize the ellipticity of the reflected light, the polarizer is adjusted to polarize light normal to the plane of incidence.

Visual Observations

The light reflected from the specimen film undergoes a Kerr rotation of the plane of polarization in a direction which depends on the magnetic polarity

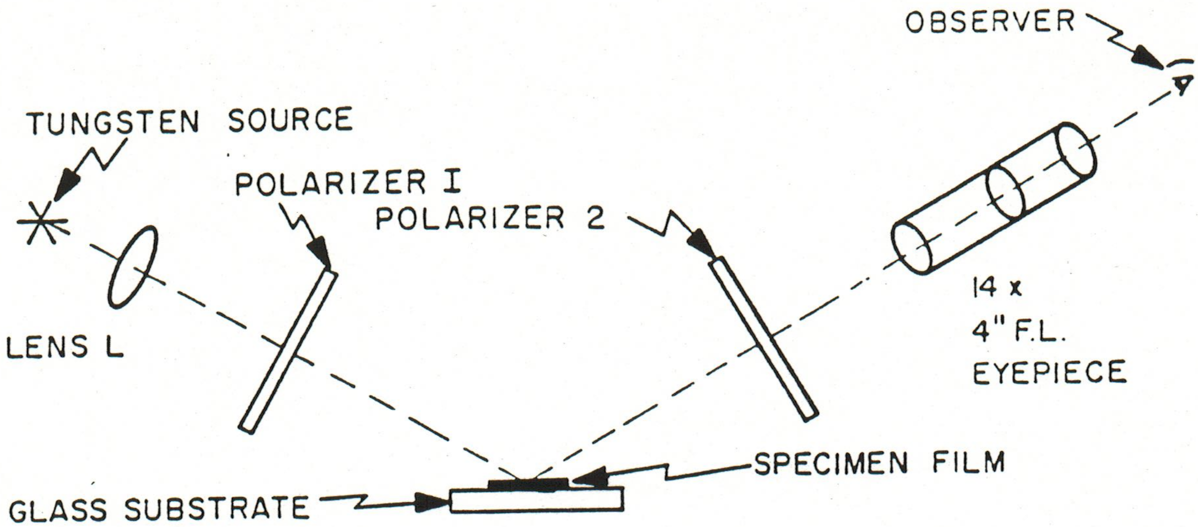

Fig. 2—Schematic representation of Fig. 1.

of the specimen. The reflected ray is then passed through polarizer 2 whose polarizing axis is at an angle of almost 90° to that of the first polarizer. Thus the emergent beam is almost fully extinguished. However, it is visible to an observer through a low-power eyepiece. Since magnetic domains of opposite magnetic polarity rotate the plane of polarization in opposite directions, light reflected from one set of domains will rotated toward extinction whereas light reflected from the other set of domains will be rotated away from extinction. Thus, to the observer, domains on one polarity appear brighter than domains of the opposite polarity, and there is a well defined boundary (domain wall) between them which is quite clearly shown in Fig. 3.

