Thin Film Magneto-Optic Materials

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Abstract

Emergence of advanced materials has been realized by the great demands for sophisticated state devices in high technology industry. It is the era of speedy evolution of science and technology, in particular, materials processing technology, which enables us to synthesize any materials with respect to its purity and its perfection of crystal structure and shape (form) that have, heretofore not been available. The availability of ultra pure, fine raw materials, single crystals and thick/thin film materials has been largely responsible for such startling progresses that have been made in the realization of unforeseen functional devices for high technology industry. Of the functional devices such as passive and active devices, non-silicon devices are mostly passive. Piezoelectric, electro-optic, magneto-optic devices, etc. are some of the examples. In this paper, magneto-optic materials for Faraday device, which is little known, are reviewed including its processing toward practical applications.

Introduction

Late 19th century, scientific as well as technological breakthroughs have laid down the foundation of the 21st century challenges in high technology. The leading edge in the high tech industry would be strongly relied upon semiconductor, communication, information, and materials technologies. Of the advanced technologies, materials science and technology has been startlingly emerged from traditional to advanced through many breakthroughs.

There are three well known materials which exhibit electronic, magnetic, and optical behaviors. Such materials have not been only academically but also technically interested, and many functional devices have been realized based upon its fundamental properties. It would be more significant to determine the dynamic characteristics such as binary relationship : electromechanical, electromagnetic, electrooptic, and magnetooptic behaviors. Lead zirconia titanate(PZT), $LiNbO_3$, and Yttrium iron garnet (YIG) are known to exhibit a binary function property. YIG type materials exhibits magnetooptic behavior.

To examine the relationships, Figure 1 describes the binary functional relationships. It is clearly seen that the relationships enable us to study any interested binary functional properties as well as related properties.

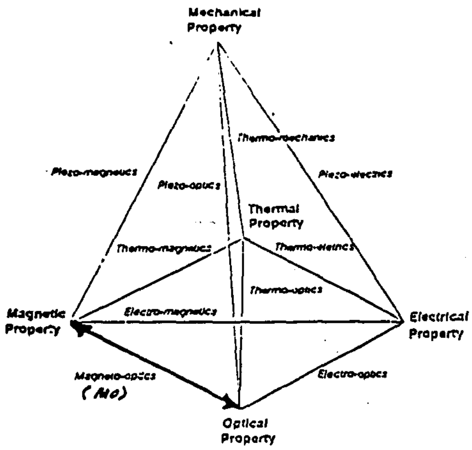

Figure 1. Relationships of physical properties of materials

In the present text it is attempted to review one of the relationships, which is relatively new, magneto-optic behavior of certain materials including its applications.

Description of Magneto-Optic Behavior

Magneto-optic behavior is known as "magneto-optical rotation", also called Faraday Effect or Kerr Magneto-optic Effect. When magnetic field is applied to a magneto-optical material through which plane polarized light is passed, there will be a rotation of the plane of polarization. This rotation, called the Faraday effect, is proportional to the length of material in the magnetic field, the strength of the magnetic field, the cosine of the angle between the magnetic field and the ray of light, and Verdet's constant, shown expression[1] below :

$$\Theta = VLB\cos\Phi\,(n^2/\lambda)(n-\lambda\, dn/d\lambda),$$

where θ =angular rotation of plane of polarization in minutes of arc., V= Verdet's constant, L= length in centimeter of material in the field, and B=magnetic field intensity in gauss, n=refractive index, and λ=wavelength. The Verdet's constant is a function of temperature, and is approximately proportional to the square of the frequency of the light ($V \propto f^2/T$). The rotation decreases with an increase in temperature. There is a time lag before this rotation after the application of the field.

