Magneto-Optical Sensors
Accurately Analyze Magnetic Field Distribution of Magnetic Materials

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Magneto-optical sensor technology offers entirely new perspectives in the field of magnetic measurement and testing.

The use of magnetic materials for manufacturing and in research has grown dramatically. The importance of magnetic measurement and testing applications will continue to rise corresponding to technological trends such as electric mobility, robotics, miniaturization and automation technologies, as well as promising magnetic materials (e.g., polymer-bonded magnets and magnetic shape memory alloys). At the same time, growing demand for sensors for use in static and dynamic magnetic measurement applications have pushed established sensor technologies to their limits. Magneto-optical sensor technology offers entirely new perspectives in the field of magnetic measurement and testing.

Magneto-optical sensors

Reliable use of magnetic materials requires accurate information about the distribution, intensity, and orientation of magnetic fields in manufacturing, quality control, and research and development. The principles of established magnetic field-measurement systems are based on different physical effects. A common feature of all these systems is the analysis of changes in electrical parameters such as voltage and current. Parameter-measurement capabilities depend on sensor design, and are altered depending on the properties of the applied magnetic field. Measured electrical values and specific material constants make it possible for sensors to determine flux density and strength of the magnetic field. For example, with Hall sensors, the Hall-effect in conductive materials (e.g., semiconductor materials) causes an electrical voltage (known as Hall voltage) that directly depends on the magnetic flux density.

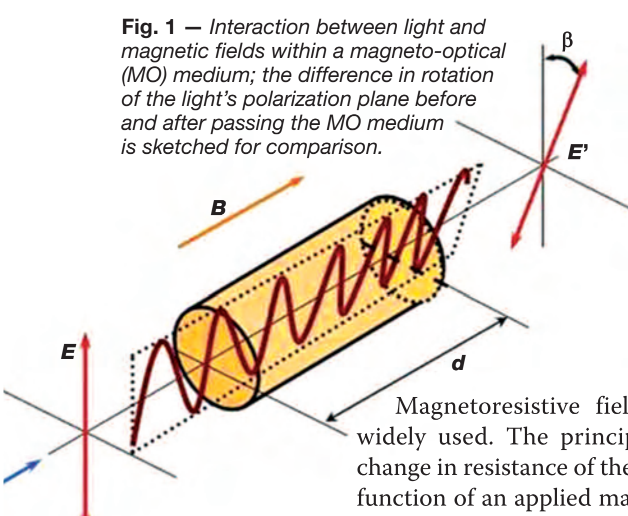

Fig. 1 — *Interaction between light and magnetic fields within a magneto-optical (MO) medium; the difference in rotation of the light's polarization plane before and after passing the MO medium is sketched for comparison.*

Magnetoresistive field sensors are also widely used. The principle is based on the change in resistance of the sensor material as a function of an applied magnetic field. Magnetoresistive sensors use the change in resistance (measured by electrical voltage) to determine the magnetic field intensity.

In contrast, magneto-optical sensors (MO-sensors) are based on the Faraday-effect instead of electrical effects to analyze magnetic fields. MO-sensors have the technical benefit of immediately obtaining measurement data directly above the surface of the magnetic material depending on the sensor size. Thus, real-time investigations of the magnet field distribution can be performed without the need for time-consuming, point-to-point scans, such as that required using Hall sensors, for example.

MO-sensor principles, characteristics, and typical applications are presented in this article.

Working principle of MO-sensors

Magneto-optical sensors are based on the Faraday-effect discovered in 1845 by Michael Faraday, who recognized that light passing through a transparent medium with an external-applied magnet field alters the light wave depending on the magnetic field. This discovery was the first indication of interaction between light and magnetism, and later led to the establishment of Maxwell's equations, which among other things, describes light as electromagnetic waves. The fundamentals of electromagnetic interactions in classical physics were created through these discoveries.

