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Design of a high current transducer based on GMR effect in multilayered nanowire

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Abstract **– The paper presents a new type of current transducer intended to measurement currents in the range of kA. Its operation principle is based on the Giant Magnetoresistance (GMR) effect occurring in multiplayer nanowires embedded in a polymer foil, providing both frequency and voltage outputs. The sensitive element works as a variable resistor mounted in a Colpitts oscillator with the oscillation frequency in the range of MHz. A negative feedback helps improving the current range and linearity**

Keywords **– current sensor, GMR, characteristic linearization, oscillator**

I. INTRODUCTION

One of the benefits associated with particle accelerators is the development of single-ion fabrication techniques. Using individual energetic heavy ions to penetrate a polymer foil, single ion tracks are obtained. After etching the foil with NaOH, the resulting nanopore is suitable to be used as template for depositing metallic nanowires inside. Such template is used to create metallic structures showing interesting effects [1-2]. One of these is the GMR effect which consists of a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment [3]. Many variants of sensors devoted to measure electrical and non-electrical quantities based on the GMR effect have been recently reported [4-5]. Most of them are using magnetic ribbons as sensitive elements exhibiting a strong GMR effect. However, magnetic nanowires revealing GMR are more and more imposed in sensors construction, even if the effect is less impressive than in ribbon case. An important advantage is their very small dimension that makes them suitable to be employed in punctual measurements of magnetic fields. Such a magnetic sensor consists of a multilayered nanowire with alternating magnetic-nonmagnetic bi-layers whose resistance depends on the mutual magnetic orientation of neighbouring Co layers

[2]. Sensitivity increases with the number of layers. However, single wires provide the best signal to noise ratio.

In order to assess the GMR efficiency, we define the magneto-resistive ratio MR as:

$$MR = \frac{\Delta R}{R_0} 100 \ [\%] \qquad (1)$$

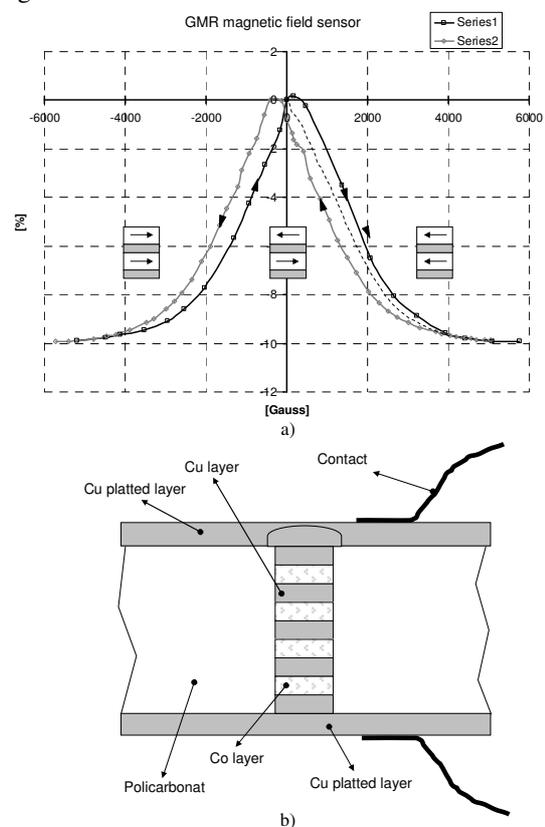The dependence of MR on the magnetic field is given in Fig. 1.

Fig. 1. a) GMR effect in a Cu/Co multilayer wire: magnetic order reduces resistance; antiferromagnetic order at zero field increases resistance; b) Cu/Co Multilayered nanowire

As can be observed from Fig. 1, the GMR effect is relatively reduced (10 – 12 %) and the characteristic is quite non-linear. However, a linear range may be defined on the characteristic for a given linearity. On the other hand, the saturation occurs at large field values (4000 – 5000 Gauss), that makes the nanowire suitable to be employed when large magnetic fields are concerned. This is the case of using the magnetic nanowire in a current transducer configuration designed for a large range of currents. In order to use it as such a sensitive element, the point must be moved in the middle of the linear region of the transfer characteristic. This can be accomplished using an electronic feedback.

