FREQUENCY RESPONSE OF A MAGNETOOPTIC SENSOR USING MAGNETIC PULSES

Guillermo Robles and Romano Giannetti

(1) Universidad Pontificia Comillas, c/ Alberto Aguilera, 23–25, 28015 Madrid (SPAIN),
tel. +34-915422800, fax +34-915411132, email: grobles@dea.icai.upco.es

Abstract — *The great advantage of using thin cobalt films as magnetooptic material in sensors to measure currents or magnetic fields is its wide bandwidth because it can reach the magnitude of several GHz. Though this fact is widely known, no effective measures have been taken. The aim of this paper, is to measure the frequency response and the bandwidth of a magnetooptic sensor based on thin cobalt films. Two experiments have been mounted regarding the range of frequencies in study. In the first stage, almost 200 Hz were reached using a sinusoidal magnetic field created with a Helmholtz coil. This frequency is suitable to measuring power lines currents or magnetic fields. Due to the fact that this coil has an extremely high impedance at high frequencies, an alternative method based on magnetic impulses has been developed. The range of frequencies is improved considerabily up to MHz.*

Keywords: magnetooptic, sensor, frequency response, magnetic pulse generation.

1 INTRODUCTION

When a polarized beam passes through a magnetized material its polarization plane rotates [1][2][3]. This effect was first discovered by Michael Faraday in 1845. The law that regulates the rotation is equation 1.

$$\theta = V \oint \vec{H} \cdot d\vec{l} \qquad (1)$$

Where θ is the rotation angle, $\vec{H}$ is the magnetic field, V is the Verdet constant (which depends on the magnetooptic characteristics of the material) and $d\vec{l}$ is the length of the path traveled by the light inside the material. Obviously, for the same thickness and the same material, the rotation angle is proportional to the magnetic field.

The magnetooptic material used in the sensor is a thin cobalt film [4][5]. When designing a sensor, one of the questions that arises is what type of signals are going to be measured, and consequently, what range of frequencies are necessary to be detected. The aim of this paper is to calculate the bandwidth of the sensor based on a thin cobalt film. Then, the uses of the sensor could be stated.

Initially, the setup included a Helmholtz coil to create the magnetic field. Measurements of the magnetic field with a fluxometer indicate that the coil is able to give 8.5 mT/A. It has been possible to reach 180 Hz without any problem. However, for frequencies higher than that, the impedance would be too high. It is necessary, then, the use of a complicated excitation circuit or to try to fabricate another coil with a higher magnetic field per ampere ratio. None of these alternatives would work if very high frequencies are going to be considered. The next step considered was to create a magnetic pulse and then study the time response of the system.

In the following sections are going to be presented the measures taken with the coil as excitation and the first results with the magnetic pulses.

2 MEASUREMENTS

2.1 Measurements using sinusoidals fields.

The setup of the first experiment is displayed in Figure 1. The sinusoidal field is created with a signal generator and a TDA7294 audio power amplifier. The excitation circuit is not able to drive high currents at high frequencies, that is why 179 Hz is the maximum frequency studied.

The plot of the amplitudes of the input signal versus the output of the sensor is shown in Figure 2. As it has been explained above, the more frequency we try to impose, the less intensity and magnetic field we get due to the high autoinductance. Then, low frequencies have high magnetic field values, around 16 mT; and high frequencies, namely, 110 and 179 Hz, only reach 4 mT.

Nevertheless, all data fit exactly in a straight line. Notice that the slope of this line is precisely the ratio between the output and the input to the system considered. The frequency response can be plotted calculating the slope of the linear function for each frequency, Figure 3. The value corresponding to 110 Hz has a slight difference compared to the rest of the frequencies. This is probably due to the fact that a different averaging method was used for this frequency point. It can be observed that the response is linear from zero to 179 Hz.

Similar plots have been calculated for different thickness of the cobalt samples. The response is also linear but the gain is different as it was expected.

