# High Speed Magneto–Optical Sensor for Magnetic Stripe Readout

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***Abstract*—We report on a Faraday–sensor to read out optically test pattern recorded to magnetic stripes on smart cards in a non–contacting way at scanning speeds of several meters per second. The pattern densities of several bits per millimeter can be resolved properly. The sensor employs a magneto–optical crystal of iron doped Yttrium–Aluminum–Garnet known to exhibit one of the highest known Verdet–constants ($\approx 130$ rad/Tm). It is epitaxially grown to a rather small thickness of approximately 50$\mu$m, a small thickness that on the one hand reduces the overall sensitivity dramatically but on the other hand allows for a very fine pitched spatial resolution to image the normal component of the magnetic flux density. The to be tested specimen in the production line is moving at a rather high speed so the optical system and the readout electronics is geared toward rapid scan and to maintain a rather high sustained data streaming rate onto a solid state disk for archival purposes. Scan rates exceeding 50.000 scans per second (@ 128 pixels per scan) were attained and the camera still is sufficiently exposed to attain a fair signal to noise ratio.**

***Keywords–Faraday effect; magnetic field sensor; magnetic field imaging; magnetic tape; quality control***

## I. Introduction

For compatibility reasons, most smart cards still have a magnetic stripe to store some basic information that typically is not cryptographically secured from inadvertent access. At the end of the production line of such cards it is necessary to also check with high speed scanners the successful magnetic recording of a test pattern, which ultimately is erased again. The characterization of these magnetic stripes that ultimately be attachted to the back of, e.g., credit cards or smart cards is necessary for the in–line quality control of the production line [1]. Typical feed rates are in the several meters per second range and the finest period of the recorded magnetic pattern is in the tens $\mu$m–range. The magnetic sensor to be employed needs to operate contact–free to avoid mechanical damages and must be able to also resolve any transversal (error–) pattern to check for cross–sectional evenness. This requirement prevents the usage of very well known and cheap magnetic tape readout heads, since those provide information about the magnetic flux (actually the time derivative of the magnetic flux) as an integral measure only.

The contribution is organized as follows. In section II the theory on the sensing effect is detailed. Section III details the chosen optical set–up and the problems encountered designing the illumination unit. This is followed in section IV by the description of the signal processing necessary to attain a sustained data and streaming rate in excess of 10 Mbytes/s. In the results section preliminary measurement results are presented followed by a short conclusion.

## II. Faraday–Effect

We developed a sensor system using the Faraday–effect [2], which is a magneto–optical effect rotating the plane of polarized light dependent on the magnetic flux density component parallel to the incident light. It's operating principle is depicted in Figure 1. Polarized collimated light that can be seen as the superposition of a right– and a left–circularly polarized light enters the medium exhibiting the Faraday–effect [3]. The magnetic field in matter can be seen as the effect of spinning or circularly moving charges. For the direction of the $B$–field indicated in Figure 1, the two superimposed rotating (circularly polarized) electric field vectors will affect differently co– or counterrotating charges thus the net $B$–field is diminished or enhanced in one direction or the other. Thus effectively the direction of polarization is rotated slightly ones superimposed again. This effect is seen in any matter to a rather small degree. There are, however, a few materials, in particular Yttrium-Iron-Garnet (YIG), that exhibit rather strong effects (show a rather large so–called Verdet constant that can go up — for near infrared light — to 130 rad/Tm).

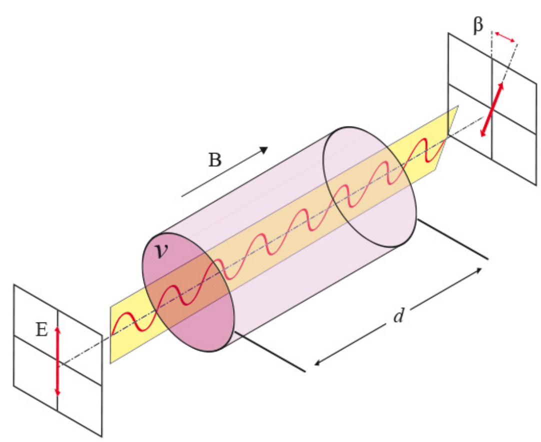


Figure 1. Faraday effect effectively rotating the plane of linearly polarized light (represented by its electric field vector $E$) dependent on the magnetic flux density $B$ in direction of light propagation [4].

In a sensor type application the YIG–crystal typically has one face mirrored so the light traverses the crystal twice thus effectively doubling the sensitivity and also giving spatial access for placing the mirrored surface in close proximity to a magnetized object to be measured.

