Frequency Response of a Thin Cobalt Film Magnetooptic Sensor

Guillermo Robles and Romano Giannetti

Abstract—The magnetooptic effect is due to a change in the polarization of the light when it is reflected or passes through a magnetized material. The rotation of the polarization plane is proportional to the magnetic field. The great advantage of using a magnetooptic sensor to measure intensity or magnetic fields is its wide bandwidth. This fact is widely known; however, no effective measurements have been taken. In this paper, we present the frequency response of a cobalt thin film used as magnetooptic material. It was first excited by several sinusoidal magnetic fields at different frequencies. The range of frequencies studied in the first experiment reached 179 Hz, which is suitable for measuring power line intensity or magnetic fields. Because the coil that creates the magnetic field has a great impedance at higher frequencies, an alternative method based on magnetic impulses has been designed to obtain high-frequency data. With the latest experiments we have been able to measure frequencies as high as 2 MHz, obtaining a flat frequency response.

Index Terms—Ferromagnetic materials, magnetic field measurement, sensors.

I. INTRODUCTION

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

$$\theta = V \int \vec{H} \cdot d\vec{l} \tag{1}$$

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 ranges of frequencies are necessary to be detected. The main usage of magnetooptic sensors is to measure the intensity in power lines. The aim of this paper is to evaluate the bandwidth of the sensor based on a 200-Å-thick thin cobalt film. If the bandwidth is well above the first harmonic, the sensor would be able to detect faults in the power line.
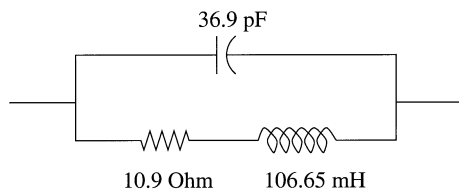
Fig. 1. Equivalent circuit of the Helmholtz coil used in the first part of the experiment.

TABLE I
MAGNITUDE OF THE IMPEDANCE OF THE COILS FOR DIFFERENT FREQUENCIES. THE SMALL COIL IS THE ONE THAT WAS USED WITH THE IMPULSE EXCITATION

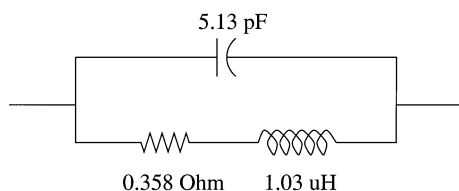| Frequency	Helmholtz coil	Small coil
180 Hz	121.1 Ω	0.358 Ω
500 Hz	335.2 Ω	0.358 Ω
1,000 Hz	670.3 Ω	0.358 Ω
10,000 Hz	6.8 kΩ	0.364 Ω

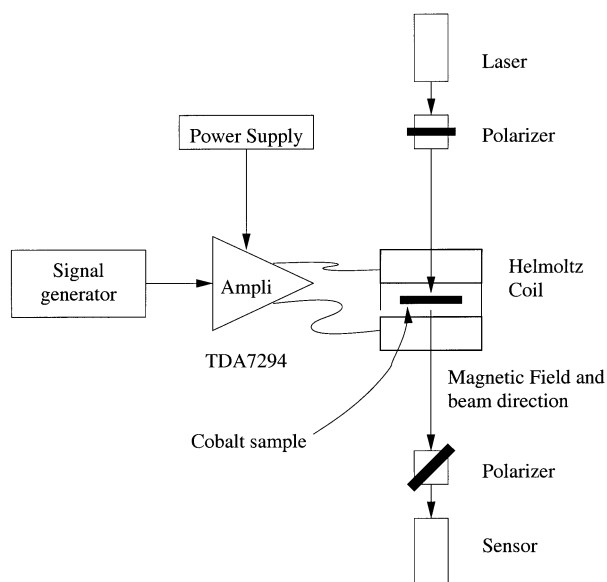Fig. 2. Equivalent circuit of the coil used in the magnetic pulse generator.

