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MAGNETO OPTIC EFFECTS AND APPLICATIONS

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November 1981

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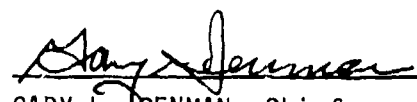
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The principles of the different magneto-optic effects are reviewed. Reflection and absorption mode devices using magneto-optic effects seem to be too small to be of interest. However, transmission mode devices, such as Faraday and Voigt effects, have received a great deal of attention in the past. The main applications reported dealt with low intensity radiation. The garnets, being so versatile and having such good magneto-optic properties, certainly are worth investigating in greater depth. However, the most likely starting materials for the near infrared are the basic YIG and			

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BLOCK 20 ABSTRACT

GdIG with some Bi or other substitution. The ferrimagnetic ordering of the garnets is a great advantage for a control system as it is field and temperature sensitive.

Another promising material group is the antiferromagnetic transition metal oxides. The switching properties of these materials are not directly field controlled, but are dependent on internal stresses and on temperature. More information is needed as to their optical properties in the spectral range of interest.

Cermets are discussed as to their possible advantage as switching elements and appears to be a virgin field regarding magneto-optic effects.

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FOREWORD

This report was prepared by the Laser Hardened Materials Branch of the Electromagnetic Materials Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories. Part of the described work was performed under Project 2422, Task 242204, WUD 24220401, under direction of Lt Col Theodore T. Saito, AFWAL/MLPJ. Dr. J. Bransky was visiting scientist at AFWAL/MLPJ, under Contract F33615-79-C-5129, Universal Energy Systems, Dayton, Ohio, during the period April-December 1980.



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SECTION I

INTRODUCTION

Magneto optic effects are divided into three main categories, related to transmission, reflection, and absorption of light by magnetic material.

1. TRANSMISSION MODE

The first category deals with the interaction of the internal magnetization of matter with the electromagnetic wave propagating through it. When linearly polarized light travels through a magnetized sample, the plane of polarization is rotated.

The magnetization in the sample might be due to the presence of an external magnetic field, parallel or perpendicular to the optical path. The first of the configurations is called the Faraday effect and is shown in Figure 1. Phenomenologically, this effect is related to the normal Zeeman effect. The magnetic field causes a splitting of the energy levels, thus shifting the original resonant frequency ν_0 , of an absorption line, to slightly higher and lower frequencies ν_1 and ν_2 . A double dispersion effect is generated. Left circularly polarized light is dispersed at ν_1 and right circularly polarized light is dispersed at ν_2 as shown in Figure 2 (Reference 1). This causes left and right circularly polarized components to have different indices of refractions. Thus, a retardation of one component relative to the other gives rise to a phase difference between them. When emerging, these components will combine to give an elliptic polarization whose major axis is rotated relative to the original direction of polarization. This angle is called Faraday's rotation, θ_F . The Faraday rotation is directly proportional to the magnetization M and to the length of the light path through the material ℓ . The proportionality constant is called the Verdet constant V .

$$\theta_F = VM\ell \quad (1)$$

Because of the linear dependence of θ_F on the internal magnetization, or in most cases, on H (the external magnetic field), the Faraday effect is called an "odd" effect. θ_F varies from a few deg/cm to 10^6 deg/cm. Sometimes, the Faraday effect is referred to as "circular magnetic birefringence" (CMB).

The birefringence Δn is related to the angle of rotation by the equation

$$\theta_F = \frac{(n^{\odot} - n^{\ominus})\pi d}{\lambda} \quad (2)$$

$n^{\odot}; n^{\ominus}$ = the two refraction indices

d = the thickness of the sample

λ = the wavelength

while the intensity variations associated with the birefringence is

$$I = I_0 \sin^2 \theta_F \quad (3)$$

When the magnetic field H is directed perpendicular to the optical path and the incident light is linearly polarized, the interaction with the material is different. This configuration is called the Voight effect. Instead of viewing the linearly polarized light as left or right circularly polarized, the electric field vector of the light is now parallel or perpendicular to the magnetic field as shown in Figure 3. The parallel component is in no way affected by the field, while the two perpendicular components are oppositely interacting with it.

This interaction implies, again, a difference in the refracting index ($\pm\Delta n$) and thus a birefringence for the two perpendicular components. This is a linear magnetic birefringence (LMB) and is independent of the fields orientation (axial). It is proportional to the square of the magnetic field H^2 (or the magnetization, M^2) and is called an "even" effect. Though misleading, it is often referred to as "Cotton-Mouton" effect. The Voight effect is very small in para and diamagnetic materials. This is not necessarily the case in ferromagnets. The angle of rotation θ_V is related to the birefringence by:

$$\theta_V = \frac{\Delta n \ 2\pi d}{\lambda} \quad (4)$$

A phenomenological theory of the Faraday and the Voight effects is given by Freiser (Reference 2).

These two magneto optic effects, related to the transmission mode, have been used extensively to get insight on the magnetic state of materials. They are also used in a large variety of optical applications, as will be specified later. But, evidently, their use is limited by the absorption of radiation by the media in the spectral range of interest. The significant factor is the ratio between θ_F , the specific Faraday rotation and α , the absorption coefficient. These two combine to give the "Figure of Merit" of the material defined as:

$$\text{F.O.M.} \left[\frac{\text{deg}}{\text{dB}} \right] = \frac{\theta_F [\text{deg/cm}]}{\alpha [\text{dB/cm}]} \quad (5)$$

A third transmission mode magnetic effect, one that is not related to the Zeeman effect, i.e., to an electronic dispersion, is the genuine Cotton-Mouton effect. This is a magnetic birefringence related to macroscopic magnetic dipoles. The configuration is similar to the Voight configuration and thus displays an even effect

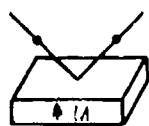
$$\theta_{CM} \propto M^2$$

θ_{CM} is the rotation of the main axis of the elliptically polarized transmitted light. This effect is usually found in colloidal solutions of magnetic particles and as M might be large - θ_{CM} is too. It is the equivalent of the Kerr electro optic effect.