To mathematically describe this phenomenon the permeability $\mu$ needs to be treated as a non–diagonal tensor as can be seen from (1) [5].

$$B(\omega) = \begin{vmatrix} \mu_1 & -j\mu_2 & 0 \\ j\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_2 \end{vmatrix} \cdot H(\omega) \qquad (1)$$

with:

| | | |
|---|---|---|
| $B$ | T | vector of magnetic flux density |
| $H$ | A/m | vector of magnetic field strength |
| $\mu_x$ | Vs/Am | components of permeability tensor |
| $\omega$ | rad/s | angular frequency of light |

The net effect of (1) can by summed into a constant $V$, the Verdet–constant (which is a function of the frequency $\omega$ of the light used). It turns out that the largest sensitivity is seen for light in the infrared region of the spectrum. The angle of rotation $\beta$ can then be written as:

$$\beta = \int_{x=0}^{d} V(x) \cdot B_n(x) \cdot dx \qquad (2)$$

with:

| | | |
|---|---|---|
| $\beta$ | radians | angle of rotation |
| $B_n(x)$ | T | magnetic flux density in the direction of light propagation as a function of position $x$ |
| $V(x) = V$ | rad/Tm | Verdet constant |
| $d$ | m | interacting distance |

With typical values of the Verdet–constant for the material YIG in the range of 100 rad/Tm.

The Farady–sensor yields a rotation angle of the polarization that, according to (2), is averaging the normal component of the magnetic flux density over the thickness of the crystal $d$. Thus the thickness of the YIG disk must be rather thin (here on the order of a few tens of $\mu$m) to measure very locally. Furthermore, one is interested to measure the magnetic flux density in a non–contacting way right at the surface of the magnetic tape. So the distance of the crystal with respect to the tape surface has to be kept constant and in close proximity to the tape. This will be accomplished in the final version of the sensor by an appropriate aerodynamic design.

The overall rotation of the polarization that can be attained while still maintaining a sufficient spatial resolution while realizing a non–contact measurement action is very limited as the example shows:

For typical magnetic stripes, two coercitivities are used (HiCo with approx. 275 to 400 mT and LoCo with 30 mT of remanence). Given these parameters and considering the mirror action close to the specimen effectively doubling the thickness of $d = 50\mu$m one can estimate the maximum rotation $\beta$ for the lower remanence ($B = 0.03$ T) zu be

$$\beta_{\max} = 2 \cdot 100 \cdot 0.03 \cdot 50 \cdot 10^{-6} = 0.15 \text{ mrad}\,. \qquad (3)$$

This rotation is barely detectable with the used low cost (foil–) polarizers resulting in an intensity modulation following the typical $\cos^2$–rule for the recorded intensity at the camera (Malus'–law [6]). In the presented sensor system we didn't aim to and probably wouldn't be able to quantitatively measure the locally averaged magnetic flux density but were only interested in visualizing the presence of magnetizable domains of similar magnetization strenghts to check for error patterns that might be present.

## III. Optical set–up

The major problem encountered while developing this magnetic field sensor was the required scan rate of more than 50,000 scans per second, which is necessary in order to accomodate the spatial resolution along the stripe direction and realizing approximately 100 pixels perpendicular to the stripe direction using a line–scan camera with sufficient resolution. While there are line–scan cameras available to cope with those requirements the problem of properly exposing them isn't trivial since the Faraday–cell readout requires crossed polarizers thereby diminishing greatly any light intensity used for illumination. Even foil polarizers attain so–called extinction ratios greater than 1:1000, transmitting only light according to Malus'–law (4).

$$I(\beta) = I_0 \cdot \cos^2(\pi/2 - \beta)\ . \qquad (4)$$

In (4), $I_0$ is the incident intensity of light to the crossed pair of polarizers and $\beta$ is the angle of rotation due to the magnetic field in the setup.

We chose a Hamamatsu camera (type S11106-10) that has a pixel size of $63.5\mu\text{m}\times 63.5\mu\text{m}$ and offers a spatial resolution of 128 pixels. It allows for a sustained data rate of 10 Msamples/s, which is equivalent to approximately 64,000 scan lines per second. In order to properly expose this camera (to a maximum of 80% of saturation value) at its spectral peak sensitivity (80 V/(lx s) @ 700 nm wavelength) very intensive light for illumination is necessary as can be seen from (5) considering the fact that the exposure time $T$ has to be lower than $20\mu$s for the intended scan rates above 50.000 lines per second.

$$I_{CCD} = \frac{U_v}{E \cdot T} \qquad (5)$$

with:

| | | |
|---|---|---|
| $U_v$ | V | analog out of camera (0.8 V max.) |
| $E$ | V/(lx s) | photosensitivity (here 80 V/(lx s)) |
| $T$ | s | exposure time (here < $20\mu$s) |
| $I_{CCD}$ | | illuminance at face plate |

