Printed Inductive Coil Realized using Inkjet Printing on Flexible Substrate for RFID Technology Applications

Rinin Parambil Ramachandran
Research Scholar
Faculty of Engineering
Albstadt-Sigmaringen University

Lutz Sommer
Professor
Faculty of Engineering
Albstadt-Sigmaringen University

Abstract

This paper details the option of fabricating a printed inductive coil using low-cost inkjet printing technology for the application in the area of RFID (radio frequency identification). The printed inductive coil is made out of conductive ink which is printable on a flexible Polyethylene terephthalate (PET) substrate. The printed inductive coil is produced from off-the-shelf desktop printer and conductive silver ink enabling the low production cost related to this product. Various design patterns including the number of turns, spacing and width are tested to find an optimal solution for fabricating a printed inductive coil comparable to the conventional copper based coils. The inductance, series resistance and the quality are measured using an I-V method for the printed inductive coil. In summary a low sensitive printed inductive coil with an effective average inductance of 746 nH (Nano henry) and average series resistance of 32 Ohm is being fabricated using this method. The result also indicates having a low quality factor (Q factor) less than 8 and higher series resistance associated indicating the room for improvement in fabrication process.
Keywords: Inductance, Low-cost printer, printed inductive coil, Printed electronics, Series resistance

I. INTRODUCTION

This paper deals with printed electronics approach which is one most of the promising technology emerging for the future electronics with large area, complex and integrated circuits manufacturing. Printed electronics is a form of transferring the conductive inks including silver on the dielectric materials producing conductive patterns [5] [6]. Printed electronics, especially inkjet printing is emerging as an alternative for the conventional circuit boards and alternative for the high sophisticated electronic manufacturing process. The conventional electronic device manufacturing process including the high cost etching and milling can be replaced by the inkjet printing methods which is a form of digital printing method without any pre manufactured mask [7]. This induces the reduction in the wastage of the material due to the reduced production process and digital additive manufacturing. Reduced cost of the flexible printable substrates including PET have accelerated the fabrication of the passive electronic components such as inductor and capacitor by inkjet printing for the application of the radio frequency identification (RFID) [8]. The aim of this research is to create a low cost flexible inductive coil comparable to conventional system by low-cost inkjet printing in conjunction with conductive silver nanoparticle ink and flexible PET (Polyethylene terephthalate) substrate. Demonstrations of the fabrication of low frequency passive components such as resistors, capacitor and inductors with an operational range of 10 MHz through inkjet printing have been put forward in the literature [9-11]. The fabrication of the conventional circuits including the Flexible printed circuits and the printed membrane switches are demonstrated in the literature [15]. The study of the stability of the inkjet printed silver nanoparticles in combination with polymer ink were demonstrated in the literature [16] [17] to understand the life time of the circuits printed by these off-the-shelf desktop printers used for fabrication. These technical works have been adopted as the basis for this research work [16] [17]. Introduction of carbon nanotubes and nanowires have also opened huge window for the development of radio frequency identification (RFID) components and different sensor based on it. This paper is focused on the development of silver nanoparticle based low profile printed inductive coil on PET substrate. The paper elaborates the challenges associated with fabrication of passive electronic component in context to the printed electronics with a low cost desktop printer and conductive silver ink. Based on the above facts following Hypothesis have been formulated.

H1:	If changes in physical dimensions including the width and spacing of the conductive traces in inductive coil is made then there is a linear increase/decrease in the series resistance around 20 % is associated with the coil.

H2:	if printed conductive traces are multi-layer printed (increase in thickness from 0.35 µm to 0.7 µm) then there is an improvement of the series resistance at least 10 % and quality factor (Q factor) related to the printed inductive coil.