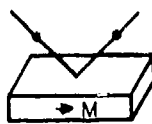
2. REFLECTION MODE

The second category of magneto optic effects deals with reflected light from the surface of a magnetized material. It is labeled, in all its different configurations, as the Kerr effect.

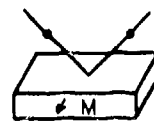
There are three different configurations of the light with respect to the magnetization in the sample: the polar, longitudinal and equatorial modes.



Polar



Longitudinal



Equatorial

For thin (ferromagnetic) films the polar configuration usually requires strong magnetic fields to overcome the large demagnetization factor, or some other kind of induced unisotropy.

The analysis of the reflection mode is complicated because of the oblique incidence involved. Usually one would expect a mixture of all the possible polarizations in each direction. However, a simplified computation based on the electromagnetic boundary conditions at the reflecting surface for the polar configurations at normal incidence, gives some insight into the effect. The Fresnel coefficient for this case, representing the reflected amplitude is:

$$r = \frac{n-1}{n+1} \quad (6)$$

The dependence on n , the refraction index, hints that like in the transmission mode, the difference in n for right or left circularly polarized light, will create a difference in amplitude and a phase shift between the two.

If the incident light is linearly polarized, the reflected light will be elliptically polarized, because the two circular components, composing the incident beam, will no longer be equal in amplitude or in phase, as happens in the Faraday effect. The main axis of the ellipse will be rotated by the angle θ_K relative to the original polarization. This angle, θ_K is very small in order of magnitude of minutes.

A special situation, however, exists for one case. In the equatorial configuration, the calculated components of the reflected lights show that only the component parallel to the field is affected by the magnetization and its amplitude is linearly proportional to it ($R_{||} \propto M$) (unlike the quadratic Voigt effect which is similar in configuration). As a result of this uniaxiality, switching the magnetization by 180° effects directly the intensity of the reflected light. This change can be detected without the use of an analyzer, which means considerable increase in efficiency. A typical value for θ_K , in the visible range, is 10 minutes. This has been reported for nickel films, at saturation.

The smallness of the Kerr rotation θ_K has been overcome to a certain extent by different kinds of multireflection methods (References 3, 4), thus increasing the signal by a factor of 20.

It is also worthwhile to note that ferromagnetic alloys like permalloy or GdFe have a greater Kerr rotation than the ferromagnetic transition metals. The equatorial Kerr effect is a principal tool in the investigation of the magnetic domain structure and the related magnetic properties of ferromagnetic materials. It also is used for computer memory read-out applications (Reference 5).

The angle of rotation θ_F , θ_V or θ_K can be measured by a static method with a Babinet compensator or by a dynamic method in which the magnetization is switched periodically and the intensity variations are measured by means of a lock in amplifier (References 6, 7).

3. THE ABSORPTION MODE

The last magneto optic effect to be mentioned is the circular magnetic dichroism: (CMD). This effect is the difference in the absorption coefficient for right or left circularly polarized light. This difference changes slightly the spectrum of absorption of a sample magnetized in the beam direction. As in the transmission configuration, there exists also a linear magnetic dichroism (LMD), equivalent to the Voight effect configuration where the magnetic field is transverse to the light.

CMD and LMD can give an insight on band structure of crystals and magnetically induced transitions (References 8, 9). It has not found any other applications.

SECTION II

MATERIALS CLASSIFICATION

Materials used in magneto optic devices can be grouped according to their magnetic ordering. There are three spontaneous kinds of magnetic order: ferromagnetic, antiferromagnetic, and ferrimagnetic. All three are characterized by a nearly regular magnetic domain pattern, not directly related to the crystal structure. The size of the domains varies from 20 μm to 0.02 μm .

In the ferromagnetic state, each atom possesses an unbalanced magnetic moment (related to the spin of the unfilled 3d band). Due to the strong exchange interaction between adjacent atoms, these magnetic moments are all parallel giving rise to a strong resultant magnetization. This, in turn, generates a strong demagnetization effect which will favor energetically a multidomain structure. Within one domain, all the magnetic dipoles are parallel. When applying an external magnetic field, the domains whose magnetization is parallel to the field direction, grow on account of the others, thus gradually forming an overall single domain (Reference 10). The magnetic order is maintained only below a critical temperature, the Curie Point, T_c , and is abruptly destroyed above it. The temperature dependence of the saturation magnetization is displayed as a step function. All the magnetization-related properties, like the Faraday rotation, vanish above T_c . The 3d transition group metals like iron, cobalt, nickel, manganese, chromium and most of their alloys are typical ferromagnets.

In the antiferromagnets, each individual atom or ion also possesses an unbalanced magnetic moment; but these moments are in an antiparallel arrangement and cancel the net magnetization completely. Though there is no demagnetization effect, the antiferromagnetic order is also broken into a domain pattern (Reference 11). This pattern is not controllable by an external magnetic field but can be affected by stresses or other induced anisotropies (Reference 12). The antiferromagnetic ordering has a slight temperature dependence but undergoes an abrupt change at the Neel temperature, above which the magnetic moments become randomly oriented.

Typical antiferromagnetic substances are the oxides of the transition metals like FeO, NiO, CoO as well as the fluorides and chlorides like FeF_2 , CoF_2 , NiF_2 (the rutile crystals), FeCl_2 , CuCl_2 and NiCl_2 .