Fig. 3. Setup scheme to create a magnetic field and to measure the magnetooptic Faraday effect.

Initially, the setup included a Helmholtz coil to create the magnetic field. Calibrating measurements of the magnetic field with a fluxometer indicate that the coil is able to give 85 Oe/A.
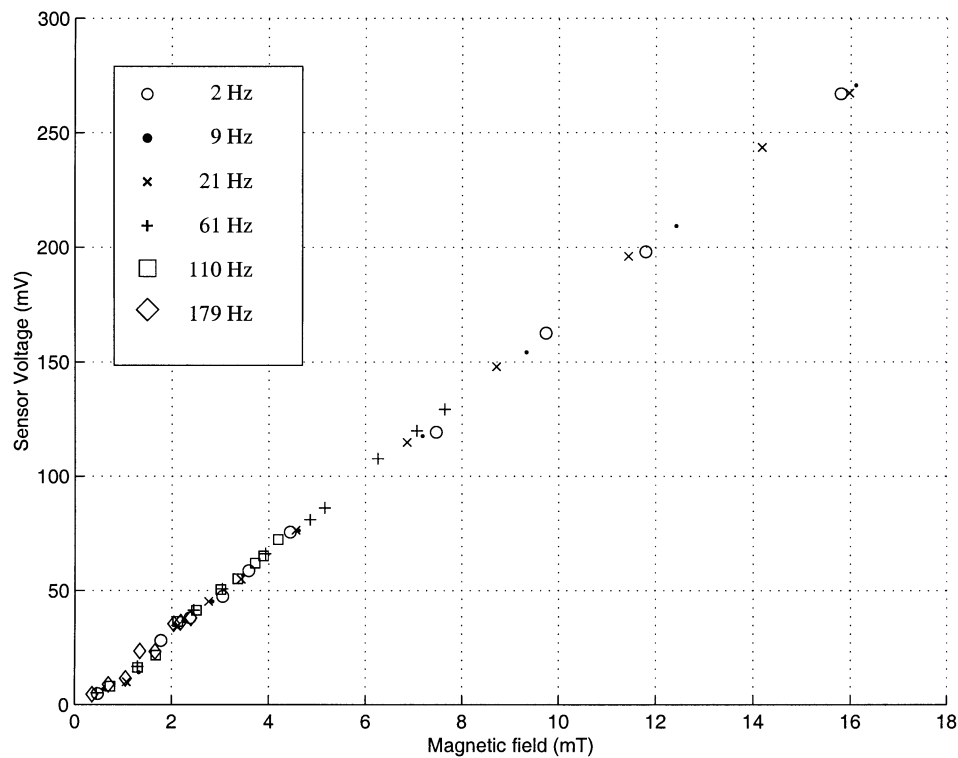
Fig. 4. Plot of the output signal versus intensity in the coil (proportional to the magnetic field) for a 200-Å cobalt sample and different frequencies.

The equivalent circuit, displayed in Fig. 1, was measured with an impedance analyzer. It has been possible to reach 179 Hz without problems or drawbacks. However, at higher frequencies, the impedance would grow too high (see Table I); and the magnetic field would prove to be too weak for our purpose. Nevertheless, interesting results can be obtained in that frequency range, and they will be reported in the next section. It is necessary, then, to design a more complex excitation circuit or try to fabricate another coil with a higher magnetic field per ampere ratio. None of these alternatives would fit our purposes if signals at very high frequencies are going to be measured.

The next step considered was to minimize the radius of the coil so that the magnetic field would increase proportionally. The turned wire should be very thin, and it would not support a high intensity during long periods of time. Hence, the average value of the intensity should be very small and so the energy delivered in every cycle. The adopted solution was to create magnetic pulses and then, to study the time response of the system with the aid of a system identification tool.