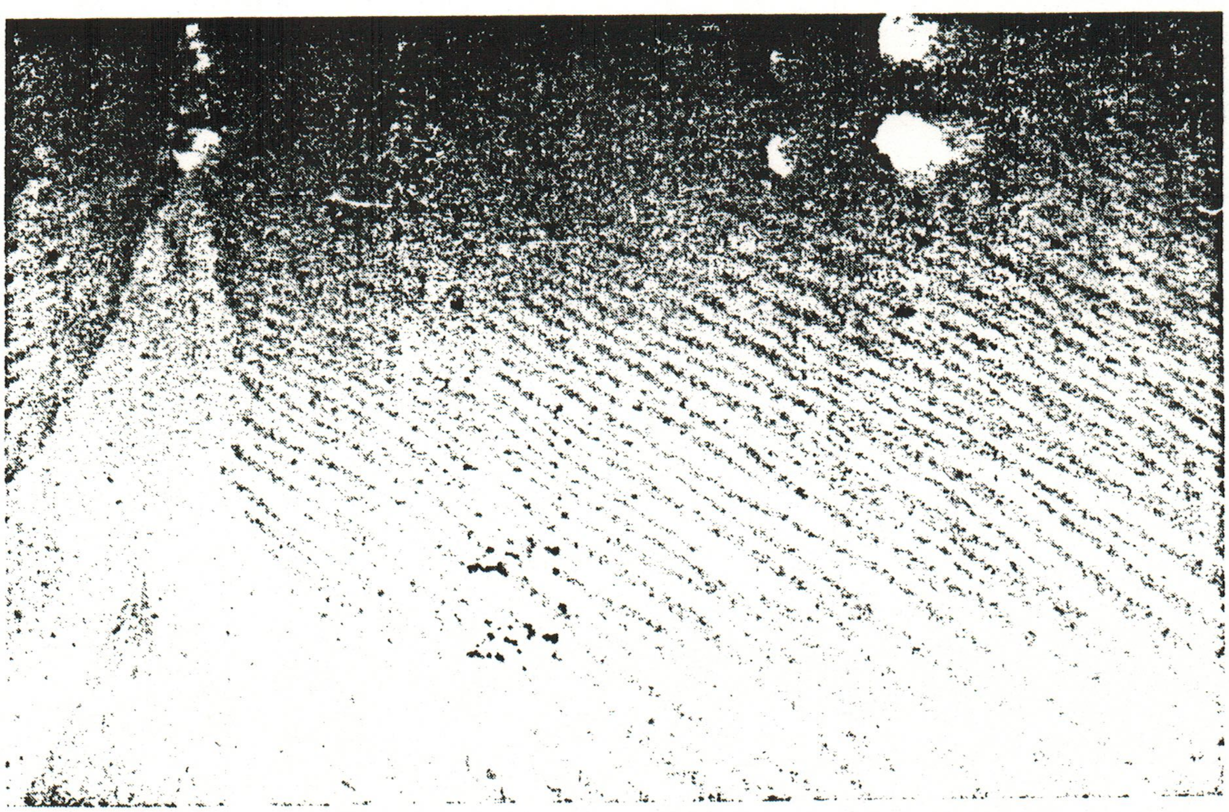

Fig. 3—Magnetic domains (magnification 15 x).

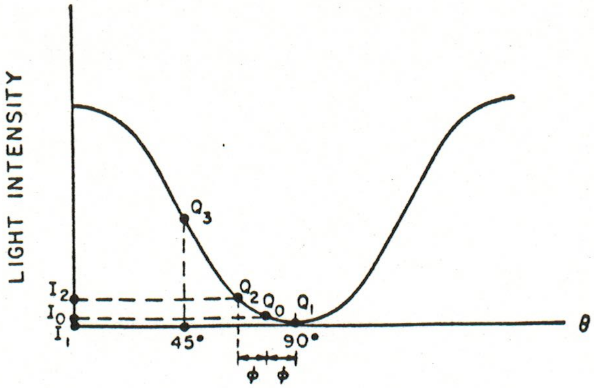

Fig. 4—Transmission curve for two polarizers at an angle θ.

The magnetic material used for this film was an 83 percent nickel, 17 percent iron alloy commonly referred to as Permalloy. At an evaporating pressure of about 10^{-3} mm the Permalloy was deposited to a thickness of approximately 1000 Angstrom units (about four millionths of an inch).

Electrical Sensing

If a photosensitive detector is placed in the path of the reflected ray after it has passed through the second polarizer, an electrical signal will be obtained which will differentiate between the two magnetic states of the samples. In this case the adjustment of the polarizers is somewhat different. Reference to Fig. 4 shows that the transmission curve through two polarizers as a function of the angle θ between their polarizing axes is a cosine-squared function with its maximum slope at Q_3 where θ equals 45°. Photoconductors are most sensitive to changes in light intensity. For this reason, the polarizing axes are separated by 45°.