For the parameters given above and an exposure time $T = 20 \cdot 10^{-6}$s aiming for 80% of saturation voltage one requires — at the cameras face plate 400 lx. The objective lens is designed to yield an optical magnification of unity which, given optical principles [6] reduces the effective aperture by two stops. Given an objective lens with a numerical aperture of $f/2.8$ becoming an $f/5.6$ lens thus requires an intensity of $400 \cdot 5.6^2 \approx 12800$ lx from the object, which is rather much. Using a LED illumination able to supply (at maximum) 40 lumens and employing an appropriate condenser optics this requirements can be met, however.

Figure 2 shows the devised first prototype of the scanning–system built using standard optical components (Linos Photonics [7]). It consists of a high power LED illumination system

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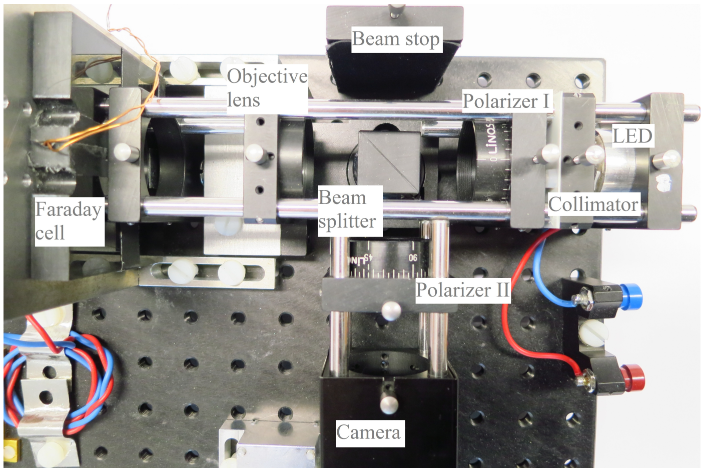


Figure 2. Optical set–up of the experimental Faraday–sensor.

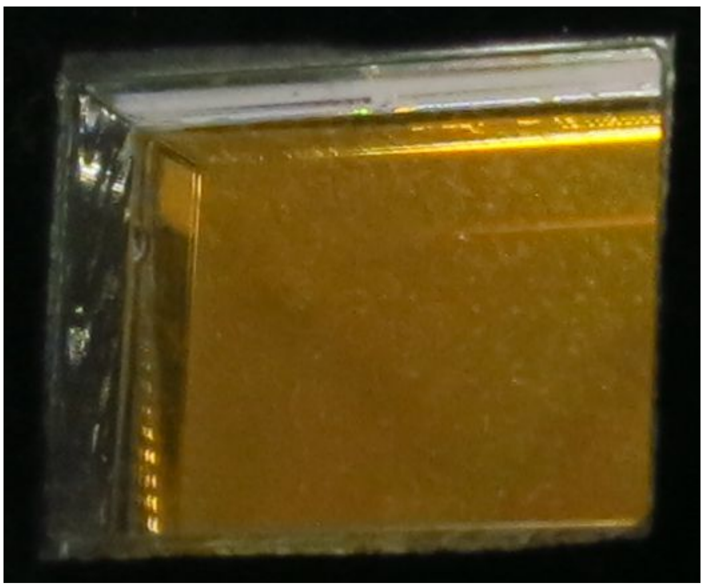

Figure 3. Photo of the thin–sheet Faraday cell.

(manufacturer Cree, type XRCRED-L1) delivering a luminous flux of 40 lm at 620 nm wavelength, a high numerical aperture collimating optics (free diameter 21.4 mm, focal length 16 mm), which collimates the emitted light into a beam of approx 12 mm diameter, the polarizer I (Linos sheet polarizer with an extinction ratio of 1:3500 at 42% transmission for randomly polarized white light), followed by a non–polarizing beam–splitter that allows for a perpendicular viewing direction with the camera path in the second arm, and a beam stop for spurious reflections off the illuminating path. On the return path an objective lens (free aperture f/2.8) is used to project a focussed image (optical magnification 1:1) of the magnetic field via the second polarizer onto the camera's face plate. The camera is a Hamamatsu S11106-10 camera with 128 square pixels ($63.5 \times 63.5 \mu\text{m}^2$).

Figure 3 shows a view onto the mirrored face plate of the Faraday crystal. The YIG–crystal is approximately 50 $\mu$m thin and is traversed twice by light thus doubling its effective rotation. To protected it from abrasion it is coated by a highly reflective and scratch–resistant layer of chemical vapor deposited nano–crystalline diamond giving it this golden color observed.