The sample was introduced between a small pair of coils. These were connected together in the same way as if they were a tiny Helmholtz coil. The length of each one was 6 mm, the outer diameter was 4 mm, and the inner diameter was 1.5 mm. This one, being so small, allowed us to obtain high magnetic fields. The equivalent circuit is shown in Fig. 2.

The measurements taken using these two coils and the interesting results obtained with magnetic pulses will be presented in the following sections.

II. EXPERIMENTAL SETUP AND MEASUREMENTS

Several sets of measurements have been taken using two different magnetic field generators. The input is the intensity

through the coil or the magnetic field created by the coil. The output is the signal detected by a photodiode amplified with an intensity-to-voltage amplifier. The spectra of these signals and the relation between them are calculated, obtaining the frequency response of the system. If this curve is flat, we can assert that the bandwidth of the cobalt is beyond the maximum frequency measured.

A. Helmholtz Coil

For the first coil, a function generator has been used to create a sinusoidal wave of different amplitudes and different frequencies. This signal is amplified with a TDA7294, and the output is connected to the Helmholtz coil (see Fig. 3).

The plot of the amplitudes of the input signal versus the output of the sensor is shown in Fig. 4. As it was explained before, the more frequency we try to impose, the less intensity and magnetic field we get due to the high auto-inductance. This is why the plot has more values in the region of low magnetic field. At low frequencies we have a maximum magnetic field in 16 mT, and the minimum field measured is 400 μT at any frequency.

Notice that the slope of the line is the ratio between the output and the input to the system considered. The frequency response can be plotted by calculating the slope of the linear function for each frequency, Fig. 5. 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 at this point the number of samples taken and averaged was different. Nevertheless, it can be observed that the response is linear from zero to 179 Hz.

Similar plots have been calculated for other thicknesses of cobalt film. The response is also linear, but the gain is different, as it was expected.
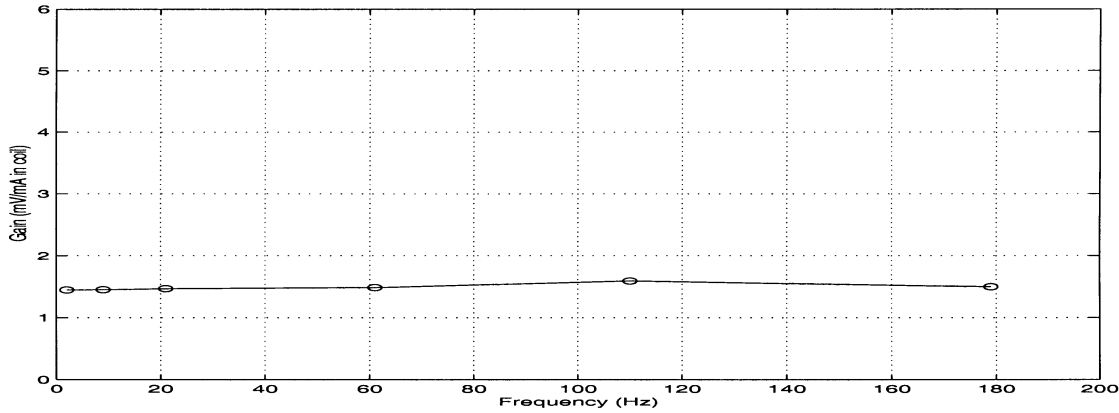
Fig. 5.   Frequency response for the 200-Å cobalt sample.

B. Small Coil

It is possible to compute the frequency response of a system by studying the response to a step in the input signal. Following this argument the use of a magnetic pulse generator has been considered. The first idea is to discharge a capacitor through a coil of N spires.

The radius should be small enough to create a high magnetic field. However, the laser beam and the magnetic field must be parallel to each other and perpendicular to the cobalt sample. Hence, the light must pass through the coil, then through the sample and finally, hit the photodiode at the sensor.