The third spontaneous magnetic ordering is one typical to the ferrites. In these substances, the magnetic ions occupy two kinds of lattice sites A and B. On the A site, all the magnetic moments are directed parallel to each other; on the B sites all are antiparallel to the ones on the A sites. But the number of ions and the magnitudes of their magnetic moment is different and thus a net magnetization occurs. As in the ferromagnets, a field controlled domain pattern is detected; again, at a critical temperature the whole magnetic order is destroyed giving rise to a sharp transition in all the properties related to the magnetization.

Typical ferrimagnets are: MnFe_2O_4 , CoFe_2O_4 , F_2O_3 (spinel) and $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG), $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ (garnets).

1. THE FERROMAGNETIC METALS AND ALLOYS

The transition group metals and some of their binary alloys have the largest known Faraday rotation, but at the same time they are highly absorbent. In the bulk, these materials are suitable only for Kerr effect measurements. As thin films they can be transmitting in the visible and near visible regions.

Some available data for thin ferromagnetic films is summarized in Table 1. It can be seen from the table that the figures of merit, even for thin films, are extremely low. This implies that only a fraction of a degree of Faraday rotation will be detectable in nickel films while losing about 90% of the intensity. It should be noted that in the Faraday configuration, i.e., magnetization parallel to the beam, a large magnetic field is required to overcome the demagnetization factor of a thin film normal to its plane. Intensity variations occur as a result of magnetization switching and the related Faraday rotation. In a recent study of Fe, Co and NiFe-thin films, intensity variations of the transmitted light of 10^{-3} were reported (Reference 13).

TABLE 1
MAGNETO OPTIC CONSTANTS OF FERROMAGNETIC MATERIALS

Material	λ_{meas} [nm]	θ_F [deg/cm]	χ [cm^{-1}]	FoM (θ/χ) [deg/dB]	T_{curie} [°K]	T_{meas} [°K]	H_{meas} [oe]	Ref.
Ni (thin film)	633	$1.36 \cdot 10^5$	$2.1 \cdot 10^5$	0.65	630	300	5000	15
Ni (thin film)	400	$7.20 \cdot 10^5$	$7.6 \cdot 10^5$	0.79	631	300		2
Fe (thin film)	546	$3.50 \cdot 10^5$	$8.5 \cdot 10^5$	0.11	1093	300	1000	2
Co (thin film)	546	$3.60 \cdot 10^5$		0.009	1428	300		2
Fe-Ni (Permalloy) (19-81)	616 950	$1.80 \cdot 10^5$ $1.50 \cdot 10^5$			900	300	50	13
Fe ₃ O ₄ (ferrofluid)	visible	$48.00 \cdot 10^5$			300	77	4000	12
CdCrS (hot pressed) Spinel	1060	120	1	28		77	3500	10

The wavelength dependence of the LMB (birefringence, in the Voigt configuration), in the visible and near infrared regions for the above mentioned films, has been measured by Birss et al, (Reference 14). These authors computed the optical conductivity from the measured LMB and found a change in sign of the LMB at a photon energy of approximately 1 e.v., for Co and Fe and at 1.5 e.v. for Ni. This change in sign of the LMB seems to be an intriguing research topic. The maximum reported rotation is about 10^{-2} of a degree.

The temperature dependence of the Faraday effect and the linear magnetic dichroism, were found to be similar to the temperature dependence of the magnetization in thin nickel films (Reference 15). The Faraday rotation, for a 600 Å thick film, portrays a "step function," decreasing from $\theta_F = 7$ deg to $\theta_F = 0$ deg at 620° K. The conclusion of the above cited data, though interesting and straightforward for analysis, is that the magneto optic effects in ferromagnetic thin films are too small to be of any practical application.

Part of the experimental and theoretical problems encountered in the thin ferromagnetic films study are avoided by working with granular compounds. In these compounds, small metallic particles are embedded in a dielectric solid matrix, like SiO_2 . These compounds are called "cermets" and have recently received some attention (References 6, 18, 19, 20). The metal concentration can be varied between 20-90% of the volume for the particle size from a few tens of angstroms up to 100 Å. Ferromagnetic particles of this size will usually be single domains (Reference 21); their magnetization process is accomplished by rotation of the magnetic moment and thus requires low energies and fields.

The magnetic behavior of the ferromagnetic cermets has been studied recently (References 6, 18) and so have the magneto optical properties (Reference 20). Unfortunately, the latter were only studied in a reflection mode. An increase of about 100% is reported for the Kerr rotation relative to thin films (Reference 6) (90% Ni/10% SiO in volume). To date no reports on a transmission mode have been presented.

Investigating the cermets in a transmission mode seems to be very worthwhile. The assumption is that each of the small magnetic particles is a dipole and thus when activated optically will generate a quasi Cotton-Mouton effect. Each of these particles might contain about 10^4 atoms, thus an almost macroscopic effect can be expected. The order of the magnitude of the Cotton-Mouton rotation is about a 1000 times greater than the Faraday or Voight rotations. This rotation might not be as high in cermets, because the polarity of the particles is not expected to be as high as in the liquid phase.

What makes the above suggested assumption feasible is the fact that small single domain particles of non metallic ferromagnets have been used in magneto-optic devices. Magnetite (Fe_3O_4) particles suspended in liquid carriers did display a Cotton-Mouton effect (References 22, 23). The birefringence reported for $\lambda = 6000 \text{ \AA}$, was in the order of magnitude of 30-90 degrees for a highly diluted liquid (0.02% volume concentration) (Reference 22). In the liquid phase, however, the particles themselves rotate; while in the solid cermets, it is the magnetization that is expected to rotate. Still, there might be some very promising effects there.