## IV. Signal processing

A position encoder is used to meter the feed rate of the stripe. This encoder via a phase locked loop circuit synchronizes the camera clock signals appropriately thus allowing a bit–synchronized optical scanning of the magnetic pattern by the camera. The analog video signal is digitized via a video AD–converter (Analog Devices type AD9057) and stored into a 4kB dual–ported RAM (type IDT72240). This RAM type allows for non–synchronized writing and reading processes to take place concurrently. By avoiding byte–by–byte memory access and reading at least 4089 (full–minus–7–byte flag asserted) the overhead of a single PC interrupt is split upon more than 4000 read bytes. This allows a sustained data rate of 10 Mbytes/s even with a medium performance Raspberry Pi unit.

Each scan–line is analyzed for mean, maximum and minimum values of the magnetization and an error is flagged (a single bit per unit length) if set thresholds are exceeded.

## V. Results

Preliminary results are shown in Figure 4 where 150 scan lines with 128 pixels each are displayed. The figure shows the normal component (out of plane direction) of the magnetic flux density at an estimated distance of approximately 60$\mu$m from the magnetic tape surface. One can clearly observe that the system is able to image with the designed scan density, although the finer pitched structures on the right hand side seem to exhibit some problems that might be attributed to aliasing effects [8] stemming from a still too low spatial sampling rate for that particular testing pattern density. The depicted result was obtained with the still experimental unit depicted in Figure 2. The optical field imaged has a width of approximately 12 mm, the acquisition rate was reduced to only 1000 lines per second and the video signal was acquired using a digital storage oscilloscope.

Unfortunately it isn't possible to ascribe numerical values to the imaged magnetic flux density. It would be possible to do so if the rotation angle $\beta$ were measured via a fast acting compensation scheme sweeping over all possible rotation angles of the local polarization, but this would require a totally different concept to be realized. For the quality control purpose it is sufficient to simply show the presence of magnetizable domains and not so much their actual magnetization, since that is only dependent on the material used and wouldn't change along the stripe.

## VI. Conclusion

We reported on the first version of a high scanning speed magneto–optical system able to image and process up to (and beyond) 50.000 scan lines (at a resolution of 128 pixels) per second of magnetic test patterns recorded on a magnetic stripe film. This system is designed to be included for the in–line inspection and quality control at the production line up to feed rates of approximately 3 meters per second (considering necessary at least two scans per bit length at the highest magnetic pattern density).

 

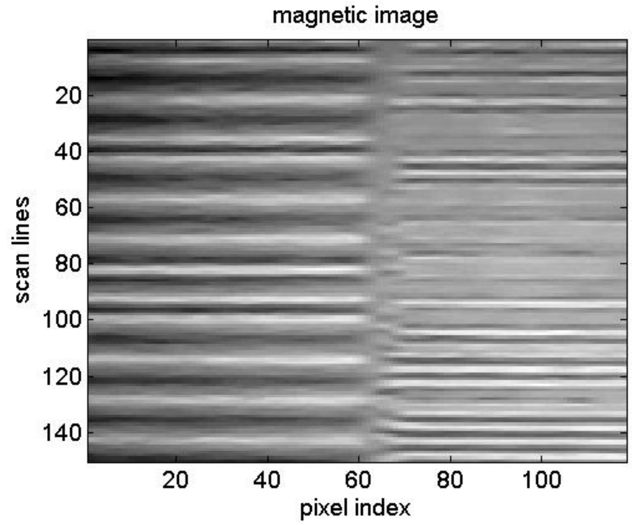


Figure 4. Image (120 pixels wide) of the magnetization of a credit card. Clearly discernible are two tracks the right one recorded with a typically density of 210 bits per inch (8.27 bits per mm), while the left track typically has a recording density of 75 bits per inch (2.95 bits per mm). Currently the magnetic flux density can only be visualized qualitatively. To ascribe numerical values of $B$ to image intenisty values had proven to be rather difficult.

The attached Linux–based PC (a Raspberry Pi/2 model B) is streaming the scanned image data via a FIFO–memory unit at a sustained rate of 10 MB/s onto a solid state disk for archival purposes. It is further planned to have a fully operational system by the end of this year. Improvements to be made include a better synchronization of the camera clocks to the position encoder signals to avoid smearing effects, a more compact optical arrangement less prone to vibrations, a better digital signal processing scheme, allowing to scan for additional quality measures to still be discussed and overall a more thourough qualification test of the complete system. Furthermore, research has to be put into the question of assigning quantitative flux denisty values to intensity values recorded by the camera. Here a standardized calibration procedure is definitely needed, and will be worked upon.

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