ISBN 972-98115-4-7 © 2001 IT

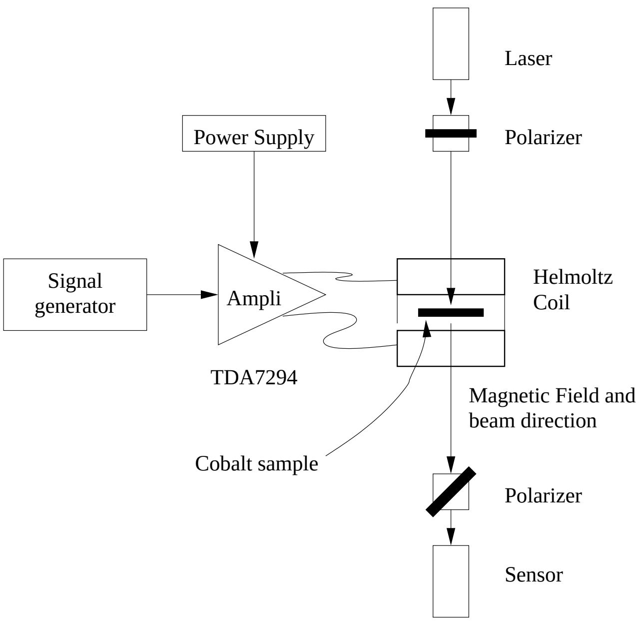

Figure 1: First setup used in the experiment. The coils were fed with a sinusoidal field using a power amplifier and a signal generator.

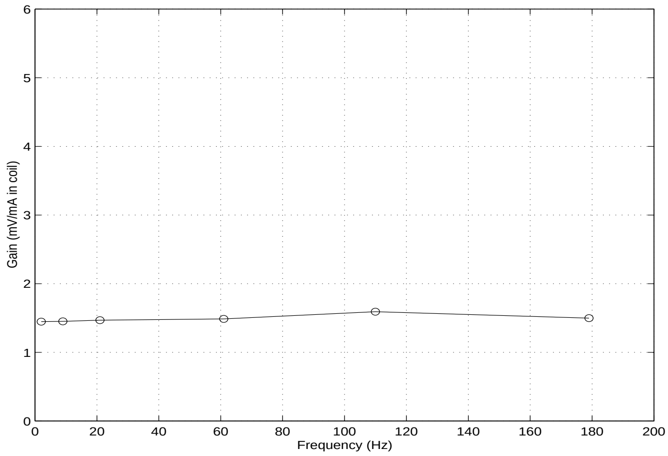

Figure 3: Frequency response for the 200 Åcobalt sample.

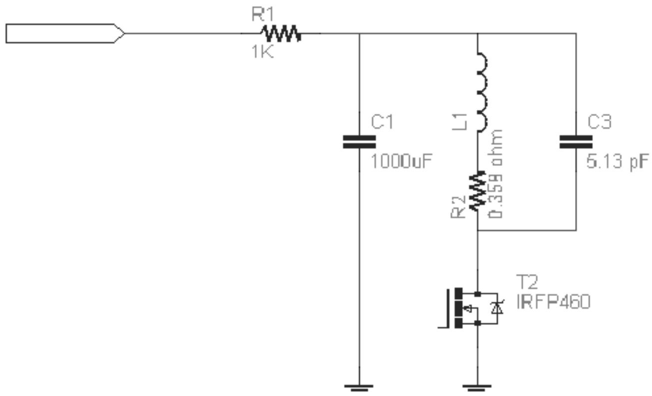

Figure 4: Capacitor discharge circuit to create a magnetic pulse.

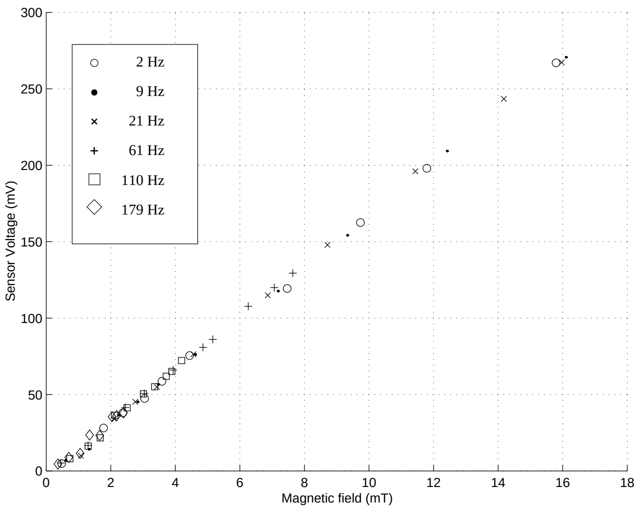

Figure 2: Plot of the output signal versus the current in the coil (proportional to the magnetic field) for a 200 Å cobalt sample and different frequencies.