However, for visual observation, θ is set at point Q_0 to achieve the maximum ratio of light intensity (to which the eye is most sensitive). It can be seen that the Kerr angle (ϕ) for one magnetic state is positive (point Q_1), with a resultant light intensity I_1. In the other magnetic state, the Kerr angle is negative (point Q_2), and yields a light intensity I_2.

III. ENHANCEMENT OF THE KERR ROTATION

One big advantage of this optical readout technique is that information can be removed from the film without destroying and thus forcing rewrite of that information. Several practical weaknesses to the method are as yet unresolved. One of these is the relative weakness of the Kerr effect. An average Kerr rotation for Permalloy films is only about 0.034°. With the apparatus previously described, and a detecting circuit consisting of a Clairex type CL-404 glass-sealed cadmium selenide photo-conductive cell and a cathode-follower amplifier, an output signal of 20 millivolts was obtained. However, the noise level generated in the photocell as well as low frequency noise due to vibration of the apparatus deteriorated this signal considerably. A bandpass network (0.1-10 cps) provided some improvement.

Sensing Elements

Obviously, a number of refinements must be made to the optical readout method before it achieves the state of a practical technique. One of the most fruitful would be the added sensitivity of a photo-multiplier tube with a rise time of one microsecond or less. One of the most dramatic would be an advance in the art of depositing photoconductors that would permit their incorporation in the same substrate with the magnetic film to form an integrated package.

Light Sources

High intensity zirconium arc lamps are an attractive possibility for increasing the signal strength with a consequent improvement in the signal-to-noise ratio. With enough added signal strength, monochromatic filters could be used which, in turn, would allow the use of optical compensation such as quarter wave plates to reduce the ellipticity of the reflected light.

Surface Treatment

A more fundamental approach to the problem of small output signals—and one of the objectives of the research reported here—is that of increasing the Kerr angle itself. Ingersoll in 1909[6] found that this could be done by adding a thin layer of certain liquids to the magnetized surfaces. He observed that the Kerr rotation was increased by a factor roughly equal to the refractive index of the liquid. In another method reported by Kranz[7] and Heinrich[8] in 1956, the Kerr rotation was increased by the evaporation of a thin transparent dielectric film on the magnetic surface. Heinrich developed an expression for the rotation of the plane of polarization of light due to the Kerr effect which is similar to that of Argyres in (1). He pointed out, however, that the index of refraction which should be used in these equations is the *relative* index of refraction of the two media which form the regions on both sides of the reflecting boundary. In the case that Argyres considered, one of the media was air, and so the relative index of refraction was the same as the absolute index of refraction referred to free space. Moreover, since the difference between this quantity squared and unity appears in the denominator, the angle of rotation can become quite large under the correct conditions.

These findings indicated a promising approach to increasing the angle of rotation of the Kerr effect and exploiting its usefulness. Thin magnetic films of Permalloy were evaporated on glass substrates over which a thin layer of dielectric material was added. Measurements of the Kerr rotation with a number of different dielectrics are summarized in Fig. 5. The angles measured by this method represent twice the Kerr rotation since the film was switched from one state to the other and the change in angle detected. Silicon monoxide was most effective with an increase of about five and one-half times the rotation observed for Permalloy alone. Films of silicon monoxide about 1000 Angstroms thick produced average rotations of 0.186° compared to the average of 0.034° for untreated Permalloy.

Although these results were encouraging, the need for further work is indicated. It is not only difficult to control the thickness of these dielectric layers but little is known of their optical properties when they are deposited as thin films.