The Faraday-effect describes the rotation of a polarization plane (plane of vibration) of linear polarized light passing through a magneto-optical medium under the influence of an external magnetic field parallel to propagation direction of the light wave (Fig. 1). The rotation angle of the polarization plane is defined by the empirical equation

$$\beta = \mathbf{V} \cdot d \cdot B$$

where (referring to MO-sensors) β is proportional to the static magnetic flux density of the external magnetic field B, d is the distance the light passes within the MO-medium, and $\mathbf{V}$ is the material-specific Verdet constant used to express the material specific rotation intensity, and differs from material to material. Therefore, the Verdet constant is dependent on the wavelength of light and the MO material-specific refraction index. Rearranging the equation

Fig. 2 — *Magneto-optical (MO) sensors in various manufacturing stages: (from left to right) initial substrate, coated with MO layer, coated with reflective layer.*

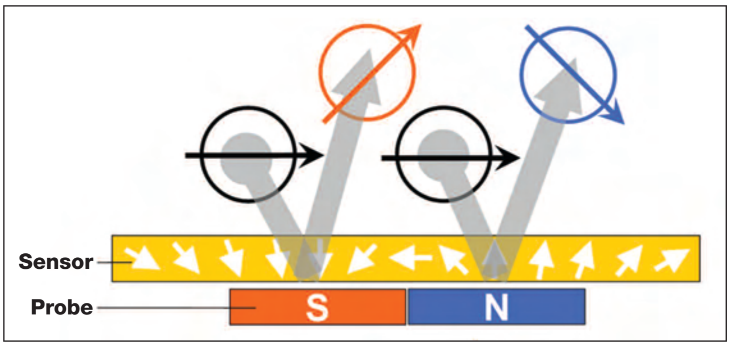

Fig. 3 — *Differences of the rotation angles depending on the magnetic field's poles of the magnetic material.*

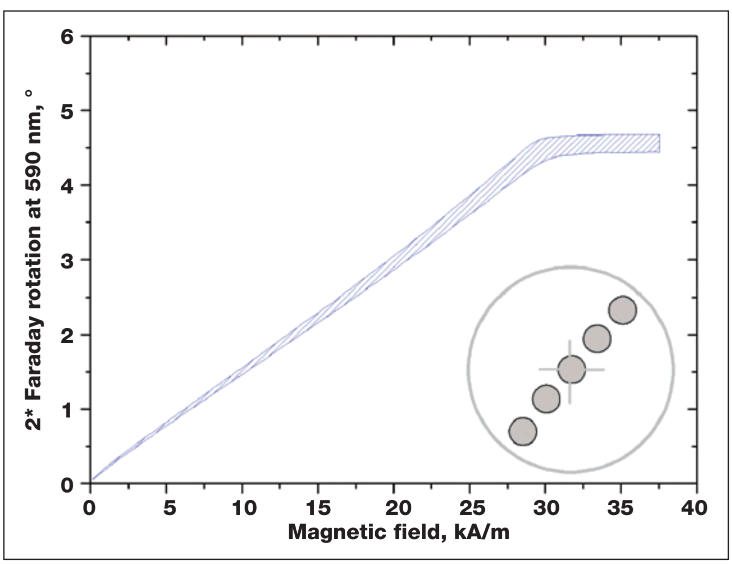

Fig. 4 — *Characteristic diagram of a MO-sensor over the entire sensor surface with a dynamic range from 0.05 to 30 kA/m.*

allows determining the external-applied magnetic field for constant boundary conditions depending only on the rotation angle. To minimize errors, it is recommended to use materials having the highest possible Verdet constants to maximize the resulting relative plane rotation, thereby maximizing accuracy of the measurement of β.

Linear polarized light consists of the superposition of a right and a left circular polarized wave having the same frequencies and phases. Light passing through a MO-medium under the influence of an external parallel magnetic field splits into two contra-rotating circular partial waves having different phase velocities. This results in a phase shift for both waves, while their frequency remains the same. The phase shift of the contra-rotating circular waves causes the polarization plane to rotate. The different intense absorption processes for both waves forms an elliptically polarized wave when the light exits the MO-medium. The resulting wave carries the magnetic-field information, which is analyzed to determine the specific magnetic properties. The resulting Faraday-rotation changes depending on the strength of the external applied magnetic field. Evaluation of the rotation angle opens the opportunity to accurately determine the properties of magnetic fields.

To provide exact mapping properties and best possible resolution, a single crystalline layer based on a special bismuth-substituted rare-earth-iron-garnet (RE-Fe-garnet) compound was developed. The bismuth within the ferromagnetic bismuth-substituted rare-earth-iron-garnet (determined by the stoichiometric azine $RE_{3-x}Bi_xFe_5O_{12}$) leads to the highest usable Faraday rotations. Besides the highly important Faraday rotation intensity, a low optical absorption coefficient is crucial to minimize the ellipticity of the polarized modulated light waves. Both Faraday rotation and absorption determine the mapping and measurement qualities of MO-sensors.

