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A multilayer planar inductor based proximity sensor operating at 4.2 K

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ABSTRACT

The design, development and testing of a multilayer planar inductor based eddy current proximity/displacement transducer is presented. Proximity/displacement of a metal surface/target in the range of 0–5 mm could be measured. The use of a cold electronics based LC oscillator operating at 4.2 K using thermal cycled stable components is reported. The frequency modulated (FM) oscillator output is a function of displacement. Calibration of the developed sensor at cryogenic temperatures was performed to ascertain the sensitivity and repeatability. Impedance analysis of the planar multilayer inductor is presented and its Q-factor is determined. Experimental results of the noise characteristics of the oscillator at various temperatures are also discussed. The developed sensor has good thermal stability, sensitivity and repeatability at the cryogenic operating temperatures.

1. Introduction

In many areas viz low temperature physics, space applications, cryo engines and superconducting magnetic suspensions, proximity or position measurement is a critical requirement [1–4]. Commonly, most of the position sensors are based on potentiometer, LVDT or eddy current principles [5,6]. Eddy current sensors operating on the principle of electromagnetic induction can precisely measure the position of a metallic target even in the presence of a non metallic barrier in between. Usually sensors operating at sub 20 K temperatures are based either on potentiometer or LVDT principle even though eddy current based sensors have higher sensitivity and large frequency responses [7]. The main reason for this is that the electronics associated with the sensor fabricated using flat coils and operating at sub 20 K region has to be kept at stable room temperature [8]. It necessitates long connecting cables from room temperature electronics to the sensor at cryogenic temperatures. As the cable is subjected to different temperatures throughout its length, it introduces significant errors in the measurement. However sensors of these types working at temperatures below 10 K are yet to be developed.

A multilayer inductor based proximity/displacement sensor with integrated electronics circuit for FM of displacement on to a carrier signal is reported here. The entire system is designed to operate at 4.2 K. The analysis and design of the multilayer sensing coil along with the circuit design and the performance are presented.

2. Design and fabrication

2.1. Principle of operation

The mathematical model of inductors in the presence of a metal target has been extensively studied in [9,10]. Consider a coil having n turns concentrated into a radius r_0 at a height h above the conductor of whose thickness t is greater than the skin depth at the operating frequency and the target conductivity is given by σ, as shown in Fig. 1.

The change in impedance of the coil is given by,

$$\Delta Z = n^2 \omega \pi \mu_0 r_0 \phi(\alpha, \beta, \rho) \tag{1}$$

where

$$\alpha = \frac{2h}{r_0} \tag{2}$$

$$\beta = r_0 \sqrt{\omega \mu_0 \sigma} \tag{3}$$

$$\rho = \frac{2d}{r_0} \tag{4}$$

are the generalized parameters and,

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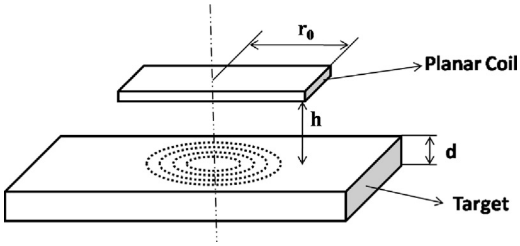


Fig. 1. Principle of operation.

Table 1
Inductor parameters.

Parameter	Value	Parameter	Value
D_{in}	4.114 mm	Conductor spacing (s)	0.254 mm
D_{out}	26.97 mm	Turns (n)	23
Conductor thickness (w)	0.254 mm	Fill factor (Θ)	0.7353

$$\phi(\alpha,\beta,\rho)=\int_0^{\infty} J_1^2(y)e^{(-\alpha y)}\frac{\beta^2(1-e^{-\rho\sqrt{y^2+i\beta^2}})}{\left(\sqrt{(y^2+i\beta^2}-y\right)^2 e^{-\rho\sqrt{y^2+i\beta^2}}-\left(\sqrt{(y^2+i\beta^2}+y\right)^2}d\alpha \tag{5}$$

here J_1 is the first order Bessel function. The impedance term $\phi(\alpha, \beta, \rho)$ is a function of h as can be seen from Eqs. (1), (2) and (5). Hence, when h is varied, ΔZ also varies and this variation can be calibrated in terms of displacement.