II. METHODS

A. *Design & Printing of the Inductive Coil:*

The fabrication of the printed inductive sensor was done in conjunction with the low cost desktop printer and conductive silver ink. The printer used in the fabrication process is off the shelf Brother MFC-J6710DW [3]. This printing is based on the Piezo-Technology with the highest resolution of 1200*6000 dpi for printing. The selection of the specific printer is based on the criteria of enabling the fabrication of the printed traces/sensor at very low level. The various design concepts for the inductive coils were adopted with distinctive number of turns, thickness and the width of the printed sensor as the variable parameters. The design of the inductive sensor was centered on the series & parallel resistance associated to the inductive coil. The thicknesses of the printed coils were kept to a maximum of 0.75 µm (micro meter) due to the limitation of the printer selected. The inductive coils were designed using eagle software with varying spacing, width and number turns of the coil. An electrically conductive Silver ink (AgIC Inc.) [1] with a sheet resistance of up to 200 mΩ/sq were used for printing. The selection of the ink was based on the fact that no additional sintering process is needed for curing, the ink can be cured with normal room temperature. The integration of the adopted silver ink to the printer was easier. The substrate used was coated and matt finished PET (Polyethylene terephthalate) with thickness of 140±12 µm from Novacentrix [2] (Novele™). This is specially coated PET (Polyethylene terephthalate) enabling the inkjet printing of the inks. The Table.1.1 shows the various design patterns made and the corresponding inductance associated with the printed coil.

B. *Measurement of the Inductance:*

The measurement of the unknown inductance was carried with I-V method with a precision resistor in series with unknown resistor [4]. The I-V employs the measurement of the current and voltage across the device-under-test (DUT) in this case the unknown resistor. The current through the precision resistor (Rref) is calculated by the voltage drop across the same. The unknown impedance is calculated numerical Equation 1 from the voltages measured.

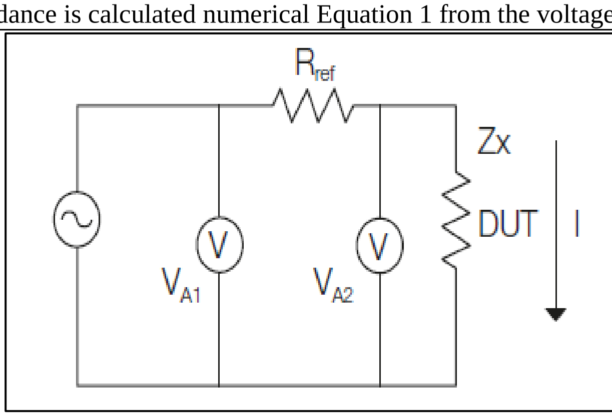

Fig. 1: Illustration of the I-V method test circuit [4]

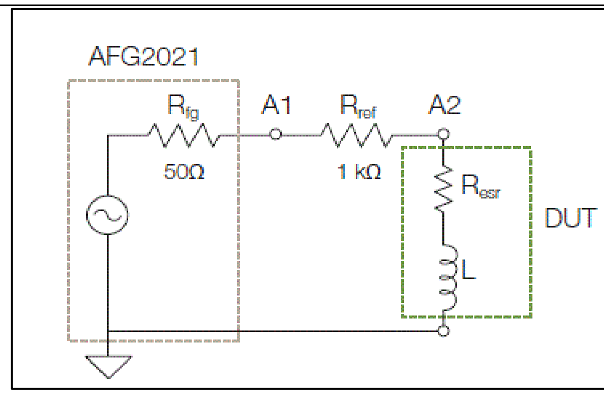

Fig. 2: Setup for measuring unknown inductance [4]

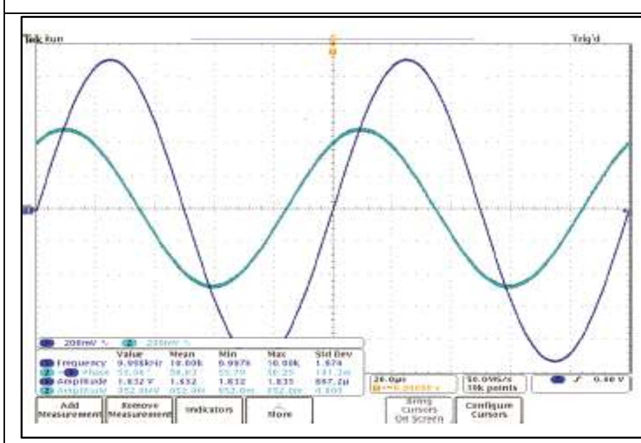
Fig. 3. Voltage waveforms at A1 and A2 [4]