Manufacturing and customization

The magnetic "point of compensation" is typical for ferromagnetic materials. This point can be tuned for RE-Fe-garnet by precise doping. Precise substitution of diamagnetic metals within the garnet crystal lattice has a large influence on the magnetization and point of compensation. Special substitution opens the possibility to customize sensor fidelity and dynamic ranges for a specific application.

The sensor layer is manufactured using liquid phase epitaxy, which is ideally suited to create functional coatings in the micron range on a monocrystalline garnet substrate. Using the Czochralski-process, gadolinium-gallium-garnet class substrates are cut from 0.5-µm thick wafers, providing the highest crystal qualities and the most precise crystallographic orientations. For epitaxial manufacturing of high-quality sensors, having a defect-free mechanically and chemically polished garnet with high surface purity is as important as having stable, reproducible manufacturing conditions. Therefore, the liquid phase epitaxy process is the best deposition method to obtain thin layers for use in an MO-sensor.

The sensor is further processed by applying both a mirror-like and protective coating to ensure long-term functionality (Fig. 2). MO-sensors can be customized in various geometries and sizes up to 3 in. diameter for use in specific applications.

Visualization of magnetic fields

Magneto-optic sensor technology is a mapping method for magnetic field analysis and visualization. To optically visualize magnetic fields, the MO-sensor is placed in direct contact with the magnetic material of interest and illuminated with polarized light. Light passes through the transparent MO-sensor layer, is reflected by the mirror coating, and passes through the MO-sensor layer again. The plane-rotated resultant light from the sensor is detected and can be analyzed with respect to Faraday-effect proportional to the double-passed layer thickness.

Based on different rotation angles of each wave, an intensity-contrast image is created via the analyzer-polarization filter module, which represents an exact map of the magnet field distribution of the investigated material (Fig. 3). The result is an optical image representing a two-dimensional cut through the magnetic stray field of the test object. Mapping of the magnetic properties along the x-y plane of the magnetic field of the test object is performed in real time and simultaneously over the entire sensor size. Thus, both static and dynamic changes in the magnetic field can be visualized and analyzed.

Illumination and detection taking place on the same side of the sensor provides a technical benefit where the functional side can be used for quick, easy test object positioning.

Resolution and saturization behavior

What resolution can be achieved for visualization and analysis of magnetic fields? MO-sensors (due to technical limitations) can be saturated depending on the strength of the external applied magnet field. Different sensor types with different dynamic ranges are available to perform specific tasks optimally. The detectable magnetic field strength range is 0.05 to 500 kA/m (0.6 to 6000 Oersted). Magnetic field strengths outside the specific sensor specifications cannot be visually differentiated due to their hysteresis graph (Fig. 4).

MO-sensor systems, such as CMOS-MagView, can perform lateral resolutions up to 1 µm. Visualization of a hard drive disk (HDD) platter clearly demonstrates the resolution capabilities of MO-sensors (Fig. 5), which also allow investigations of single bit-structures. The size of the magnetically stored binary zeros and ones (yellow-green-contrast in the upper left area of Fig. 5) are in the size range of 1 µm.

Industrial applications

Integrated into the CMOS-MagView (a measuring set-up of CMOS digital camera and analysis software), MO-sensors can be used for quality management of widely used industrial magnetic materials as NdFeB, SmCo, AlNiCo, and hard ferrite. CMOS-MagView is capable of visualization, analysis, and characterization of magnetic materials or products such as:

- Plastics-bonded permanent magnets
- Encoders
- Steel alloys
- Magnetic stripe cards
- Magnetic ink (e.g., on bills or fraud-protected documents)
- Thin sections of magnetic minerals
- Domain material such as magnetic shape memory alloys

Quick and reliable in high resolution

In each application, the sensor is adjusted and customized to achieve optimal visualization of the magnetic field. In other applications, MO-sensors can be integrated into a microscope objective to be used directly with polarization microscopes to map magnetic structures with additional optical zoom.

The main field of application is the "goods-in and goods-out" control of permanent magnets.