2.2. Design of multilayer planar inductor

The design of a multilayer planar inductor is presented in detail elsewhere [11]. The initial considerations for the prototype are the dimensions of the sensor. As the sensor has to be inserted in the sample chamber of the cryostat, the dimensions have to be limited. The other considerations were the operating frequency and the Q-factor of the coil. The operating frequency of the sensor is a function of the inductance of the coil. The Q-factor decides the sensitivity of the transducer. For a high enough Q-factor of above 10 and for a PCB based sensor the inductance needs to be above 10 μH. Initial step was to design a single layer inductor.

Table 2
Modified equations for 3 layer inductor.

Parameter	Equation	Experimental values
L_{total}	$L_1[3+4K_1+2K_2]$	59.8 μH
R_s	$3R_1$	8.4 Ω

Using the inductor parameters, given in Table 1, the inductance of a single layer can be calculated using the "Greenhouse formula" given by

$$L_1=\frac{1.27\mu_0 n^2 d_{avg}}{2}\left[\ln\left(\frac{2.07}{\Theta}\right)+0.18\Theta+0.13\Theta^2\right] \tag{6}$$

Here Θ is called the fill factor given by,

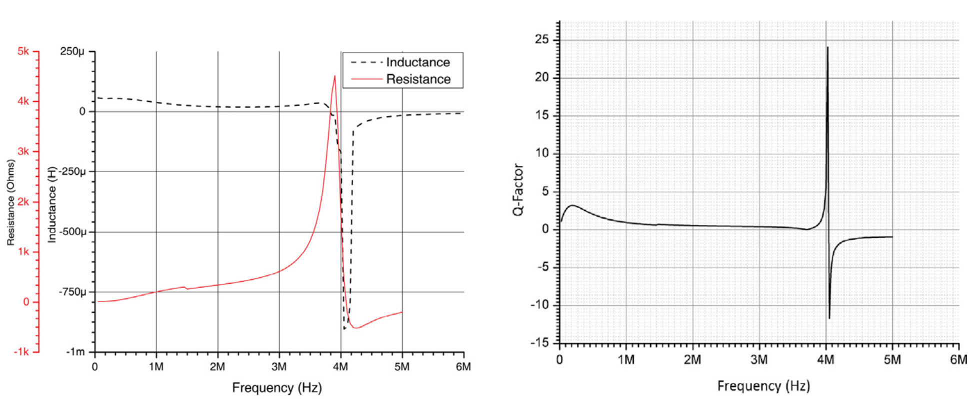
$$\Theta=\frac{D_{out}-D_{in}}{D_{in}+D_{out}} \tag{7}$$

From Eqs. (6), (7) and from Table 1, L_1 can be computed and it was 8018.9 nH. An inductance measurement at room temperature using an LCR meter at 1 kHz also gave the inductance value at 7800 nH, agreeing to the calculation. The series resistance of this single layer was measured to be R_1 = 2.8 Ω (Table 2).

Here R_1 is the series resistance of single layer; K_1 and K_2 are coupling coefficients. For a multilayer inductor, magnetic coupling exists between the different layers of the inductors. Hence the total inductance will be much more than a simple sum of the individual inductances of the three layers. All the parameters gets modified. An approximate relation to determine the total inductance L_{total} and the series resistance R_{series} is available elsewhere [11]. The equations are modified for a 3 layer stacked inductor and are shown in Table 4. The impedance analysis of the 3 layer inductor was done using E4990A Impedance Analyzer and the results are given in Fig. 2.

The inductance of the multilayer coil at the operating frequency of 150 kHz is 59.8 μH and the resistance is 15 Ω as can be seen from Fig. 2(a). The Q-factor of the coil and Self Resonant Frequency (SRF) of the coils were also determined using the impedance analyzer. The SRF of the 3 layer inductor was found to be 3.71 MHz. The Q of the device at SRF is 24 and that at operating frequency (150 kHz) is around 3 as can be seen from Fig. 2(b). This Q-factor is sufficiently high enough to provide good sensitivity for the sensor.

Fabrication of a 3 layer inductor was taken up as per standard FRP PCB fabrication process. The inductor alignment and current directions in coils were designed to give additive mutual inductance to the overall inductance value as discussed by Islam et al. [11]. The sensor and its associated electronics are shown in Fig. 3.



(a) (b)

Fig. 2. Frequency response for 3 layer inductor (a) inductance and resistance (b) Q-factor.