II. CIRCUIT DESCRIPTION AND SENSOR DESIGN

Self oscillation sensors using magnetic wires were presented before in the literature [6]. They were either supplying voltage output when using magnetic wires in Colpitts oscillators, either frequency when using magnetic ribbons. Colpitts oscillators have usually nonlinear dependence of the oscillation frequency versus elements involved in circuit [5]. For the nonlinearity of the response it is also responsible the nonlinear dependence of the resistive and inductive components of the sensor versus the magnetic field. In order to have a linear response, the input quantity domain is limited to small values, or feedback is used for enlarging it. Such feedback has been used in order to get linear amplitude response. The present paper is using the magnetic nanowire in the loop of a Colpitts oscillator for obtaining the linear frequency dependence versus magnetic field and in the end versus the measured current.

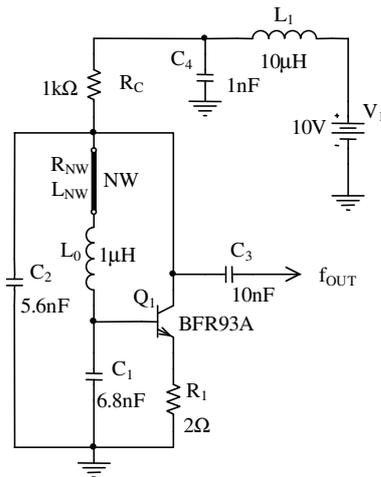The Colpitts oscillator is presented in Fig. 2.

Fig. 2. The schematic arrangement of the Colpitts oscillator

This kind of circuit is very useful for obtaining a stable and sensitive current sensor using as sensitive element a GMR nanowire. The GMR effect is amplified in the resonant circuit of the oscillator due to the simultaneous change of both impedance and current amplitude with the applied magnetic field. It creates change in both oscillation frequency and amplitude. The frequency dependence versus the circuit parameters is according to the following equation:

$$f = \frac{\sqrt{\frac{1}{C_2} + \left(1 + \frac{R_{NW}}{R_{inQ}}\right) \cdot \frac{1}{C_1}}}{2 \cdot \pi \cdot \sqrt{L_{NW} + L_0}} \qquad (2)$$

where R_{NW} and L_{NW} are the components of the impedance of the nanowire sensor, R_{inQ} is the input equivalent resistor in the active device and L_0 is the main inductance of the oscillator.

The sensitive element is a multilayered Cu/Co nanowire that acts like both reactance and resistance:

$$Z = R_{NW}(f, B) + j\omega L_{NW}(f, B) \qquad (3)$$

The nanowire inductance is much less than the inductance L_0, thus we will neglect it in the following design.

Looking to the experimental data, the linear region is between 600 Gauss to 2000 Gauss. This domain will be used for designing the circuit. The electronic feedback will extend the domain to ±2000 Gauss while moving the working point for zero field intensity in the middle of the linear domain. In order to extend the input domain and to move the zero point the circuit in Fig. 5 is used.
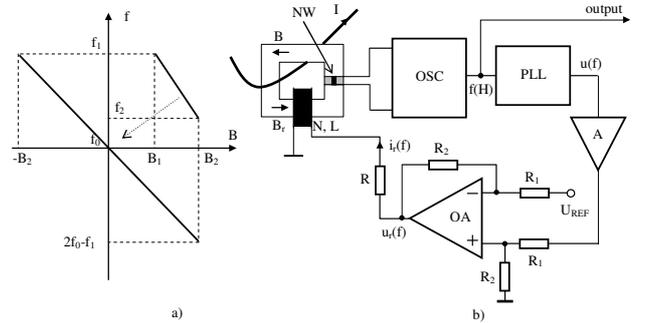
Fig. 3. The characteristic translation (a) using the schematic diagram shown in (b)

