# *Exploiting MO Crystals and Faraday Effect in Magnetic Sensing*

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## Introduction:

Magneto-optics (MO) technology is believed to be far more advanced in the former Soviet Union when compared to the US. This is evidenced by the existence of factories geared for the production of Yttrium Iron Garnet (YIG) wafers. The potential advantages to MO Crystal Technology over other magnetic sensing technologies are (1) light weight and compact construction, (2) low cost, and (3) low power implementation concepts.

A candidate sensor consists of a low power laser, polarizers, sensors, and housing. Such components can be combined in a fashion to keep weight down by using light-weight construction in the housing.

Cost can be reduced by mass producing components. Tera Research purchased a wafer for evaluation. This wafer yielded over 100 crystals for individual use. When mass produced, the engineering recurring cost will be far less. The other components will be commercial off the shelf parts that when ordered in bulk quantities will be inexpensive as well.

The required power is determined by the laser supply, processing computer and any necessary signal generators. The first two can easily be manufactured from low power semiconductor components. The latter is a separate engineering task which can exploit low data rates and low background noise transponder frequencies or modulations.

## Magneto-optical properties:

By working closely with the wafer manufacturer in Moscow, we can custom order wafers with unique and valuable specifications. The magnetometer theoretical limits for sensitivity are better than a milligamma. One milligamma = $10^{-8}$ Gauss = 1 picoTesla. This is below natural background noise levels which typically are around one gamma = one nanoTesla. The details outlined here will be presented in more detail at the 46th Magnetism and Magnetic Materials conference in Seattle, Washington in November, 2001. [1]

The iron garnet wafers we use consist of a Gadolinium Gallium Garnet GGG ($Gd_3 Ga_5 O_{12}$) substrate with epitaxially grown RBiFeGa Magneto Optic (MO) thin films (R = rare earth element.). These wafers possess the fundamental properties outlined in Table 1 on the next page.

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**Abstract**

**Subject Terms**

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**Table 1: Properties of YIG wafers**
**$\mu$ Mo = 0 … 1000 G**
**specific Faraday rotation $\Theta$ F = 2.3 grad/$\mu$m = about 2° per micron**
**absorption coefficient: a = 0.35… 0.40 dB/$\mu$ m**
**MO figure of merit $\Psi = 2\Theta$ F/$\alpha$ > 10 grad/dB = 9° per dB**
**Magnetic domain wall velocity = 200 … 2800 m/s**
**coercivity < 0.1 Oe = 0.1 Gauss**

Wafers can be grown with characteristics favoring sensitivity or image processing depending an the application of interest.

Combined with properly chosen epitaxial growth parameters to increase transparency, the Bi substitution yields high Faraday effect producing high-contrast domain structure patterns. Domain wall shifts from external magnetic fields normal to the FVF plane result in change of total Faraday signal, and visualization of the presence / characteristics of sample objects containing ferromagnetic structures with image processing.

The Faraday effect is the rotation of the polarization of electromagnetic radiation propagating through the Yittrium Iron Garnet (YIG) crystal lattice parallel to a bias magnetic field. The rotation is directly proportional to the field strength. By employing Bismuth atoms in place of Iron in the crystal sublattice, the Faraday effect, may be enhanced [2]. Studies have shown that, although extreme sensitivities to minute magnetic fields are possible, the Faraday effect is sensitive to thermal fluctuations and hysteresis, or coercivity. The parameters described above are specifically chosen to minimize these effects.

Sensitivity is hampered by limitations in mobility of the magnetic domain walls. Dr. Andre Chervonenkis[1] points out that to increase the domain wall mobility, one must not use fast relaxing rare earth ions such as Sm or Pr. Instead one ought to use rare earth ions with low relaxation time such as Lu, La, or Dy. The increased mobility achieved by incorporating these elements yields a faster response to external field changes and enhanced Faraday effect. The maximum domain wall velocity can reach velocities of up to 3000 m/s by either utilizing the (210) orientation of the Substrate, or by introducing an additional in plane magnetic field. In either case, the so-called *orthorhombic anisotropy* is created. Linear birefringence has also previously been cited as a source of instability in such crystals[3]. In our case, there is no problem with linear birefringence with these garnets, since this structure is cubic.