Magneto - Optic(MO) Materials

During last three decades new syntheses of polycrystalline, single crystals, and thin films of oxide compounds have been extensively progressed with advent of technology of growing silicon as well as non-silicon crystals. Among the magnetic materials, rare earth (RE) doped iron garnet type[2] is known for exhibiting strong magneto-optic behavior ; $RE_3Fe_5O_{12}$, where RE^{+3}(M)=Y, Lu, Yb, Tm, Er, Ho, Dy, Gd, and Sm. Garnet type single crystals have been successfully grown by flux and CZ pulling techniques, and some of the RE garnets are shown of its magnetization (Ms) in Figure 2, from which one enables to choose based upon its transition temperatures.

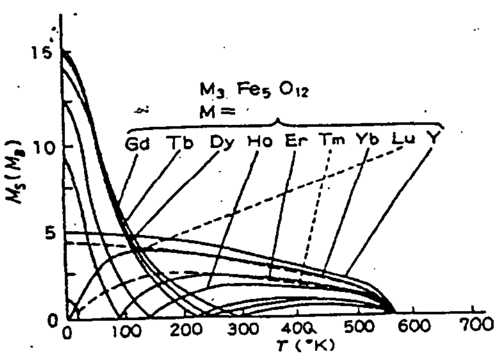

Figure 2. Ms vs T (K) of RE iron garnets

Currently, high quality YIG crystals with variety of compositions are commercially grown by Floating zone technique. It is interesting to find further refined technique of preparing thin films of the garnet compounds by LPE technique.

The thin film garnets of magneto-optic devices are more attractive and demanded for the sophisticated devices, and in Table I some of the thin films properties are listed. Table II. gives some of MO properties of Bi substituted garnet epitaxial films by LPE.[3]

Table I. Characteristics of Garnet Thin Films (LPE Method)

Composition	T= μm	FR=deg/cm	n (RI)	Δa,Å	Remark
YIG	4.08	234.9	2.2132	8.2×10^{-3}	$RE_3Fe_5O_{12}$
(YNd)IG	5.84	252.1	2.2131	0.5x "	
(YSm)IG	3.65	223.5	2.2148	-10.08x"	
(YNd)IG	3.80	114.6	2.1766	-8.0x"	$(FeGa)_5$
(YNdBi)IG	5.03	-309.4	2.2073	-32.5x"	"
(YbPrBi)IG	3.42	-767.8	2.2323	0.9x"	"
(TmNdBi)IG	5.49	-676.1	2.2243	-66.0x"	"

In Table I, a wide range of Faraday rotation with thin film compositions can be discerned, while in Table II, the temperature dependence of optical rotation decreases with increasing Tc and magnetic field for saturation (Oe) also varies in a wide range from 300 to 3000 Oe.

Table II. MO Properties of $RE_{3-x}Bi_xFe_5O_{12}$[4] @ λ=1.3 um

R	Lu	Yb	Tm	Er	Dy	Gd	Y
x	0.85	0.77.	0.58	0.30	1.07	0.40	1.31
TcK	583	581	580	574	603	585	611
$d\theta/dT$),10^{-2} degK	7.7	7.7	7.9	8.4	6.2	7.6	5.8
Hc (Oe)	3000	2500	1600	1200	1000	300	1900

In Figure 3, temperature dependence of the Faraday rotation at λ =1.3 μm for (RE, $Bi)_3Fe_5O_{12}$ films is shown. It is interesting to observe that the coefficient of RE varies considerably; Er doped is shown a little change, while Y doped shows a strong temperature dependence.

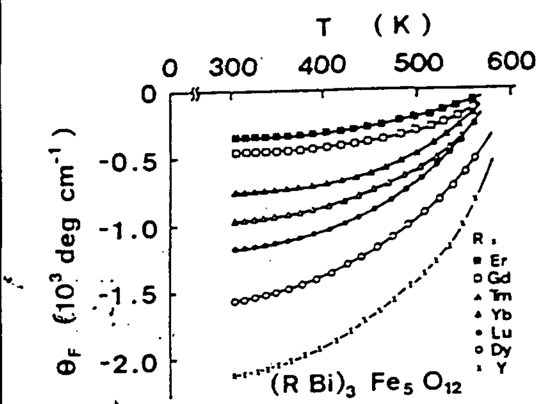

Figure 3. Temperature dependence of the Faraday rotation @ λ=1.3 μm for (RE,Bi)YIG films.[4]

Much progress has been made in Magneto-optic devices such as Faraday and Kerr effect rotators through the advancement in materials synthesis technology. In Figure 4, its absorption coefficient of flux grown garnet rotator is shown as a function of wave length, where its absorption is rapidly decreased beyond $\lambda=1\mu m$. However, Bi substituted garnet has shown further improvement in its absorption as can be realized in the figure.