The nanowire (NW) is connected into the feedback loop of a Colpitts oscillator (O). The output signal carries out the information as frequency f(B). The feedback loop needs a voltage as feedback signal, and the conversion of the frequency to voltage is obtained with a PLL loop (PLL). The signal coming from the oscillator is not pure sinusoidal but the PLL will lock on the fundamental component of its spectrum [7]. The voltage at its output u(f) is amplified (A) and then mixed with a DC voltage (UREF) and applied to the feedback coil as a current $i_r(f)$. The feedback coil creates a feedback field (Br) in opposition with the measured one (B) generated by the measured current. Br contains a DC field that moves the zero field point and a frequency dependent field that decrease the sensitivity for domain extension.

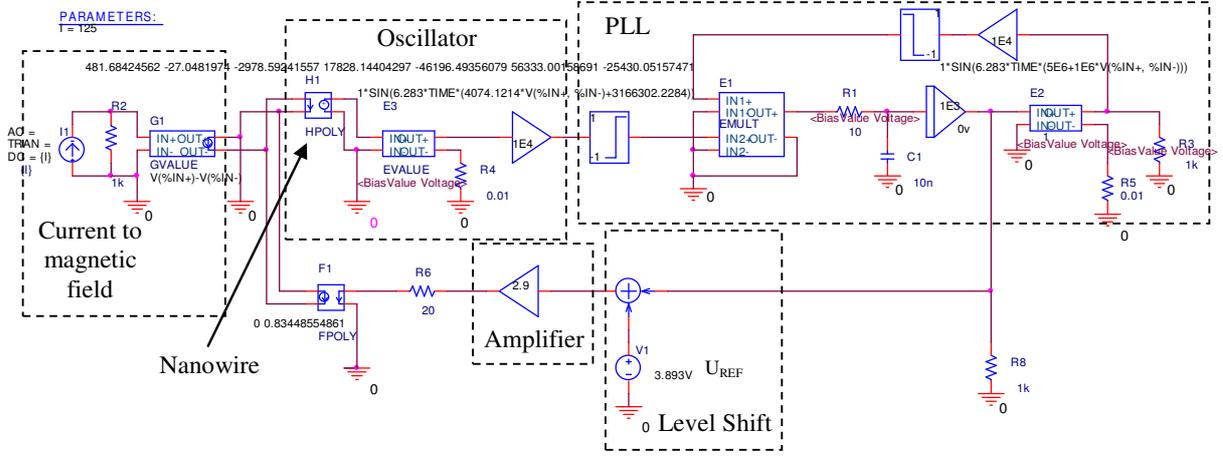We assume that the fundamental component of the output signal is:

Fig. 4. Simulation schematic

$$s(f) = U \cdot \cos(2\pi f t + \varphi) \tag{4}$$

and the PLL output voltage will have a linear dependence versus f [7]:

$$u(f) = \frac{f - f_0}{K_{PLL}} \tag{5}$$

This is amplified (A) and shifted with a DC component on the OA stage:

$$u_r(f) = \frac{R_2}{R_1} \cdot [-U_{REF} + A \cdot u(f)] =$$
$$= \frac{R_2}{R_1} \cdot \left[-U_{REF} + A \cdot \frac{f - f_0}{K_{PLL}} \right] = \tag{6}$$

The current that will drive the feedback coil is dimensioned through the resistor R is:

$$i_r(f) = \frac{u_r(f)}{R + R_L} =$$
$$= \frac{1}{R + R_L} \cdot \frac{R_2}{R_1} \cdot \left[-U_{REF} + A \cdot \frac{f - f_0}{K_{PLL}} \right] \tag{7}$$

Thus, the feedback field is:

$$B_r(f) = \mu_0 \cdot \mu_r \cdot \frac{N}{L} \cdot i_r(f) = \tag{8}$$
$$= \mu_0 \cdot \mu_r \cdot \frac{N}{L} \cdot \frac{1}{R + R_L} \cdot \frac{R_2}{R_1} \cdot \left[-U_{REF} + A \cdot \frac{f - f_0}{K_{PLL}} \right]$$

where N is number of turns, and L is the length of the magnetic circuit.