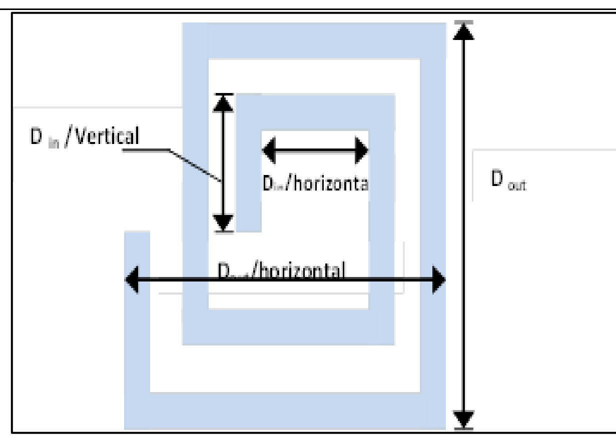

Fig. 4. Design specification of spiral inductive coil [18]

$$Z_X = \frac{V_{A2}}{I} = \frac{V_{A2}}{V_{A2}-V_{A1}} R_{ref} \quad (1)$$

Figure 2 illustrates the test setup using I-V method to calculate the unknown inductance (L) using a function generator and oscilloscope. Rohde & Schwarz HMF 2525 model was used as the function generator with an output frequency range of 25 MHz and HAMEG HMO 2524 model digital oscilloscope was used to visualize and measure the output voltage sinusoidal waveforms from the nodes A1 and A2. RESR is the series resistance associated with the unknown inductor (L) and Rfg is the 50 Ω function generator's output impedance. Rref is the 1kΩ precision resistor taken as the reference for the measurement. The amplitude of the voltage from the function generator is set to 1.9 V. The frequency of the function generator adjusted until there is a phase difference between the input sinusoidal waveform and the waveform generated across the unknown inductance (L). The property of inductive impedance with current waveform lagging behind the voltage waveform is used as the principle for the measurement. Measurement of the voltage across the nodes A1 and A2 were made. This will be denoted as VA1 and VA2 in the Equation (2) [4]. Oscilloscope was used to measure the phase difference (θ) of the voltage measured at A2 relative to A1. Calculations were made to calculate the impedance expressed in polar form as per the Equation 2. Calculation is made as per Equation 3 to get the angle of impedance (α). The calculation of the unknown inductance is carried according the Equation 7 [4] where Z is the impedance of the circuit expressed in polar form, α is the calculated angle of impedance and the f is the resonating frequency measurement through the oscilloscope. Impedance expressed in polar form [4]

$$Z = \frac{V_{A2}R_{ref}}{\sqrt{V_{A1}^2 - 2V_{A1}V_{A2}\cos\theta + V_{A2}^2}} \quad (2)$$

Angle of impedance [4]

$$\propto = \theta - \tan^{-1}\frac{-V_{A2}\sin\theta}{V_{A1} - V_{A2}\cos\theta} \quad (3)$$

Converted rectangular form of impedance to calculate the resistance and the unknown inductance [4]

$$Z = R_{ESR} - \frac{j}{2\pi f L} \quad (4)$$

$$Z = Z\cos\alpha + jZ\sin\alpha \quad (5)$$

$$R_{ESR} = Z\cos\alpha \quad (6)$$

Calculation to find the unknown inductance of the DUT and Quality factor [4]

$$L = \frac{Z\ sin\,\alpha}{2\pi f} \quad (7)$$

$$Q = \frac{2\pi f L}{R} \quad (8)$$

III. RESULTS

For the Hypothesis H1 different design was adopted to test the inductance and the series resistance associated with the printed inductive coil. The variable parameters for the test include the spacing, width and Thickness of the inductive coil. Single layer printing and multilayer printing was adopted to visualize the change in the series resistance associated with coil.

Table – 1
Characteristics of the printed inductive coil [18]

Sample No.	*Spacing in mm*	*Width in mm*	*Thickness in µm (micrometer)*	*Number of Turns*	*Series resistance in Ohms*	*Inductance in nH (nano Henry)*	*Number of layers*	*Quality (Q) Factor*
1	*1*	*1.5*	*0.35*	*3*	*56.26*	*980*	*Single*	*1.4834*
2	*1*	*1.5*	*0.35*	*2*	*25.5*	*1390*	*Single*	*3.4232*
3	*1.5*	*2*	*0.35*	*2*	*13.33*	*640*	*Single*	*4.0885*
4	*1*	*0.5*	*0.35*	*2*	*80*	*600*	*Single*	*0.6387*
5	*1*	*0.5*	*0.7*	*2*	*28.1*	*530*	*Single*	*1.6062*
6	*2*	*2.5*	*0.7*	*3*	*14.15*	*760*	*Multi*	*5.7341*
7	*1*	*3*	*0.7*	*2*	*6.87*	*610*	*Multi*	*8.3642*
8	*1*	*0.5*	*0.7*	*2*	*28.1*	*530*	*Multi*	*1.606*