Recently, thin film of MO materials by LPE has been introduced for future applications of optical integrated circuit. Such materials are listed including MO basic properties in Table Ⅱ. Although much development is needed in controlling (its properties, sufficiently high MO functional properties; @$\lambda=1.15\mu m$ 167 deg/dB were demonstrated.

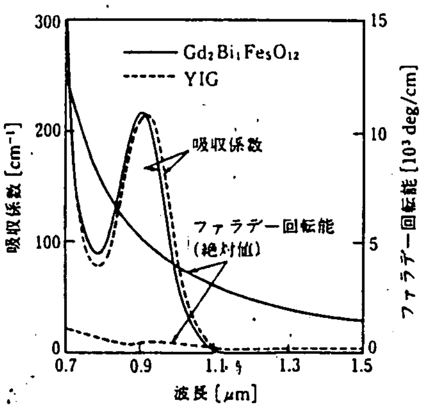

Figure 4. Faraday rotation and absorption loss of flux grown garnet single crystals.[5]

Recent breakthrough in processing of further refined and improved thin films of Bi substituted garnet compositions, Lucent Technologies, Bell Labs announced LPE Faraday rotator garnet films for optical isolator applications, as shown in Table Ⅲ.

Table III. Material Properties of the Improved films[6]

Parameter	Std. xG22 series	Latching xL22 ser.
Composition	$(BiTb)_3(FeGa)_5O_{12}$	$(BiRE)_3(FeGa)_5O_{12}$
$d\theta$ /dT(deg/℃)	-0.06	-0.09
Density(g/cc)	6.88	6.94
Expansion, α/ ℃	11x10⁻⁶	11x10⁻⁶
Saturation, H(Oe)	390	not applicable
Poling, H(Oe)	not applicable	4000
Tc (℃)	250	185

As discernable in Table Ⅲ, a breakthrough is realized; two thin film compositions do not require for poling (sustaining) field.

In Figure 5, the photomicrograph of Faraday rotator of the newly developed thin films shows the single transparent

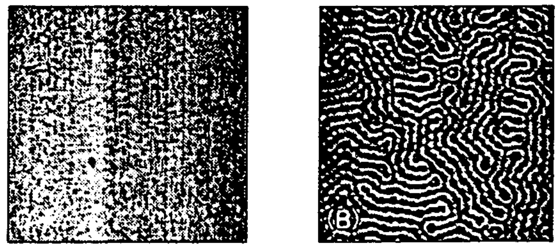

Figure 5. Domain patterns of new films.

domain with no applied magnetic field magnetic domain (A). It is remains saturated and single domain indefinitely, even in the presence of stray fields up to 100 Oe and at temperature up to 100℃ The serpentine domain structure (B) is typical for garnet epitaxial films and is readily saturated with a modest bias magnet.

Applications

In addition to microwave resonator, iron garnet type rare earth (RE) elements doped single crystals are utilized in magneto-optic device or optical window (isolator). Specifically, Bi substituted RE iron garnets $(BiRE)_3(FeGa)_5O_{12}$, are transparent in the near infrared wavelengths of telecommunications interest. They also have the property of rotating a plane of polarized light in a nonreciprocal manner.

Optical isolators are necessary for advanced optical fiber communications and precise optical measurement systems to prevent the reflected light to coherent laser sources. Relevant characteristics for isolator materials are, of course, large Faraday rotation, small temperature dependence, low optical absorption, and a low magnetic field for saturation for practical applications. An example of applications in advanced optical fiber communications is illustrated in Figure 6. In a typical confocal optical package design, all possible sources of optical reflections are assigned. The MO isolator plays an important role in the system, whereby all the reflections are blocked so that possible laser damage can be prevented. In designing the actual devices, the device package can be compact with thin film wafer and not requiring poling magnet.