Considering the equations for the two straight line segments in Fig. 5.a:

$$f = m \cdot B + n \qquad f = m' \cdot B + n' \tag{9}$$

we find the coefficients:

$$\begin{cases} m = \frac{f_2 - f_1}{B_2 - B_1} \\ n = \frac{f_0 \cdot (B_2 - B_1) + f_1 \cdot B_2 - f_2 \cdot B_1}{B_2 - B_1} \end{cases} \tag{10}$$

$$\begin{cases} m' = \frac{2 f_2}{B_2 - B_1} \\ n' = \frac{f_0 \cdot (B_2 - B_1) - f_2 \cdot (B_2 + B_1)}{B_2 - B_1} \end{cases} \tag{11}$$

Replacing in (8) the field B with $B_m + B_r$ and notating

$$W = \mu_0 \cdot \mu_r \cdot \frac{N}{L} \cdot \frac{1}{R + R_L} \cdot \frac{R_2}{R_1} \tag{12}$$

we obtain:

$$\begin{cases} m' = \frac{m}{1 - m \cdot W \cdot A \cdot \frac{1}{K_{PLL}}} \\ n' = \frac{n - m \cdot W \cdot U_{REF} - m \cdot W \cdot A \cdot \frac{f_0}{K_{PLL}}}{1 - m \cdot W \cdot A \cdot \frac{1}{K_{PLL}}} \end{cases} \tag{13}$$

where $f = m' \cdot B_m + n'$. Identifying the coefficients m' and n' in equation (11) we obtain the gain A and the reference voltage U_{REF}:

$$A = K_{PLL} \cdot \frac{f_1 \cdot B_1 - f_2 \cdot B_2 + f_0 \cdot (B_2 - B_1)}{(f_2 - f_1) \cdot (f_0 - f_1) \cdot W} \tag{14}$$

$$U_{REF} = \frac{f_1 \cdot B_2 - f_2 \cdot B_1 + f_0 \cdot (B_2 - B_1)}{(f_2 - f_1) \cdot W} \tag{15}$$

Replacing in equations (14) and (15) with the real values B_1=600 Gauss, B_2=2000 Gauss, f_1=5.093MHz, f_2=4.906MHz, K_{PLL}=1MHz/V, R_L=18Ω, N=1000, L=0.128m, μ_r=80 and assuming that R=2Ω and R_2/R_1 =20, we get:

$$A = 2.86 \quad \text{and} \quad U_{REF} = -3.934 \text{ V} \tag{16}$$

III. SIMULATION RESULTS

The purpose of the proposed approach is to apply a feedback to the sensor in order to shift the open loop response (f_{ol}) around origin and to extend the input domain (f_{cl}) like it is shown in Fig. 5.
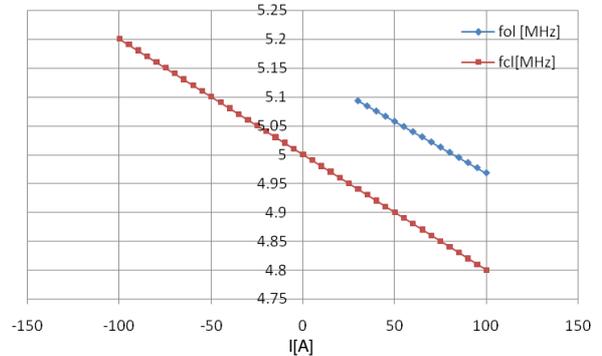

Fig. 5. Transfer function shifting

The whole application is simulated using Pspice (Fig. 4). The GMR multilayer nanowire resistance changes from 423 to 481 ohms when the magnetic field varies from 0 to 5500 Gauss. It is simulated with a HPOLY (H3 - current controlled voltage source) whose 6th order polynomial equation has been extracted from experimental data:

$R(B) = -25430.0510357 \cdot B^6 + 56333.0010069 \cdot B^5 - 46196.4932098 \cdot B^4 + 17828.1439784 \cdot B^3 - 2978.5924208 \cdot B^2 - 27.0481963 \cdot B + 481.6842458$

The simulation shows a very good approximation of real data (Fig. 6 top). The source E_3 (voltage controlled voltage source) is the Collpits oscillator that generates a sinus wave around 5 MHz. Its simulated output is presented in Fig. 6 bottom). While the magnetic field applied to the sensor varies from 0 to 4500 Gauss, the oscillation frequency changes from 5.125MHz to 4.9MHz and the characteristic is nonlinear.
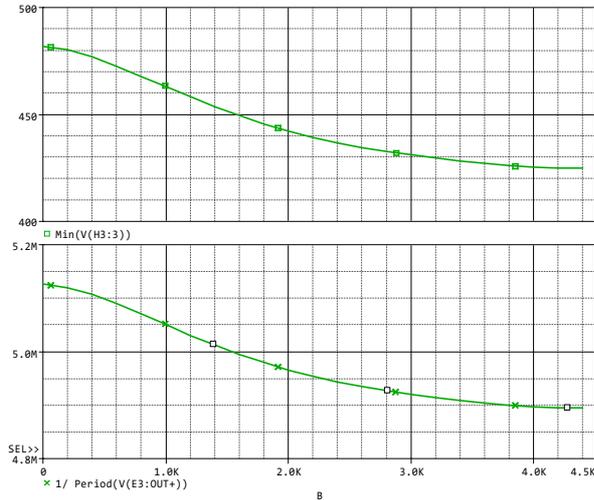

Fig. 6. Nanowire (top) and Colpitts oscillator (bottom) simulation result

The PLL loop, used to extract the frequency information, is modeled with a multiplier (E_1) as the mixer, a low pass filter (R_1, C_1) and an integrator and a voltage controlled voltage source (E_2) as the VCO (Fig. 4). The input and the feedback signals are triggered using a gain block with high gain (1000) and a limiter and transformed into a square wave in order to keep the independence of the frequency versus the amplitude of the input signal. The DC voltage that drives the VCO is used as feedback signal. The current controlled current source (F_1) models the coil that creates the feedback magnetic field. The source I_1 models the measured current; it has been varied from -100 to +100 A.

IV. CONCLUSIONS

A new type of current sensor using multilayered nanowire has been presented. Starting from its nonlinear characteristic, a linear sensor able to detect the sense of
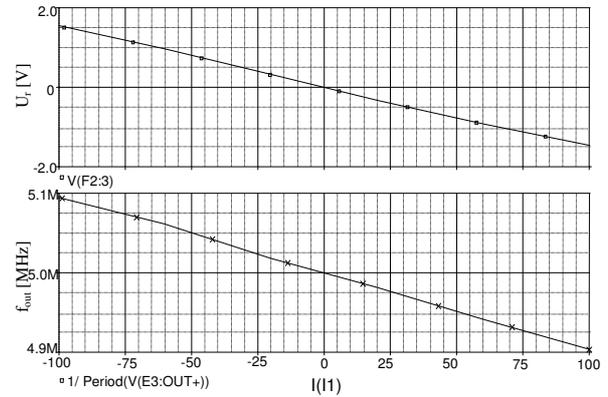

Fig. 7. The current sensor - simulation results: a) square - voltage output, b) x – frequency output

the current has been developed.

The construction is based on a simple Colpitts oscillator working around 5 MHz. The frequency domain has been chosen because the inductance of the nanowire can be neglected against the fixed coil (L_0=1 µH) of the oscillator. The negative feedback loop applies a reverse magnetic field for extending the measuring input range [-100, 100] A. The sensor has either, a frequency output [5.125, 4.967] MHz or a voltage output [-1.5, 1.5] V with linearity up to 1.8 % (Fig. 7).

V. ACKNOWLEDGMENT

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