2.2 Measurements using magnetic impulses.

2.2.1 Schemes and plots

It is necessary to obtain measures at higher frequencies. Studying the response of the system to an impulse at the input, the frequency response can be stimated. Following this argument the use of a magnetic pulses generator has been considered. The first idea considered was to discharge a capacitor through a coil. This coil should have a radius small enough to create a high magnetic field and should allow the passing of the laser beam through it. Besides, the current through the spires would depend on their impedance. Then, this impedance must be low so that the current can be high. These characteristics maximize the magnetic field as is shown in Equation 2, where a is the coil radius and L is its length.

$$\vec{B} = \frac{N\mu_0 I}{\sqrt{a^2 + \left(\frac{L}{2}\right)^2}}\vec{u}_z \qquad (2)$$

The discharge circuit is quite simple, see Figure 4. A capacitor of 1000 μF is charged up to 60 V through a resistor of 1 KΩ and 1 W. Feeding the gate of the MOSFET with a driver, the capacitor is discharged abruptly trought the coil. When the capacitor is completely discharged and the MOSFET is still con-

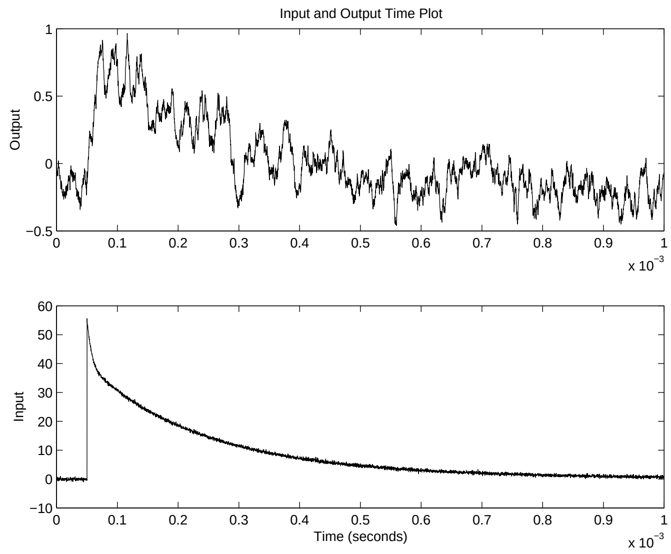

Figure 5: Plot of the signal in the sensor and time response of the magnetic pulse.

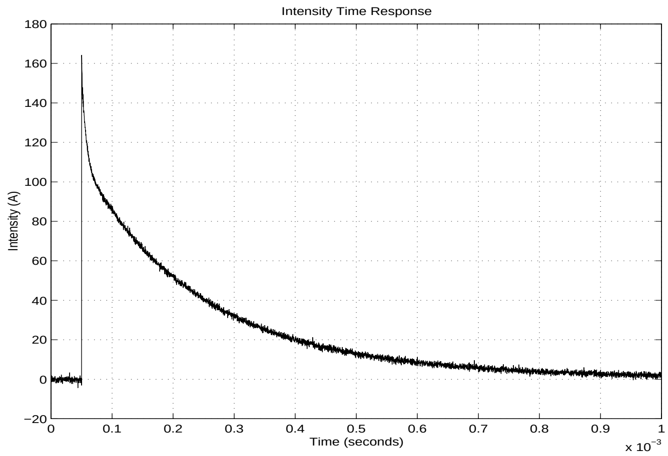

Figure 6: Calculated intensity through the coil. Notice the high value achieved and the short time of the impulse.

ducting, a tiny current flows through the coil, however this does not interfere with our measures.

The impedance of the spire has been measured and its equivalent circuit is also shown in Figure 4. The values for the resistor, the inductance and the parallel capacitor are 358 mΩ, 1.03 μH and 5.13 pF respectively.

The first curve in Figure 5, is the response of the magnetooptic sensor. It is only a sample, no averaging method has been used because it could disturb the following calculations. The units are in volts.

The results of the impulse created are also shown in Figure 5. The second curve is the voltage measured at the ends of the coil, as its impedance is known it is possible to calculate the intensity through it. The magnetic field is proportional to the current, hence, it is also known.

In order to obtain the time response of the intensity in the spire, and then the magnetic field, it is necessary to perform some calculations: The frequency response of the voltage step is obtained, calculating the FFT of the time response, let it be called $\tilde{V}(f)$. Then it is computed the s transformation, $Z(f)$, of the equivalent circuit of the spire in the same points as $\tilde{V}(f)$. Dividing these two functions we get the frequency response of the intensity. Then it is calculated the inverse FFT to get the time response of the current and the magnetic field. The intensity is displayed in Figure 6, notice that the value is above 160 A, which is extremely high for such a small coil. As a consequence, the magnetic field is also sufficient to excite the cobalt film and to be sensed by the device.