To reduce thermal sensitivity, one can compromise the composition of garnet between RE ions possessing positive and negative inputs to the thermal effects coefficient. When these components counteract each other, the result is a thermally stable compound.

Coercivity has in some cases proved problematic as well. To decrease coercivity, Chervonenkis has the ability to produce high quality garnet films (one or zero dislocation per 1 cm) and large thickness of the film (if it possible considering the restrictions in composition). The ability to achieve all of the above design implementations will yield an extremely useful and versatile material for a wealth of applications.

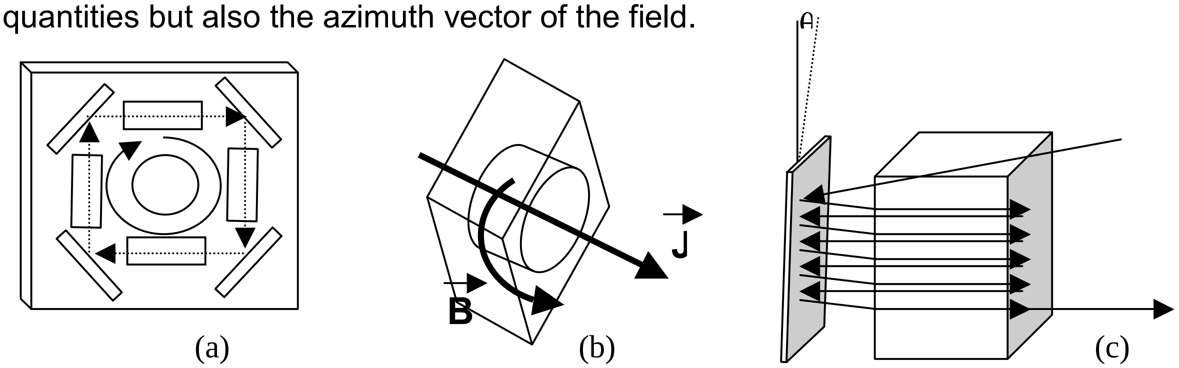
**Putting the theory to work:**

This technology may be implemented in constructing devices for sensitive magnetic field measurements, or for precise magnetic characterization and sophisticated optical imaging,

Extreme magnetic field sensitivity allows magnetometers to not only measure minute quantities of magnetic field, but to measure typical fields from larger distances. Constructing a sensitive magnetometer utilizing YIG crystals relies on the components in the standard equation for the Faraday effect: $\theta_F = kBl$, where $k$ is the Verdet constant, $B$ is the magnitude of the magnetic field, and $l$ is the path length in the crystal lattice. By increasing the effective path length, we can theoretically measure smaller field values.

Since the optical path is along the crystal lattice and parallel to the bias field, crystals may be oriented so as to enhance the Faraday effect. This can be accomplished by splitting the beam into multiple beams that travel parallel to one another through the lattice or by inserting mirrors for multiple traversals within the lattice structure (see Figure 1). The enhancement of the Faraday effect produced by multiple passes through a crystal lattice can only be accomplished in case of transparent crystal and only so near IR, but it's not proved viable in case of visible light. These techniques can be implemented into a more standard magnetometer design utilizing lasers, polarizers and optical sensors[4].

We really are able to measure not only magnetic field with great sensitivity but also typical fields from larger distances, in particular to measure not only the quantities but also the azimuth vector of the field.



(a) (b) (c)

**Figure 1: We anticipate that it may be possible to measure minute currents in conductors by placing crystals in aligned parallel to the magnetic field generated by the currents (a), (b). Enhancement of the Faraday effect could result from multiple passes through a crystal lattice (c).**

We anticipate measuring changing magnetic field values from DC to 1 GHz with spatial resolution to 0.1 microns. This precise resolution when coupled with the enhanced sensitivity of these unique crystals will provide a key component for a wealth of applications.