2. FERRIMAGNETIC COMPOUNDS

A very important group of materials which displays high quality magneto optic properties, are the rare earth garnets. These are ferrimagnetic oxides having a quite complex cubic structure, similar to the natural mineral by the same name: $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$. In the basic and most investigated garnet, known by the name: "YIG", the silicon ions are replaced by three iron ions on one kind of lattice site (4 fold oxygen coordination) and two iron ions on a different kind of lattice site (6 fold oxygen coordination). The other metal ions are replaced by a non magnetic trivalent ion like yttrium. A crystal of the composition $\text{Y}_3[\text{Fe}_2](\text{Fe}_3)\text{O}_{12}$ is thus synthesized (Reference 11). The different parentheses show the different kinds of lattice sites that the Fe ions occupy. This is a body centered cubic lattice of complex structure, it contains 160 atoms in its unit cell which is $12.4 \text{ \AA}$ in size.

YIG has been extensively studied and broadly used in microwave and magneto optics technologies. YIG is very transparent in the microwave region (Reference 24) and in the near infra red; its so called "IR window" extends to the 1μ range. The transmission in the microwave region and the absorption coefficient and Faraday rotation in the visible are given in Figures 4 and 5, respectively, according to Andlauer (Reference 24).

As stated by Andlauer, (Reference 25) the onset of absorption of YIG at 1μ range results from the lowest electronic excitations of the octahedral Fe^{3+} ions. These relate to the splitting of orbital degeneracy of the $3d^5$ electrons, by the Stark effect. The unusually large absorption of this magnetic dipole transition, is due to a special mechanism of exciton-magnon-pair-creation which lacks inversion symmetry. This mechanism is typical only to magnetic antiparallel sublattices and gives an electric-dipole-like transition.

The ferrimagnetic structure of YIG is due to a super exchange interaction through the oxygen ions that causes the two sublattices to be antiparallel to each other. A net magnetic moment results, which is $1/50$ of the total magnetization ($3\mu_B - 2\mu_B$ for each formula unit). The amount of the net magnetization can be varied by substitution of the iron ions on one of the sublattices by non magnetic ions, usually rare earth ions. This causes appreciable changes in all the related properties, like the Curie temperature, the Faraday rotation and the absorption. All these different YIG "descendents" are called garnets of rare earth iron garnets (REIG). The garnets are grown epitaxially from liquid phase (LPE), usually on a single crystal of GdGa garnet (GGG). Their composition is thus easily controlled, and can be tailored according to needs. In some of the REIGs, the yttrium ion is substituted, partially or completely, by rare earth atoms such as Sm, Eu, Gd, Tb, all diamagnetic materials.

Of all the multitude of reported compositions, the Bi substitution improved considerably the magneto optical properties in the visible range, as reviewed by Scott and Lacklison (Reference 26). As an example, the wavelength dependence of the FoM of a typical Bi substituted REIG is given in Figure 6, where the sharp changes result from absorption lines of the constituents neglecting one line of Sm^{+3} at 1102 (nm). (Note the change in scale for the IR region).

If other spectral ranges are of interest, probably other substitutions can be devised to suit the needs. The values of the figures of merit for different REIG's in the near IR and in the visible are given in Table 2. As can be seen from the table, the figure of merit of the REIG's, specifically the Bi substituted ones, is extremely high in the 1μ region, while the driving fields are reasonably low.

The Néel temperature of YIG is 550°K and for GdIG is around 300°K . Above this temperature, all the magnetic order and related optical phenomena are destroyed. In some of the other garnets, another critical temperature point exists. This is the compensation temperature T_c , in which the sublattices' magnetization just balance so that the net magnetic moment is nearly zero. Many interesting devices (References 32, 35) are based on this transition temperature as will be stressed later.

3. ANTIFERROMAGNETIC COMPOUNDS

The transition metal fluorides like MnF_2 , FeF_2 , CoF_2 , NiF_2 , and RbFeF_2 also have a noticeable magnetic birefringence, i.e., a large Faraday rotation (Reference 36). They have a distinct magnetic ordering transition which is controlled by temperature as well as by magnetic field (Reference 37). The fluorides' limitations for use in MO devices rise from the fact that this controllable magnetic birefringence is masked by a much larger natural birefringence. This natural birefringence might be minimized by using polycrystalline bulk or films. The quantitative available data is summarized in Table 3. The Néel temperature of the fluorides ranges around 70°K . Most of the recent work was performed in the visible and below the Néel temperature, i.e., at low temperature (20°K). This is probably the reason why the fluorides have not been put to applications like the garnets, regardless of their transparency and high Faraday rotation. However, their magnetic birefringence of the same order of magnitude as the garnets' and the sharp magnetic transition at T_N , might still make them appealing for further investigations.