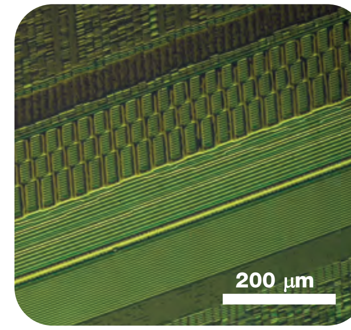

Fig. 5 — *Visualization of individual local magnetizations of stored bits on a hard drive disk (HDD) platter using an MO-sensor under a polarizing microscope.*

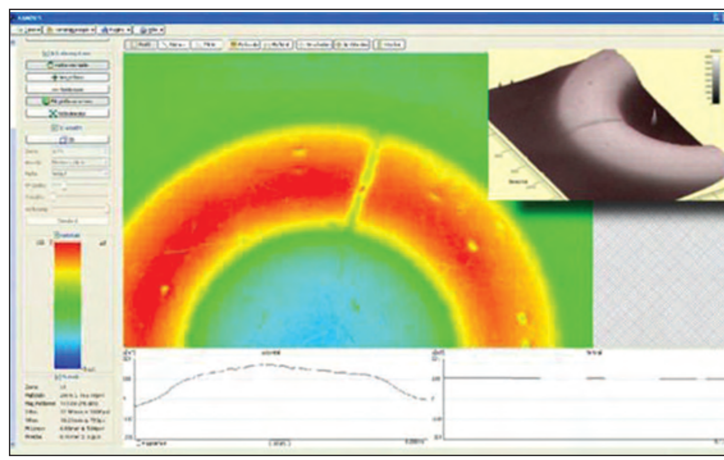

Fig. 6 — *CMOS-MagView software analysis of inhomogeneities of a ring magnet.*

Magnets with exactly defined magnetic properties, such as high homogeneity, are needed due to multiple applications. Measuring these quality parameters can be performed with the help of MO-sensors optically subjective or by using a CMOS-MagView measurement set-up including CMOS-MagView analytical software, even automatically if desired (Fig. 6). The same investigation can be performed not only just for permanent magnets, but also for magnetic encoders (Fig. 7) and magnet stripe cards.

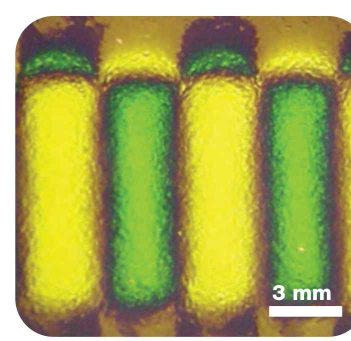

Fig. 7 — *Magneto-optical recording of linear encoder band.*

Magnetic encoders use a barcode-like structure to determine the relative and absolute position of a working unit while operating. The working unit and its sensor recognize north-south orientations as it passes by, as well as a sinusoidal course of intensity within each north or south pole. From these data, a computer calculates the position of the working unit. Information about the changes in distance between north and south poles is necessary to perform these calculations. Magnetic encoders have to be analyzed precisely to provide functionality and accuracy for long term use.

Fig. 8 — *Magneto-optical recording of a mono audio tape showing a clearly visible "erasing" imprint by the writing-head and deleted sector; track height = 3 mm.*

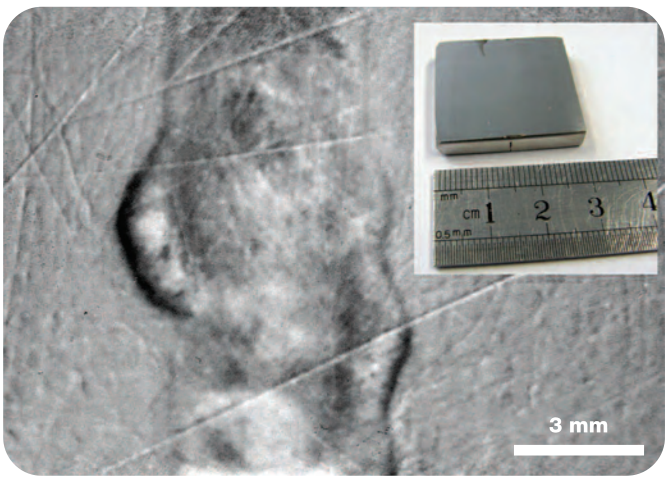

Fig. 9 — *Welding seam of a polished test sample.*

Magnetic stripe cards have similar demands on the quality of the magnetic material. A barcode-like structure is used to store data on the card. Because the information is of a highly sensitive nature (e.g., name and address of holder) there is also a need to manage the quality of the magnetic material, and to investigate defective magnet stripes.