2.2.2 *Analysis of the measurements*

We consider the voltage drop in the coil as the input variable to our system and the output voltage of the sensor designed, the output of the system. Performing a frequency study on both signals gives a first approximation of the frequency response. Being strict, the input signal should be the intensity through the coil or the magnetic field created by it. However, the relationship between the voltage drop and the intensity in the solenoid is linear and known because its impedance has been calculated. The voltage drop is preferred because it is not affected by the pole introduced by the impedance at 10 KHz. If the input-output function is constant up to a frequency, it can be stated the bandwidth of the system. The following calculations are aimed to obtain this result.

To determine the energy of the signals through a range of frequencies, a power spectral density analysis was performed. It showed that both signals had no energy above 2 MHz; whatever the case, the results will not be accurate above this frequency, but it can give us an idea of the behaviour of the system.

With the aid of matlab, a Blackman-Tukey spectral analysis was performed. The averaging was 10 samples to obtaing a fairly smooth result.

As it is shown in Figure 7, the response is flat up to the maximun reliable frequency, that is, 2 MHz.

2.2.3 *Theoretical bandwidth*

Observing the system, it is possible to determine the stage in which the most probable frequency bottleneck is encountered. The first amplification stage in the sensor has a gain of 100 dB. This stage is critical because of the capacitance of the photodiode and the transconductance amplifier. This topology introduces a double pole [6] at a relatively low frequency, see Figure 8.

This double pole can be calculated approximately with 3.

$$f = \sqrt{\frac{f_c}{2\pi R_F C_I}} \tag{3}$$

where, f_c is 8 MHz, the zero-gain frequency of the amplifier, R_F is the feedback-resistor used in the amplification and $C_I = C_P + C_{CM} + C_D$ is the input capacitance, which includes, the capacitance of the photodiode and the common mode and differential capacitances of the operational amplifier.

The result is $f \simeq 300$ KHz.

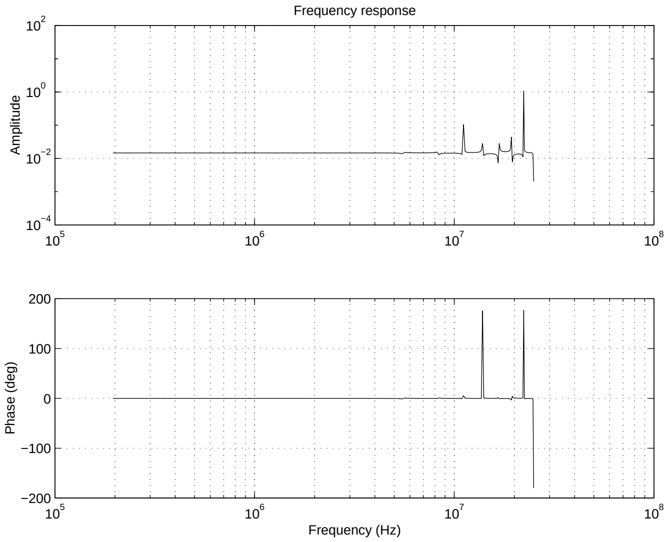

Figure 7: Frequency response of the system estimated with the Blackman-Tukey method. Notice that the input is the voltage drop in the coil, and the output is the voltage obtained with the sensor.

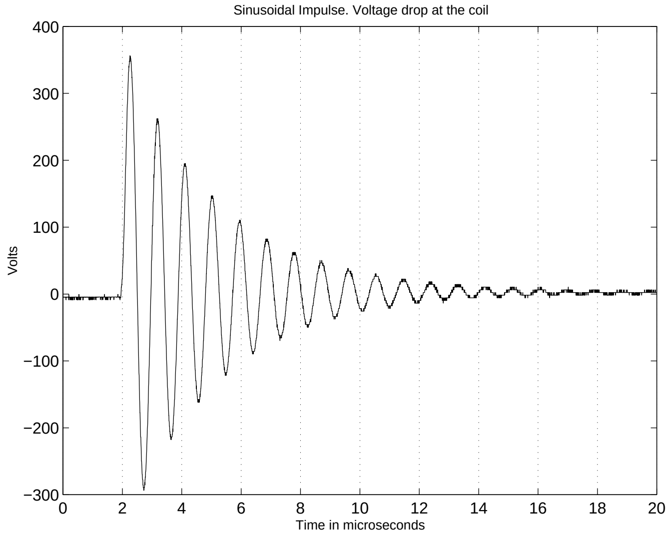

Figure 9: Sinusoidal impulse.