TABLE 2
MAGNETO OPTIC CONSTANTS FOR GARNETS IN THE VISIBLE AND NEAR IR

Material	λ [nm]	θ_F [deg/cm]	α [cm ⁻¹]	FoM θ/α [deg/dB]	H[oe]	Ref.
YIG - Y ₃ Fe ₅ O ₁₂	1200	240	0.069	800		2
YIG - Y ₃ Fe ₅ O ₁₂	1150	260			500	27
Bi ₁ Sm ₂ Fe ₃ 8Ga ₁ 15O ₁₂	1150	1956	0.500	900		26
Bi _{1.63} Tm _{2.3} Fe _{3.8} Ga _{1.2} Pb _{0.01} O ₁₂	1152	1300	6	50	2000	33
Gd ₂ BiFe ₅ O ₁₂ (single crystal)	1150			1000		30
Gd _{4.45} Y _{2.55} Ga _{1.1} Fe _{3.3} O ₁₂	1150	1200	2.300	120		31
Tb ₃ Fe ₅ O ₁₂ (single crystal)	1150	2300	4	100	2200	28
Bi _{1.55} Yb _{2.1} F _{3.8} Gd _{1.1} Pb _{0.06} O ₁₂	1152	1800	7	60	6000	33
YIG - Y ₃ Fe ₅ O ₁₂	560	3500	1150	0.7		26
Gd _{3-x} Bi _x F _{5-y} Ga _y O ₁₂	514	3400	2800	0.28		32
Bi _{1.1} Sm _{1.9} Ga _{1.1} Fe _{3.9}	560	30000	1150	7		34
(BiTmFeGa) ₃ O ₁₂	560			4.6		26
P _{0.4} Ga _{0.6} Yb _{0.4} Bi _{0.0} Fe _{3.8} Al _{0.3} O ₁₂	633	13000	600-1400	5		30

TABLE 3
MAGNETO OPTIC CONSTANTS FOR TRANSITION METAL FLUORIDES

Material	λ_{meas} [nm]	θ_F [deg/cm]	α [cm ⁻¹]	FoM (θ/α) [deg/dB]	T _{Néel} [°K]	T _{meas} [°K]	H _{meas} [oe]	Ref.
MnF ₂	633	6825			66.9	20	2K	36, 63
NiF ₂	633	9100			7.5	20	10K	36
CoF ₂	633	1137			38	20		36
FeF ₂	633	4550			85	20		36
RbFeF ₂	625	12000 (Cotton-Mouton)	2	1380	102	77	2K	39

The transition metal oxides like MnO , CoO , NiO have also been investigated (References 38, 40, 41) for their magneto optic properties. They do not possess a crystalline birefringence. Usually the oxides are antiferromagnets at low temperatures and display a sharp magnetic disordering transition at the Néel temperature. This transition is accompanied by a more gradual decrease in the birefringence. Typical values are summarized in Table 4. As can be seen, the overall size of the effect is of the same order of magnitude as in the garnets or fluorides. The transition temperatures are more convenient, mainly in NiO ($515^\circ K$). Though the transparency in the visible is lower, there still is quite a noticeable effect. No magneto optic data for NiO in the infrared has been disclosed so far. The dependence of the birefringence in MnO , on magnetic field, has been investigated (Reference 40) and no such dependence had been detected. A single domain structure has been obtained throughout the crystals by a special cooling technique (Reference 41).

$FeBO_3$ has been of interest because of its high figure of merit in the visible, but like the fluorites possess a "natural" birefringence (Reference 25). A considerable amount of work has been done on the ferromagnetic oxide Fe_2O_3 (Hematite) (References 43, 44). This oxide has a Morin transition, i.e., a transition from an antiferromagnetic state to a ferromagnetic state. The Faraday rotation has a very distinct change in sign, jumping from 640 deg/cm to -2000 deg/cm . Near $265^\circ K$, the exact temperature of the jump is controlled by a magnetic field.

4. FARADAY EFFECT IN MAGNETIC SEMICONDUCTORS

Some magnetic semiconductors have been investigated lately as possible optical device material. The results of these are summarized in Table 5. Though the Faraday rotations are quite large, the high absorptions and low temperature ranges make them less attractive for straight forward applications.

TABLE 4
MAGNETO OPTIC CONSTANTS OF THE TRANSITION METAL OXIDES

Material (Single Crystals)	λ_{meas} [nm]	θ_F [deg/cm]	α [cm ⁻¹]	FoM (θ/α) [deg/dB]	T_{Neel} [°K]	T_{meas} [°K]	Ref.
CoO	633	28800			285	250-310	38
NiO	633	8400	400	21	515	400-550	41
MnO	769	1222			122	90-130	40
FeBO ₃	460	2000	800	.6			25, 42
FeBO ₃	514	2200	20	25	348		25
Fe ₂ O ₃	1150	640			$T_M=265$		43

TABLE 5
MAGNETO OPTIC CONSTANTS FOR VARIOUS SUBSTANCES

Material	λ_{meas} [nm]	θ_F [deg/cm]	α [cm ⁻¹]	FoM (θ/α) [deg/dB]	Temp [°K]	Ref.
CdCr ₂ Se ₄ (semiconductor)	860			5.0	20	45
CdCr ₂ Se ₄ (semiconductor)	1050			1.8	20	45
CdCr ₂ Se ₄ (semiconductor)	680	$4.0 \cdot 10^5$				8
EUSE (semiconductor)	755	$1.4 \cdot 10^5$	$2 \cdot 10^3$	720	4.2	2
CrBr ₃	493	$2.0 \cdot 10^5$	$2 \cdot 10^3$	23	1.5	2

SECTION III

MAGNETO OPTICS APPLICATIONS AND DEVICES

1. THE OPTICAL SWITCH

The straight-forward application in the transmission MO mode is an optical switch. This is shown in Figure 7.

The analyzer's angle, β , relative to initial polarization can be made equal to the Faraday rotation $\theta_F d$, so that for one magnetization direction ($+\theta_F d$) the transmitted light will be extinct. For the other direction ($-\theta_F d$), the transmitted intensity will be

$$I_t = I_0 e^{-\alpha d} \sin^2(\beta + \theta_F d) \quad (1)$$

In practice this is not a very efficient device. If we assume a very large Faraday rotation $\theta_F d$ of 20° , and disregard all the other possible losses, the transmitted light in the "on" position will reach only 40% because of the " $\sin^2$ " behavior of the analyzer.