Magnification by Reflection

Multiple reflection of the incident light was also considered as a means of increasing the angle of Kerr rotation. A thin layer of a nonmagnetic material (e.g., aluminum) was deposited on the surface of a one millimeter thick glass slide opposite the Permalloy as shown in Fig. 6. By this means the incident

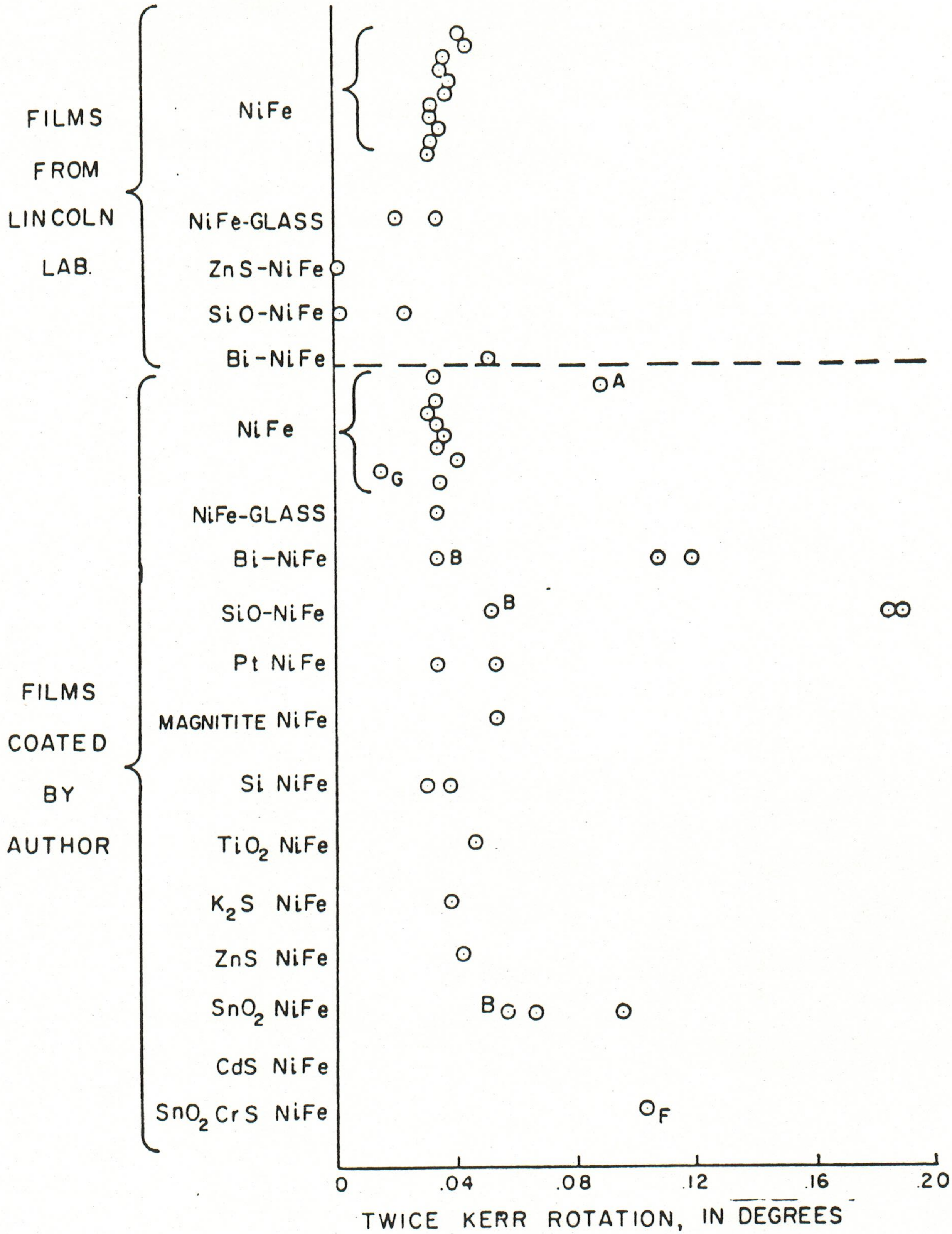

Fig. 5—Effect of dielectrics on Kerr rotation.