**Applications, current and future:**
Applications already being pursued from for the exploitation of this technology are latent marking of articles (including concealed weapons), security (anti-counterfeit) testers and flaw detectors in magnetic and nonmagnetic metals.

This technology also lends itself to arraying sensors in efforts to heighten sensitivity in preferred directions, gradiometry to subtract out background components, and signal processing techniques to further enhance the range of detection.

The MO crystal design specifications are entirely compatible with additional low power devices and subsystems. These include solar powered sensors, rechargeable power supplies, and long life power cells.

The applications for this technology are the principal drivers for technology transfer and new concept development. With recent events in the USA, the need for unobtrusive or covert metal detectors useful for the detection of concealed weapons is significant. The small size of MO magnetometers hides easily in any environment. Sensors could be arrayed into door frames to provide enhanced sensitivity and wider coverage.

Monitoring the movement of battlefield troops or long range detection of large ferromagnetic objects in the air over land or sea could be possible by mounting sensors in UAV's. The small size will allow arraying sensors along the fuselage or along the wings of such a vehicle.

Sensors can be arrayed along roadsides or across bridges to monitor traffic to report speed, road usage, or traffic congestion. The compact size will allow mounting on posts or fences to mitigate potential interference or shielding from rad composite materials.

Realizing the potential sensitivities of MO technology, levels comparable to SQUID magnetometers, opens the doors to fantastic possibilities. Medical research could benefit from more portable imaging systems to diagnose illness or injury. Although such devices are quite a ways from actual development, exploitation of the sensing capabilities, mitigation of the internal and background noise sources, and the avoidance or compensation for additional thermal sensitivities will provide the foundation for realization and eventual development of such devices.

Today, MO Technology already does more than just magnetic sensing. Wafers can be designed and grown to provide images of metallic stress fractures or encode / decode personal data including photographs.

MODIS Corporation has provided images generated with crystals provided by Dr. Chervonenkis in Figures 2 and 3 below.

**Figure 2: $100 Bill Sector MO Image**

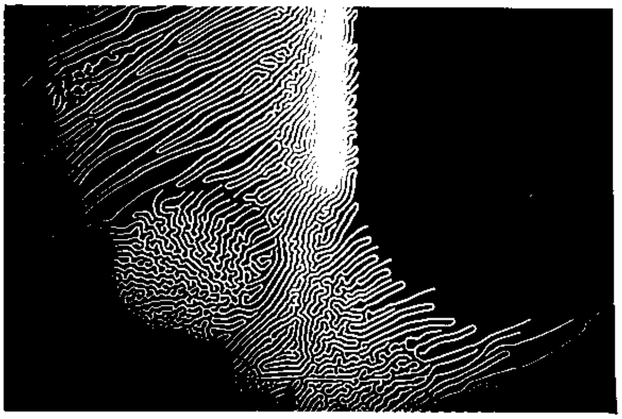


**Figure 3: MO Image of Impurities within a Steel Plate**

## Summary:

We have discussed recent advances in construction of YIG wafers consisting of GGG ($Gd_3 Ga_5 O_{12}$) substrates with thin films and have proposed some compelling applications for implementation of this technology. We have produced such wafers in the laboratory and are continuing to investigate their properties. We are currently pursuing techniques to further demonstrate the performance of these crystals in an application framework. We are also investigating ways to reduce power requirements and packaging while maintaining the discovered attributes of sensitivity, resolution, and thermal stability.

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[1] A. Y. Chervonenkis and R. C. White, to be published in the MMM Proceedings, Journal of Applied Physics in May, 2002.

[2] Komada O., Minemoto H., Ishizuka S., Application of Bismuth-Substituted Iron Garnet Films to Magnetic Field Sensors, J. Magn. Soc. Jap. 1987. Vol.11. Suppl. NS1` P. 1001-1004.

[3] Magnetic Sensors and Magnetometers, Pavel Ripka editor, Artech House, Norwood, MA, 2000.

[4] Doriath G., Gandry R., Hartemann A., A Sensitive and Compact Magnetometer using Faraday Effect in YIG Waveguide, J. Appl. Phys. 1982. Vol. 53., pp.8263-8265.