An optimum thickness can be computed from Equation 1. It is dependent on the figure of merit ($\frac{\theta}{\alpha}$) of the switch material:

$$d_{opt} = \frac{1}{2\theta} \tan^{-1} \frac{4\theta}{\alpha} \quad (2)$$

From Equation 2, the transmission can be calculated. Losses by reflection and absorptions by the polarizing elements must be taken into account. The result of such a calculation for a garnet film with a figure of merit of 6.3, is a transmission of 5% only (Reference 26). This can be increased to 13% by using polarized light and omitting the polarizer, but still is quite low. The optical switch setting has been used for MO display (Reference 26) on a microscopic scale, using magnetic bubbles techniques and others (Reference 47).

An attempt at making a large scale optical switch in the IR (10600 nm) has been reported recently (Reference 16). A large hot pressed sample of CdCr_2S_4 (Table 1), 3750 μ thick, produced a Faraday rotation of 45° , in a field of 3.5 K oe. A rotation of 45° naturally increases the theoretical optical efficiency to 100% as can be seen from Equation 1. The experiment had to be carried out at 77° K and the difficulty encountered by the fabricants was the uniformity of their large sample.

The required magnetic field (3500 oe) was provided by liquid nitrogen cooled solenoids with 2400 turns. Another report (Reference 46) used YIG single crystals $\langle 111 \rangle$ at 1150 nm, for $\beta = 45^\circ$. A magnetic field of 900 oe was produced by a couple of cylindrical SmCo permanent magnets (3 mm thick) or by a closed circuit magnet.

2. THE LIGHT MODULATOR

The Faraday effect has been exploited for constructing light modulators. The basic arrangement of Figure 7 is used with one modification: the analyzer angle β is oriented at 45° to the polarizer. This is the steepest part of the " $\sin^2$ " curve and thus the most sensitive and efficient.

The relative changes in intensity can be shown to be:

$$\frac{\Delta I}{I_0} = e^{-\alpha d} \sin 2\theta_F d \quad (3)$$

Because of the linear dependence of I on $\sin 2\theta_F d$, large changes in the transmittance, ΔI , can be achieved (60-70%) with relatively small Faraday rotations (Figure 8). Note that no complete extinction is achieved. For Bi substituted garnets, the saturation field is lower than 100 oe and the magnetization can be driven by a coil. Almost any frequency of modulation, in the low radio ranges, can be achieved. The limitations on frequency are the inductance of the coil and some hysteresis losses that might heat up the sample. This high frequency range can give an idea about the amount of time required for switching. The light modulators

have been used in double beam spectrometers (micron region), wave guides (References 33, 48) and many other devices replacing mechanical choppers. Another intensity modulator is based on the reflection mode, i.e., on the Kerr magneto optic effect.

The Kerr effect has been enhanced by interference (Reference 34) and by multiple reflections (References 49, 50) so that it has been used as an intensity modulator (Reference 51) but the magnitude of changes in intensity are in the order of 10^{-3} and so do not seem to have much value for applications.

3. MAGNETO OPTIC MASS MEMORIES

Each of the two previous described settings has been used as "read-out" techniques for computer mass memories. One of the methods used for the information storage is the thermomagnetic writing (Reference 32). The information is being coded with the two directions of magnetization perpendicular to the film; these are being used to represent 0 and 1. In mass memory, a pulsed laser beam is directed by an optical deflector (see next section) toward the required cell heating it up close to its magnetic-order temperature. A pulsed magnetic field simultaneously determines if the cell will be magnetized to "1" or "0" direction. Only the heated segment will vary its magnetization. In order to be able to apply small magnetic fields (80 oe), it has been suggested to use garnet films near their compensation temperature, so that low magnetization and low demagnetization energies prevail. This also reduces the energy requirements for the "writing" laser. Very small temperature changes are involved, as well as faster writing rates. The resetting time reported is 50μ sec.

$(\text{GdBi})_3(\text{FeGa})_5\text{O}_{12}$ garnet has been used for this purpose, enabling an easy "read out" (Table 2), by intensity changes in the transmitted beam due to the Faraday rotation. The thermomagnetic writing technique has been pushed to even lower energies as far as $1\mu\text{W}$ for the heating laser, by using a sandwich of the magneto optic material and a photoconductor. The photoconductor is driven by a pulsed electric field; thus, when illuminated,

it produces a current in a given direction. This current generates the necessary heating and the magnetic field.

In all the different "writing" techniques, most of the "read out" is performed by the Faraday effect using a polarizer and analyzer in the "modulator" configuration. An optical contrast of 1:2 is reported. The great advantages of this "reading" are its nondestructive character and its speed. Some "read out" systems are using enhanced Kerr effect techniques (Reference 52).

4. MO DEFLECTORS

When the garnet sample is not saturated in one direction, but has a strip domain configuration as in Figure 9, alternately parallel or anti-parallel to the light path, then it acts as a diffraction grating (Reference 53). In order to achieve a complete zero in the center of the diffraction pattern, the Faraday rotation $\theta_F d$ has to be 90° . All the light is then deflected to higher orders (81% to the first order) (Reference 26). The intensity of the diffraction of the n^{th} order is given by:

$$I_{(n)} = I_0 \left(\frac{2}{\pi n}\right)^2 e^{-\alpha d} \sin^2(\theta_F d) \quad (4)$$

As already shown, such large rotation of 90° cannot be attained in practical materials. If the optical efficiency of a light deflector is defined by:

$$\eta = \frac{4}{\pi^2} e^{-\alpha d} \sin^2(\theta_F d), \quad (5)$$

an optimum thickness can be computed which is found to be proportional to the intensity of the first order and is given by:

$$d_{\text{op}} = \frac{1}{2\theta} \tan^{-1} \left(\frac{2\theta}{\alpha} \right) \quad (6)$$