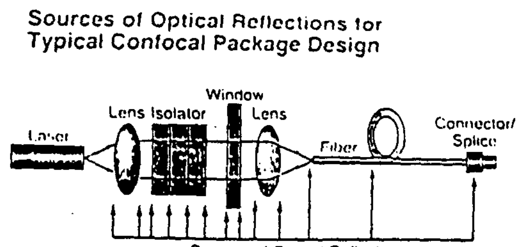

Figure 6. Sources of optical reflections for a confocal package design.[7]

Table IV. Functional Properties of XG22 and XL22 materials.[8]

Parameter	Wavelength	Wavelength
	1310 nm	1550 nm
Specific Faraday rotation	-1300, /l(deg/cm)	-900, /l(deg/cm)
Thickness for 45 rotator	380 l(um)	550, l(um)
Insertion loss (dB)	0.1	0.1
Extinction ratio (dB)	> 40	> 40
$d\theta/d\lambda$ (deg/cm)	-0.08	-0.054

The functional properties, which are required for Faraday rotator are available to the device designers. In fact, the thin films are readily procured from Lucent technologies, Bell Labs. Therefore, when combined with the correct polarizer elements, these materials can be used as an element for an optical isolator.

Recent new application of MO is memory disk (PD), CD-read/write as illustrated in Figure 7. The CD read/write is achieved based upon Kerr rotation effect. In multimedia era PD would undoubtedly be playing an important role.

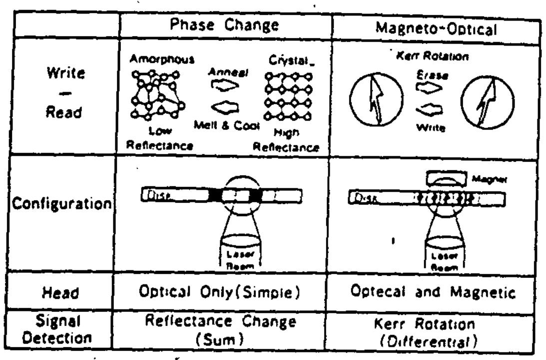

Figure 7. Magnetooptic disk memory (write/re-write).[9]

Summary

Materials science and technology have been continuously advanced to be accompanied with high tech systems. Functional materials development has been greatly emphasized : in particular, recent interests are electromechanical (piezoelectric), electrooptic, magnetooptic materials.

Magnetooptic materials are most recent interest in high tech systems such as optic fiber transmission and PD in multimedia system. Materials science has led its development, and the applications are realized. Therefore, it can not over emphasizes to continue materials science and development toward the 21st challenge.

Reference

1. C. F. Hix, Jr. and R. P. Alley, *Physical Laws and Effects*, John Wiley & Sons, Inc., New York, 1958, pp 281.
2. Take Takei, *Theory and Applications of Ferrites*, Maruzen Co., Tokyo, Japan, 1960, pp 282.
3. T. Okuda et al., J. Apple. Phys., 55, 2176 (1984).
4. K. Machida, et al., J. Appl. Phys., 61, #8, 3256-3258 (1987).
5. T. Hiraga, *Ferrites*, Maruzen Co., Tokyo, Japan, 1961, pp 246.
6. C. D. Brandle and S. J. Light, *Adv. Res. Products*, Lucent Technologies-Bell Labs., Feb. 1996.
7. W. L. Emkey, *Video/Access Network Architecture and Fiber Optic components*, Proc. Fber Optic Communications Conf., Korean Telecom/Lucent Technologies-Bell Labs., Mar. 1996.
8. C. D. Brandle and S. J. Light, ibid.
9. Ryoichi Imanaka, *Optronics* (Photonics-Japan), 12, #168, 1982, 123~138