2.2.4 Sinusiodal impulses and future measurements.

Due to the differences in these results, it was decided to test the bandwidth with an alternative method. Instead of creating single impulses, an impulse of sinusoidal waves was used. The idea is to provoke an oscillation with the autoinductance of the coil and an external capacitor in parallel with the coil. During less than 10 μs, the MOSFET is closed and a high current is flowing through the coil. The MOSFET is opened abruptly and the current starts to oscillate in the second order system. The capacitance is calculated to oscillate at a prefixed frequency. In the tests performed, this capacitance was 22 nF and the oscillation frequency around 1MHz. This method requieres a MOSFET transistor which can hold high overvoltages between drain and source pins. The voltage at the drain can be several hundreds of volts at the moment of cut-off. The plot of the excitation signal is displayed in Figure 9.

To obtain this seignal, the voltage of the discharge capacitor, see Figure 4, was excited only with 20 Volts instead of 60 V. This was because the maximum oscilloscope scale is 100 V, and larger excitations would give an over-ranging signal.

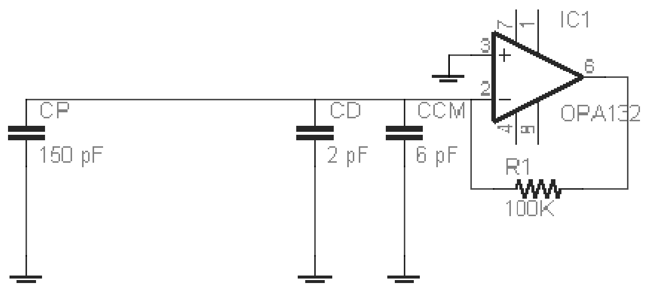

Figure 8: First stage of the amplifier. The capacitances are the input capacitances to the operational amplifier and the capacitance of the photodiode.

In the experiment different capacitors were used to study several frequencies. The cut-off frequency of the system can be determined comparing the results obtained and checking when the output is 3 dB under the gain at low frequencies. The measurements obtained at the sensor using this excitation system show that the cut-off frequency is around 800 KHz. However, these data have to be double-checked because the noise introduced by the abrupt cut of the MOSFET spoils the measurement.

3 NEXT STEPS

Currently we are trying different approaches to overcome the drawback of the noise introduced by the photodiode [7]: better isolation, filters in the voltage supply of the devices, weaker excitation signals. Once this is achieved, a more reliable bandwidth measurement will be swiftly obtained.

As the cut-off frequency will be that of the magnetooptic sensor due to the electronic involved in its construction, the operational amplifiers will be changed to improve the bandwidth. A fast photodiode, SFH203 is being used in the new set of the measurements, the rise-up time is as low as 2 ns. Its capacitance is also very low, only 11 pF which would give us a theoretical cut-off frequency well above that obtained in the first experiment.

Besides, all of the steps must be done with different cobalt samples in order to test the bandwidth dependece with the thickness of cobalt. It will be very interesting to maximize the bandwidth according to the thickness.

4 ACKNOWLEDGMENTS

The author would like to thanks to Dr. F.Briones from the IMM (Instituto de Microelectronica de Madrid) for his greatly valuable help in the fabrication of the thin cobalt films used in this experiment.

5 CONCLUSIONS

In this paper we present a characterization study of thin cobalt film magnetooptic sensors. Two methods using magnetic pulses are proposed to extend the frequency measurement of the system. The first one requires one single impulse and needs a frequency response stimation to obtain the bandwidth study. The second one is based in a train of sinusoidal impulses at a fixed frequency. Changing the oscillation frequency it is possible to calculate the point where the gain has dropped 3 dB.

References

[1] G.W. Day and A.H. Rose. Faraday effect sensors: The state of the art. In *Fiber Optic and Laser Sensors VI*, volume 985, pages 138–150. SPIE, 1988.

[2] G.W.Day, M.N.Deeter, A.H.Rose, and K.B.Rochford. Faraday effect sensors for magnetic field and electric current. In *Interferometric Fiber Sensing*, volume 2341. SPIE, 1994.

[3] Marvin J.Freiser. A survey of magnetooptic effects. *IEEE Transactions on magnetics*, 4(2):152–161, June 1968.

[4] R.Carey, B.W.J.Thomas, and D.M.Newman. The magneto-optical properties of thin cobalt films. *Thin Solid Films*, (67):35–40, 1980.

[5] G.Robles and R.Giannetti. Magneto-optic faraday effect current sensor based on thin cobalt films. In *IEEE IMTC'2000 Proceedings*, pages 1548–1551, 2000.

[6] Jerald Graeme. *Photodiode Amplifiers*. Mc Graw-Hill, 1995.

[7] Henry W. Ott. *Noise Reduction Techniques in Electronic Systems*. Wiley-Interscience, 1988.