The optimum thickness and the efficiency are directly related to the Figure of Merit of the material. The intensity at the 0th diffraction order is given by:

$$I_{(0)} = I_0 \cdot e^{-\alpha d} \cos^2(\theta_F d) \quad (7)$$

Assuming $\frac{\theta}{\alpha} \approx 7$, for a practical bismuth substituted garnet, these values will yield approximately:

$$\eta = 4.5\%$$

$$I_{(0)} = 9\%$$

$$d_{op} = 16 \mu m$$

and an overall attenuation of 80% will prevail. The angle of deflection of the first order diffracted light is given by:

$$\sin \gamma = \frac{\lambda}{2t} \quad (8)$$

where t is the width of the strip domain. Because of demagnetization energy considerations, a strip domain pattern can be achieved, in which the width of the strip is about 1/10 of the sample thickness. This means in our example that $t = 1.6 \mu$ or a deflection angle (for $\lambda = 560$ nm) of $\gamma = 10^\circ$.

Naturally this angle will be larger for longer wavelengths. The width of domain strips can be controlled by a small in-plane magnetic field (50 oe). The deflection angle γ can also be varied gradually as for small angles it is roughly inversely proportional to the magnetic field (Equation 8). Though the obtained transparency is 20% and only half of the transmitted light will be deflected, this method still seems attractive. The simplicity of its construction, the practically zero relaxation time and its non destructive character makes it worth further investigations.

SECTION IV

SUMMARY

The principles of the different magneto optic effects have been reviewed. Little was said about the reflection mode devices and even less on the absorption mode. Both effects seem to be too small to be of interest.

The transmission mode: The Faraday and Voight effects have received a great deal of attention in the last years and were used in many different devices. The main applications reported dealt with low intensity radiation. As mentioned in Section III, some attempts to produce optical shutters for high intensity flux have been made (Reference 16). The author is not aware of extensive research on this area.

The garnets, being so versatile and having such good magneto optic properties, certainly are worth investigating in greater depth. This could require mastering the LPE growth technique and finding the suitable composition for the specific spectral range in question.

The basic YIG and GdIG with some Bi or other substitution are most likely the best starting materials for the near infrared. Both the optic switch and the light deflector seem to be promising devices in which to use the garnets. The ferrimagnetic ordering of the garnets is a great advantage for a control system as it is field and temperature sensitive. Large effects can be achieved by relatively small changes in both.

Another promising material group is the antiferromagnetic transition metal oxides. Though there is no data on their specific Faraday rotation in the longer wavelengths range, their absorption is quite low in this region and if their large Faraday rotation, known in the visible, is maintained even partially in that region, they might be promising candidates for the near IR applications. The switching properties of the anti-ferromagnetic oxides are not directly field controlled, but are dependent on internal stresses and on temperature. A single domain pattern has to be constructed and destructed to function as a switch.

More information is needed as to their optical properties in the spectral range of interest, and the possibilities of a reproducible domain pattern.

In Section II, the cermets were discussed and their possible advantage as switching elements. This seems to be a virgin field regarding magneto optic effects. A thorough basic research would be needed before looking into applications. Several groups are presently interested in this topic and more information might be available in the near future.

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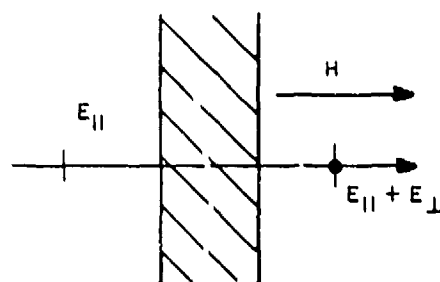