The intensity through the spires would depend on its impedance. It must be low so that the intensity can be high. The impedance of the coil has been measured, and its equivalent circuit is shown in Fig. 2.

These characteristics maximize the magnetic field as is shown in (2), where a is the radius of the spires, L is the length of the solenoid, N is the number of spires, I is the intensity, and $\vec{u}_x$ is the unitary vector in the direction of the magnetic field

$$\vec{B} = \frac{N\mu_0 I}{\sqrt{a^2 + \left(\frac{L}{2}\right)^2}}\,\vec{u}_x. \tag{2}$$

The circuit is quite simple; see Fig. 6. When the MOSFET is off, a 1000 μF is charged up to 60 V through a resistor of 1 kΩ. The time constant should be less than the trigger cycle. In the experiment the gate is in low level during 5 seconds, which is enough to finish the charge of the capacitor. When the MOSFET is on, the intensity is abruptly conducted through the coil and the R_{DSON} of the MOSFET. This resistance is the same order of magnitude as the impedance of the coil. In order to reduce it, up to 4 MOSFETs were connected in parallel, with the same trigger input. The driver was an IR2110, and the MOSFETs were some IRF530.

The intensity in the spire must be calculated; it cannot be measured because a probe resistor would diminish the voltage drop in the coil and hence, the intensity in the coil. In Fig. 7, the signal measured at the sensor and the time response of a voltage step created by the discharge of the capacitor are shown. The measurements have been taken with an oscilloscope Tektronix TDS 544A. The sampling frequency was $5 \cdot 10^7$ samples per second.
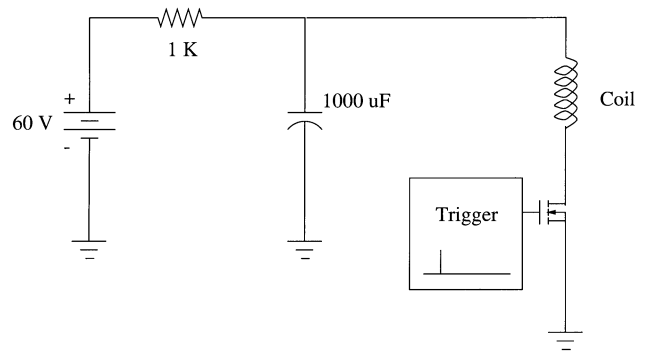

Fig. 6.   Circuit designed to create a magnetic pulse.

The maximum frequency appreciable would be 25 MHz, theoretically. The total time sampled was 1 ms, so the minimum frequency we can appreciate is 1 kHz.

In order to obtain the time response of the intensity in the spires, it is necessary to perform the following calculations:

The frequency response of the voltage step is obtained by calculating the fast Fourier transform (FFT) of the time response of the input; let it be called $\tilde{V}(f)$. Then $Z(f)$, the frequency response of the equivalent circuit of the spire in the same points as $\tilde{V}(f)$, is computed. Dividing these two functions, we get the frequency response of the intensity discharged through the coil. Then, the inverse FFT is calculated to get the time response of the intensity, see Fig. 8.