light was reflected from the surface of the Permalloy a number of times before it passed through the polarizer. It was expected that upon each reflection the plane of polarization would be rotated by the Kerr angle so that the emerging beam would have a total rotation equal to the Kerr angle times the number of reflections from the Permalloy. Visual observation of the resulting beam

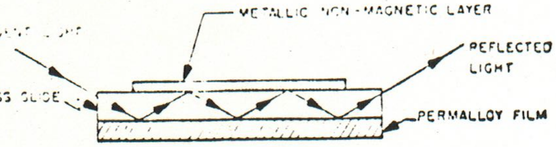

Fig. 6—Multiple reflection.

was difficult because the glass slides were only 1 millimeter thick and the emerging beam was extremely narrow. Nevertheless it was found that the total Kerr rotation was proportional to the number of reflections. Quantitative measurements were not possible due to the insensitivity of the photocell and its associated amplifier. The high gain and low level sensitivity of a photmultiplier tube would make it a much better detector for this purpose. Moreover, its fast response would also allow measurement of the speed of the Kerr effect which theoretically should be as fast as the film switches, i.e., a few millimicroseconds. Although worthy of further investigation, the method of multiple reflection has the inherent drawback that the total light output and thus the resulting signal is greatly reduced.

IV. POTENTIAL APPLICATIONS

Computer Displays

Aside from its use as a laboratory tool for the observation and study of domains and domain walls, the Kerr effect might become the basis of a new series of visual display devices; that is, applications in which detection of magnetic polarity is performed by the human eye. Fowler and Fryer[9] have done some interesting work in this area.

A typical example would be the display of the contents of a binary register in a digital computer on a screen or panel. Such information can be displayed at present only by maintaining the information in the flip-flop for the entire period of display. If the contents of the flip-flop were transferred to a row of thin films, these could be read optically and the results displayed. Meanwhile, the flip-flop register would be free to accept other information.

Similarly, characters or curves could be displayed on a screen. Current practice is to take information from the computer memory and convert it for display on the face of a cathode-ray tube. The optical sensing method that has been described incorporates a stored image so that a cathode-ray tube would not be needed. Williams, et al,[12] have made use of the Faraday effect to successfully produce stored images in thin films MnBi. A drawback to their scheme is the relatively high coercive force required to alter the stored information (3000 oersteds).

Probably the most obvious application of Kerr effect with a photo-sensitive detector is that in a computer memory. Sheets of substrate material on which an array of small spots of thin magnetic films is deposited would comprise the storage media. An identical array of photo-sensitive areas would form the sensing plane. A collimated light beam would project the image of the storage plane directly on the corresponding sensing plane. Thus, for every elementary storage unit there would be a corresponding elementary sensing unit on which to project the image of the storage unit. Depending on the magnetic state of the storage unit, a bright or dark image impinging on the sensing unit would