Figure 1. Polarized Light in the Faraday Configuration

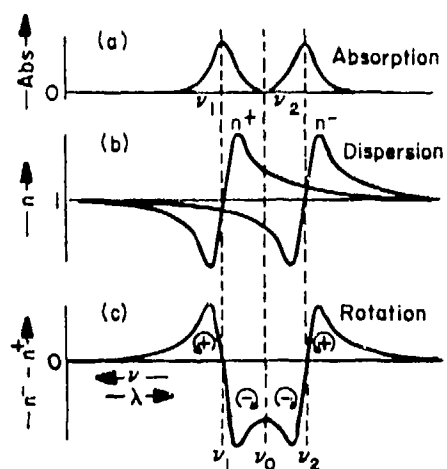


Figure 2. Magnetic Splitting of an Absorption Line Causing a Faraday Effect

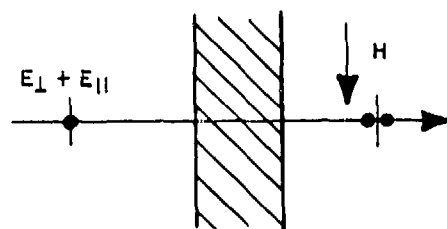


Figure 3. Polarized Light in the Voigt Configuration

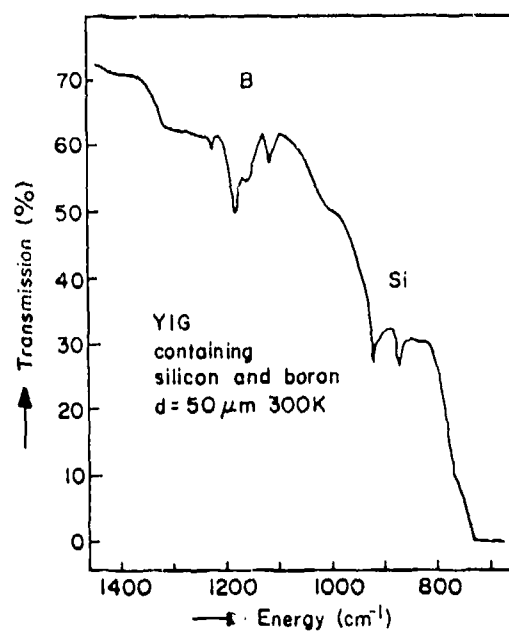


Figure 4. Transmission of YIG in the Microwave Range

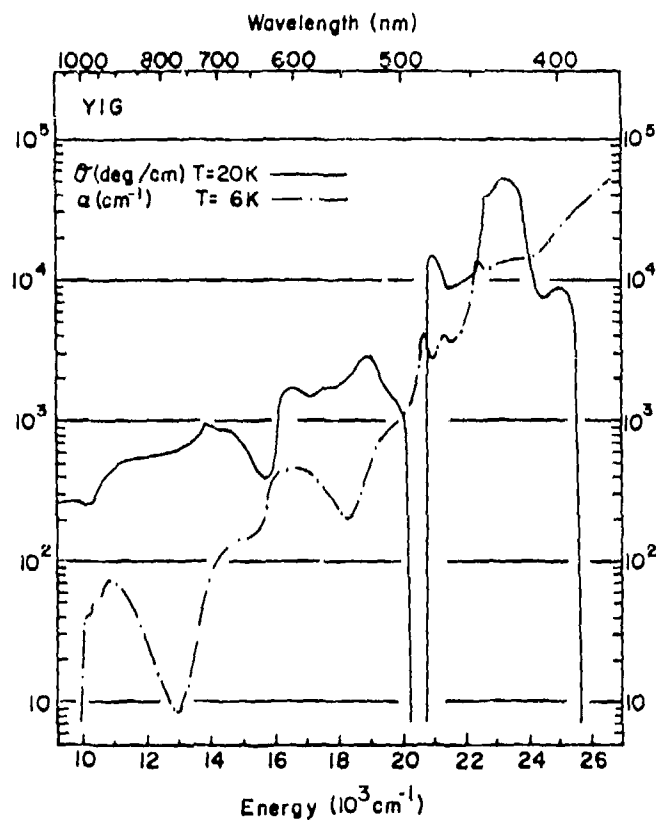


Figure 5. Optical Absorption α and Faraday Rotation θ of YIG Between 9000 and 27000 cm^{-1} , at 6 and 20K Respectively

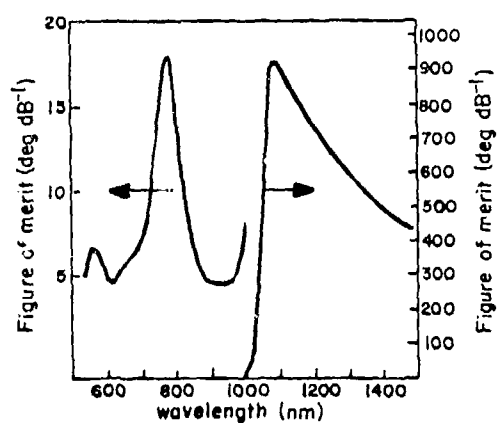


Figure 6. Figure of Merit of $\text{Bi Sm}_2 \text{Fe}_{3.85} \text{Ga}_{1.15} \text{O}_{12}$ Versus Wavelength. The Effects of the Sm^{3+} Absorption Lines Around 1100 nm have been omitted

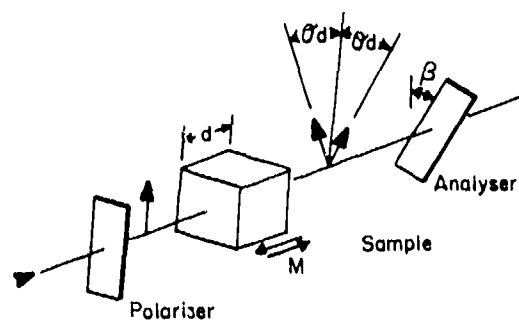


Figure 7. The Optical Switch Set-Up

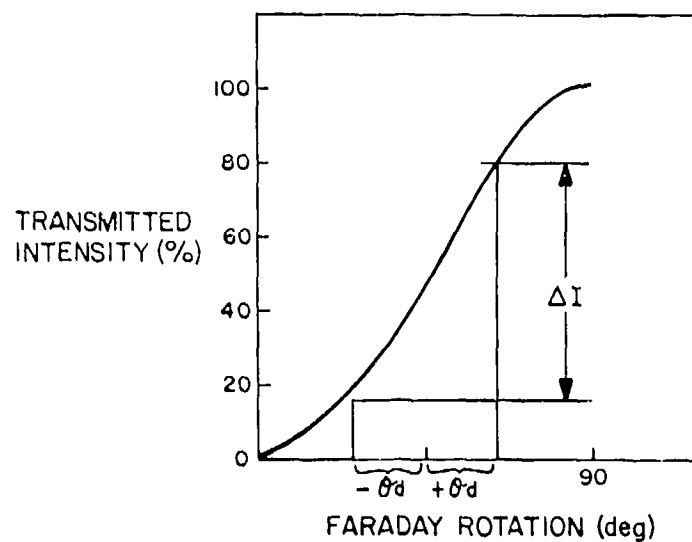


Figure 8. Transmitted, Intensity Versus Faraday Rotation for a Magneto Optical Modulator

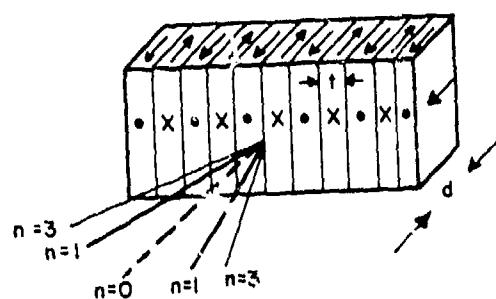


Figure 9. The Light Deflector