If we look back to (2), and once we have obtained the intensity in the spire, we could deduce the value of the magnetic field theoretically. However, this equation is valid for the value of the magnetic field inside an ideal solenoid and infinitely long. In the experiment, the solenoid was far from being ideal. It was divided into two coils, very likely to the shape of a Helmholtz coil, and the sample was placed between them. The magnetic field will not follow a simple equation as (2), but a much more complicated one or none at all. It is preferable to follow an indirect way of obtaining the magnetic field. As it has been shown before, in Fig. 4, the relationship between the magnetic field and the response of the magnetooptic sensor is linear, at least up to 200 Hz. We can use these data to calibrate the response and convert the signal of the sensor into a magnetic field. Moreover, we can compare it with the theoretical one.
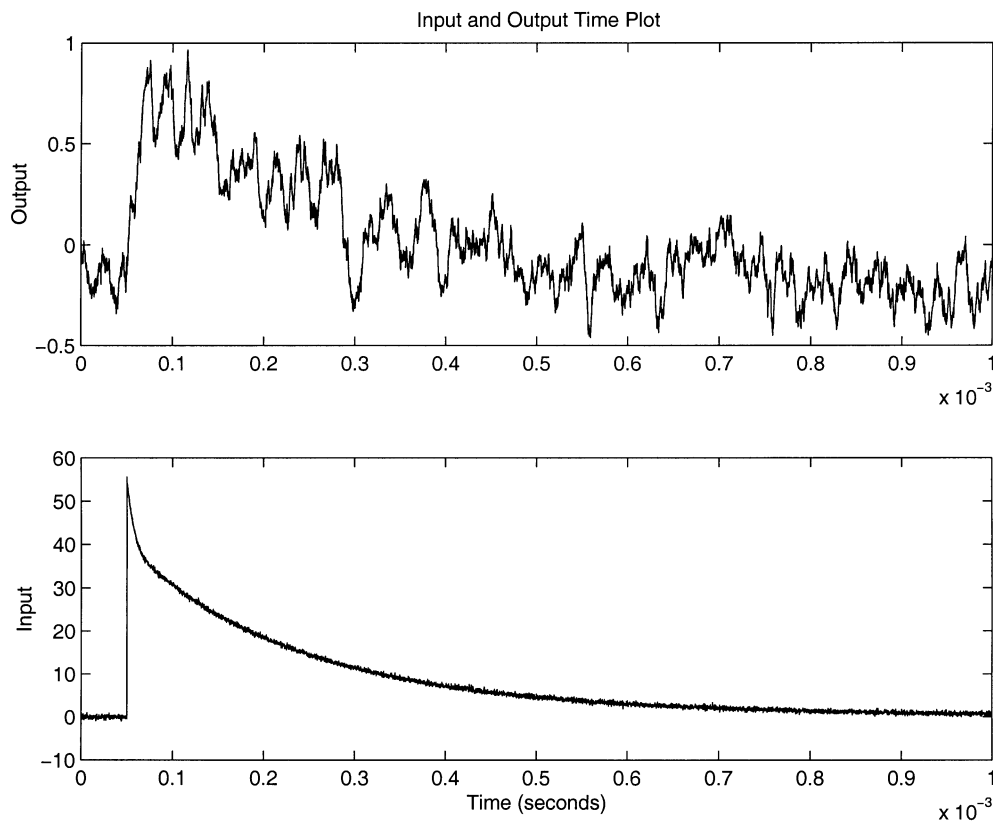
Fig. 7.   Time response of the input signal and the output of the sensor. Notice that the units at the input are volts. This voltage must be converted into intensity by dividing by the impedance of the coil over a wide range of frequencies.
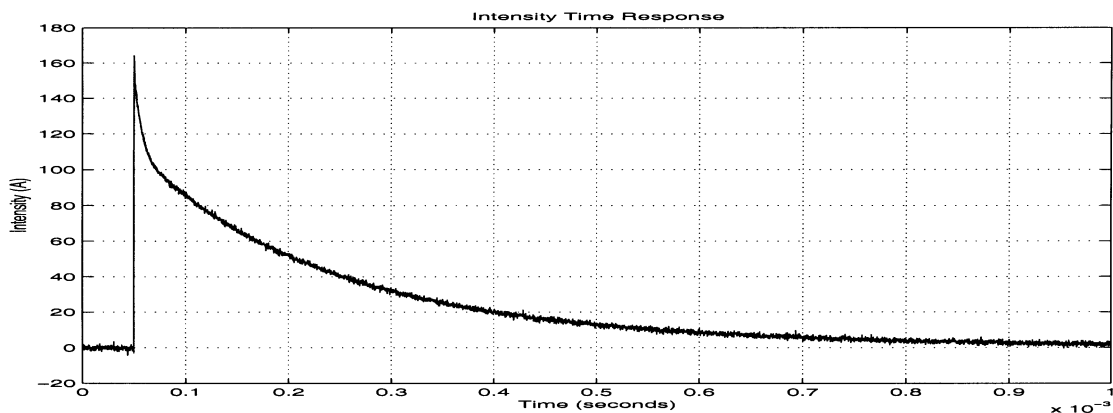

Fig. 8.   Time response of the intensity in the spires. This intensity is proportional to the magnetic field.