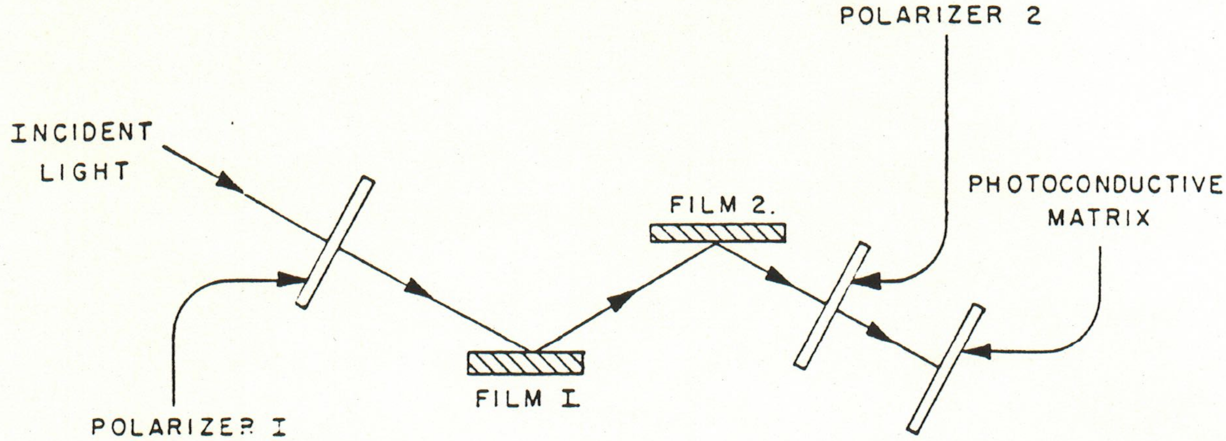

Fig. 7—Example of magneto-optic computer logic.

be converted to an electric signal. Since this operation would not affect the magnetic element, nondestructive readout would be obtained.

Computer Logic

Schemes for performing computer logic with such thin film and optical components are conceivable. The configuration shown in Fig. 7 could be used to perform either the AND, the OR, or the NOT function, as can be explained by consideration of the operating points shown in Fig. 8. The angle θ between the plane of polarization of the light incident upon the second polarizer and its polarizing axis is determined by the angle between the two polarizers, plus the rotations contributed by each of the films. The angle of rotation of polarized light reflected from each of the films is $\pm\,\phi$, since each film will always contribute either a positive or a negative increment. If the axes of the two polarizers are initially set at an angle of 45°, the operating point is Q_1. The total angle between the light and the second polarizer is therefore

$$\theta = 45° \pm \phi_1 \pm \phi_2 \tag{2}$$

Assume that a film is in the ZERO state if it rotates light so as to increase θ, i.e., add an increment ϕ in the positive θ direction; conversely, a film in the ONE state adds an increment ϕ in the negative θ direction. Figure 9 shows the four possible states for the two film system. When both films are in the ZERO state, (system state A), an output voltage E_{00} is obtained, correspond-

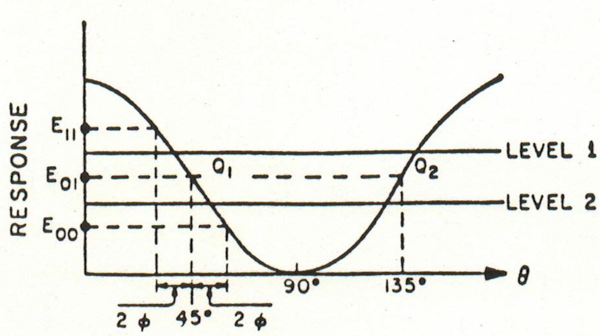

Fig. 8—Explanation of magneto-optic logic.

SYSTEM STATE	FILM STATE	
	FILM 1	FILM 2
A	0	0
B	0	1
C	1	0
D	1	1

Fig. 9—Possible system states.

ing to $\theta = 45° + 2\phi$. When the two films are in the ONE state, ($\theta = 45° - 2\phi$), an output voltage E_{11} is obtained. With the films in opposite states, the effects cancel, and an output E_{01} is obtained. If the sensing element is biased or constructed so that the minimum level for response is chosen as level 1 in the figure, then the AND function has been performed, since an output results from the sensing element only when both films are in the ONE state. If the minimum level of output response is chosen as level 2, the OR function has been performed, since an output from the sensing element results only when either one or the other film (or both) is in the ONE state (system states *B*, C, and *D*). If the operating point is shifted to Q_2, by rotating the second polarizer, the NOT function can be generated in a similar manner.

One of the major requirements of magneto-optic logic is a high speed photoconductor with a low threshold sensitivity to preserve the significantly high speed of this form of logic.

V. CONCLUSION

An optical method for information recovery from thin films appears worthy of further investigation. It offers a nondestructive readout, and, with further research along the lines suggested, may well offer an increase in output signal over that of magnetic readout. The potential applications fall into two distinct categories. First are visual display devices which lend themselves nicely to computer applications. Secondly, electronic detection which offers a fast memory element as well as the ability to perform magneto-optical logic.

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