Forensic and nondestructive testing applications

Because MO-sensors are capable of visualizing and analyzing wide areas immediately, the systems are used increasingly in forensic applications. Specific tasks include investigations of manipulated magnetic-data carriers like audio and video tapes (Fig. 8), visualization of magnetic safety seals on fraud-protected documents and magnetic ink (used on most currency banknotes), and revealing hidden welding seams and investigating their quality (Fig. 9).

Even mechanically removed (ground) serial numbers on steel (on weapons and car parts, for example) can be visualized using MO-sensors (integrated in the measurement system CMOS-MagView) within seconds (Fig. 10). MO-sensors take advantage of the effect of creating magnetic deformation martensite by punching serial numbers into austenitic steel. The deformation martensite spreads much deeper than the original serial numbers. Therefore, working the surface by grinding reveals both changed martensite microstructure and the punched structure. In applications like these, nondestructive magneto-optical material testing is capable of replacing conventional techniques like etching-methods or use of magnetic particle testing.

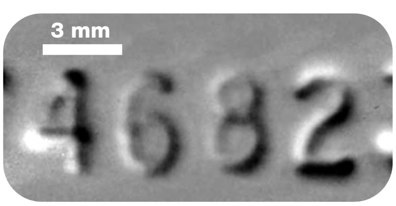

Fig. 10 — *Reconstructed serial number on a gun with the help of magneto-optical sensors.*

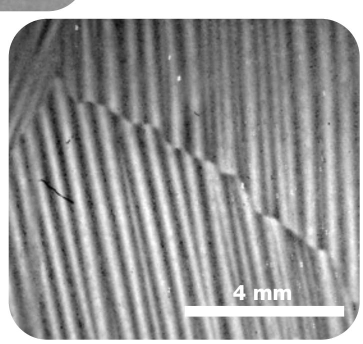

Fig. 11 — *Magneto-optical domain structure recording of a steel alloy.*

Future research prospects

MO-sensors offer a wide variety of application opportunities for research tasks regarding magnetic domain analysis and investigation. A magnetic domain structure is characterized by neighboring areas of different magnetization directions, also known as Weiss domains (Fig. 11). The magnetic moments within a Weiss domain are parallel to each other, creating locally saturated magnetization. For a variety of research and manufacturing tasks—mainly in the fields of magnetic storage and sensor techniques—these investigations are crucial because the saturation grade within a Weiss domain, as well as the shifting movement of domain walls, is a functionally determining factor. With the help of MO-sensors, this information can be determined, analyzed, and graphically visualized (Figs. 12 and 13).

Conclusion

Magneto-optical sensors are already much more than just an alternative to conventional magnet field-measurement systems. Growing demand for higher material quality and manufacturing quality requires new direct testing and measurement methods, which are not easily performed using other technologies. MO-measurement systems like CMOS-MagView are, therefore, the first choice to quickly, reliably analyze and visualize magnetic stray fields. In addition, in many areas, they offer innovative ways to research, investigate, and manufacture magnetic materials. ❍

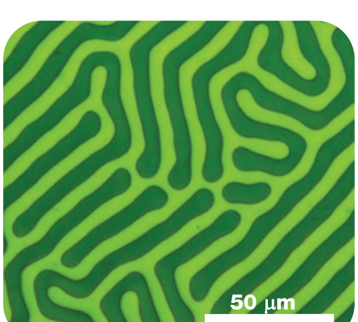

Fig. 12 — *Meander domain recording using CMOS-MagView.*

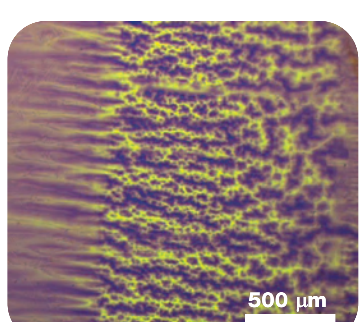

Fig. 13 — *Domains of a magnetic shape memory alloy recorded using CMOS-MagView.*

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