C. Frequency Response up to 2 MHz

The input and output to the measuring system in the study were analyzed with the assistance of MATLAB and the System Identification toolbox. The energy of the signal is shown in Fig. 9. It can be seen that the signal is negligible for frequencies higher than 2 MHz, so in spite of being able to observe signals containing frequencies of 25 MHz, in practice, those signals are hidden by the noise in the output. For the time being, we will only consider frequencies up to 2 MHz; nevertheless, we are studying different approaches to this drawback, and we hope to overcome it by introducing a white noise signal as excitation.

The spectra analysis was performed with MATLAB. The results are shown in Fig. 10. The data in this figure are the frequency response of the whole system, output voltage versus input intensity. The cut-off frequency is 40 kHz. Then, the gain decreases with a slope of 20 dB/dec. This fact is due to the frequency response of the coil; the magnetic field or the intensity through the coil diminishes at high frequencies.

However, the frequency response representing output voltage versus input voltage—voltage drop in the coil—is absolutely flat (see Fig. 11). These results are unquestionably encouraging, and we are very confident in reaching responses at higher frequencies in a short period of time.

III. NEXT STEPS

The experiment described above was done with a single trigger at the input gate of the MOSFET. Therefore, the information
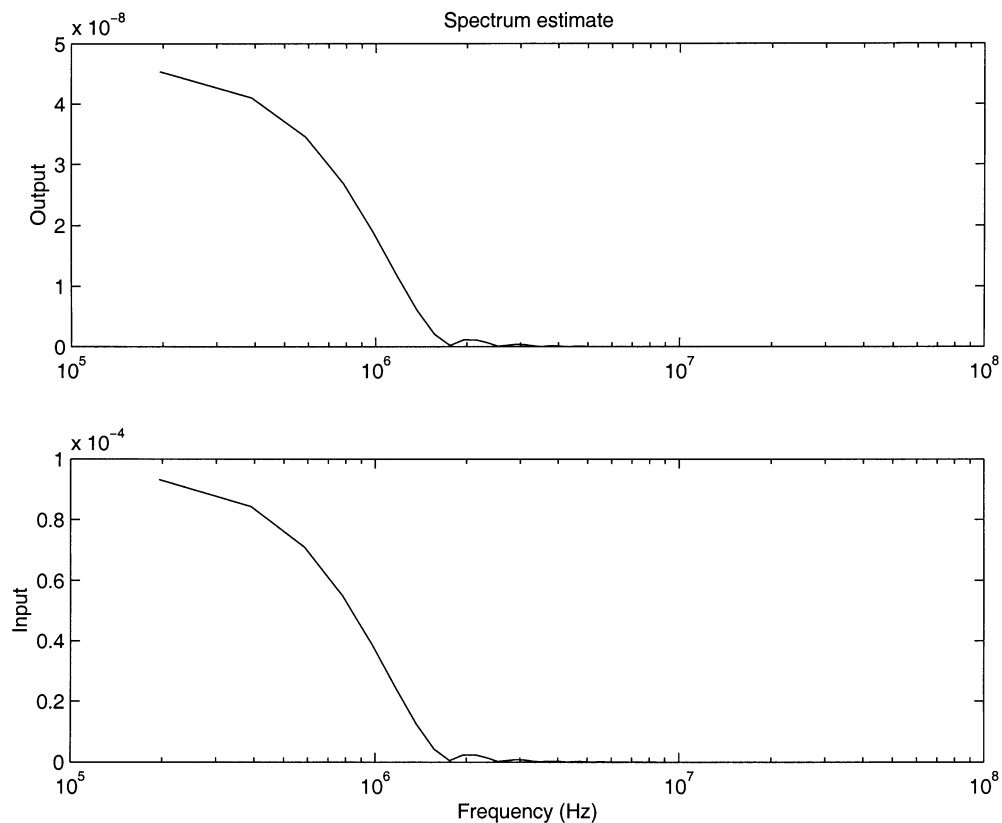
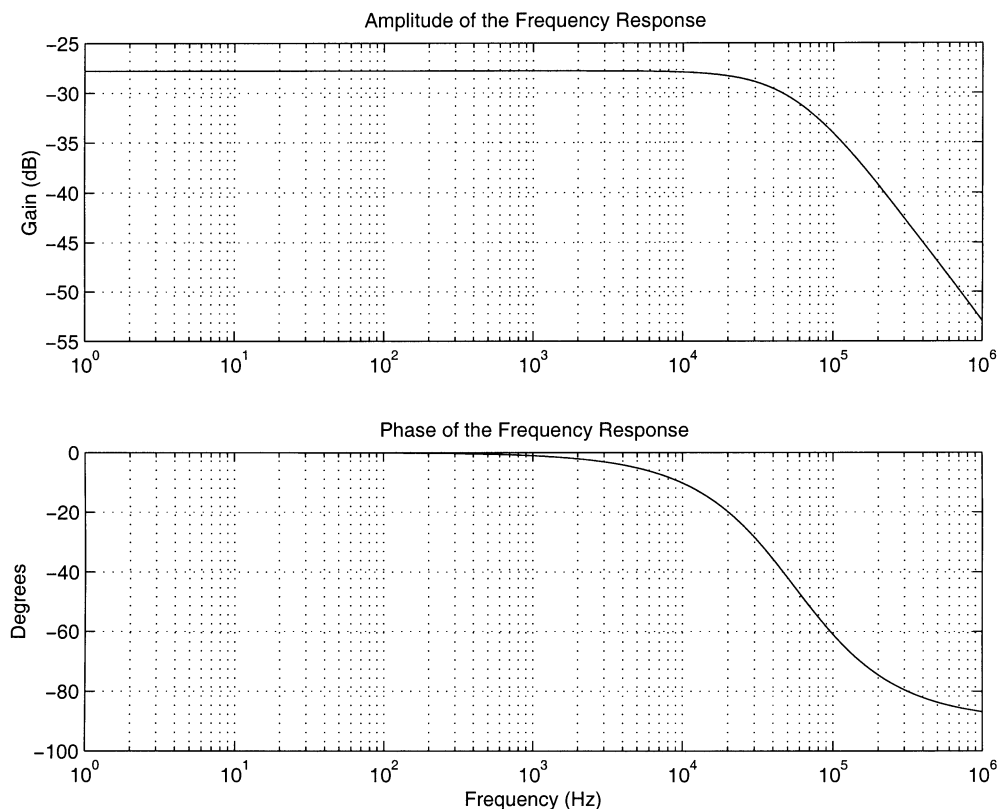Fig. 9. Spectrum estimate of the signals. Above 2-MHz the energy of the signal is practically negligible.

Fig. 10. Frequency response of the system. Output voltage at the sensor versus input intensity in the coil.

in terms of energy contained in the data is somewhat limited. The next step in developing new measurements is to introduce a different signal through the MOSFET gate. This new signal must contain more information about high-frequency harmonics. A
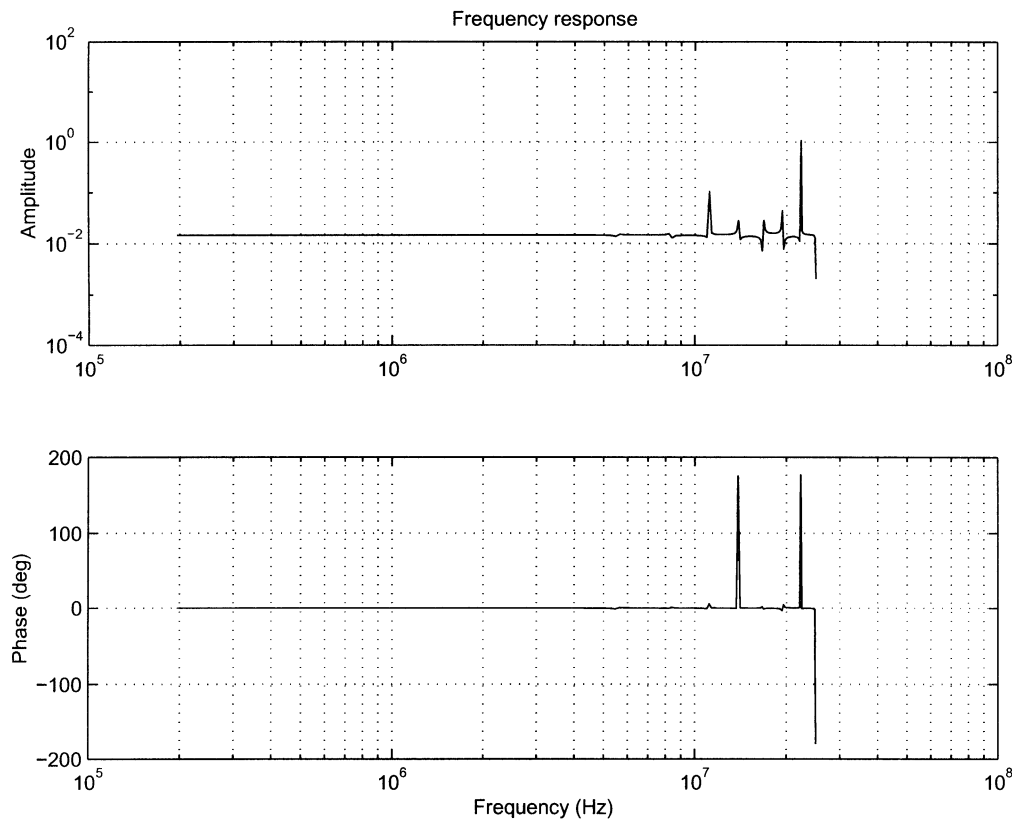
Fig. 11. Frequency response of the system. The input and output are the voltage drop at the coil and the voltage measured at the sensor respectively. The data above 2 MHz is not significant and should be ignored.

white noise will accomplish the requirements. It can be simulated with a pulsed random binary signal (PRBS) at the gate. However, in order to observe high frequencies, the charge of the capacitor should be quick enough to be discharged at a high rate. If a single capacitor is not sufficient, an array can be disposed in an array and sequentially discharged through the same coil.

The high-frequency noise, which is present in Fig. 7, should be reduced to improve the signal-to-noise ratio. This noise is thought to be thermal noise due to the resistors and noise from the photodiode. We will explore different techniques to diminish its effect in the final signal [6], [7].

The complete experiment should be repeated for a set of samples with different thicknesses. It is very interesting to test the bandwidth dependence on the thickness of cobalt. It will be applied to maximize the bandwidth according to the thickness in the case there is an appropriate relationship.

IV. CONCLUSION

In this paper, we present a characterization study of thin cobalt film magnetooptic sensors. An exhaustive analysis for low frequency was performed, presenting results up to 200 Hz. Moreover, an alternative method to increase the range of frequencies studied has been developed. The intensity of the experiment has reached a frequency as high as 2 MHz. Another technique is being studied to widen the maximum frequency studied at present. The final response of the system has proved to be linear and extremely flat as it was desired.

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