Table 1 characterizes different parameters which were considered for the design of the inductive coil. The highest quality factor (Q factor) was achieved with the sample number 7 which has spacing between the winding as 1mm and width of the windings as 3 mm. The goal of this research was to find an optimized design of a printed inductive coil which can be used in the application of the radio frequency identification (RFID) [18]. Various design concepts were adopted to optimize the series resistance and increase the active area of the printed inductive coil. The Table 2 characterizes different geometrical parameters adopted to increase the active area of the printed inductive coil keeping the number of turns as constant variable [18]. At least five sample models of each design have been fabricated and tested to improve the repeatability of the experiments and reduce the error associated with the fabrication process. The average values of electrical parameters have been taken into account and are depicted in Table 1 & 2. For the inductance measurement the frequency is varied in the range of 6 MHz – 17 MHz so that property of inductive impedance with current waveform lagging behind the voltage waveform is visible. The calculations of the resonating frequency in combination with parallel connected capacitor (tank circuit) of the printed inductive coil have not been taken into the measurement perspective. Calculation of the quality factor (Q factor) is done based on the equation 8 [4].

The multilayer printing was employed to create the sample 7 and due to the limitation of the printer [3] used for fabrication, more layers was not possible. The higher resistance associated with the sample 1 & 4 were also due to the limitation of the printer to print accurately the thin traces below 0.35 µm (micrometers). From the Table 1 observation can be made that best inductive coil fabricated using the single layer printing was sample 3 with a quality factor (Q factor)of 4.0885 and best sample for the multilayer printing was sample 7 with quality factor (Q factor)of 8.3642.

Table – 2
Design specification of adopted for spiral inductive coil [18]

Sample No.	D_{in} /horizontal in mm	D_{out} /horizontal in mm	D_{in} /Vertical in mm	D_{out} /Vertical in mm	Number of Turns	Series resistance in Ohms	Quality (Q)Factor
1	19	26	11	19	2	25.5	3.4232
2	11	23	8	11.5	2	13.33	4.0885
3	20	25	10	14	2	80	0.6387
4	20	25	10	14	2	28.1	1.6062
5	15	29	7	22	2	6.87	8.3642

When compared to the commercially available inductive coil the quality factor (Q factor) was pretty low cannot be used in any application including the RFID tags. The lower sensitivity of the printed inductive coil was also major roadblock for implementing into any RFID Application. From the quantitative information from Table 1 the fabrication of inductive coil was possible with low cost off the shelf printer in conjunction with silver nanoparticle inks and flexible substrates with a range of inductance 600-1400 nH (Nano Henry) and quality factor (Q factor)less than 8. The practical application of these kinds of cheap and low-cost inductive coils in RFID application is not applicable due to its poor electrical parameters.

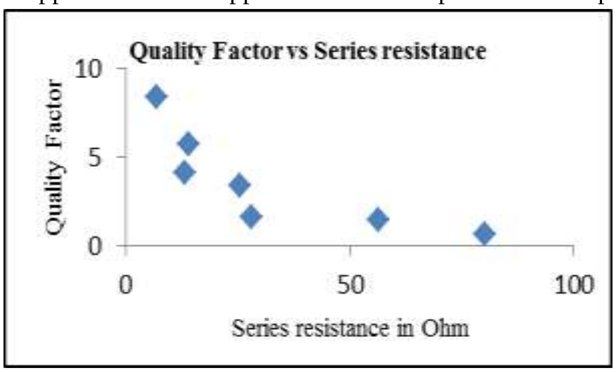

Fig. 5: Plot between the series resistance and quality factor

Fig. 6: Printed inductive sensor [18]

IV. Discussion

A. *Hypothesis Testing:*

1) Hypothesis 1:

Hypothesis 1 is confirmed from the experimental data visualized in the Table 1. The change in the physical dimensions of the printed spiral inductive coil including the spacing and width of the conductive traces influences the series resistance. This can be visualized by the comparison of sample number 2 and 3 in from the Table 1. An improvement for the series resistance of sample 3 of 13.33 ohms from 25.5 Ohm is observed when the width of the conductive traces is increased from 1. 5 mm to 2 mm when compared to the sample 2. The improvement of the resistance of 47.72 % is observed with the change in the dimensions of the printed inductive coil for the compared samples. This also points to the fact that improved series resistance and hence the improved quality factor (Q factor) can be achieved by increasing the active area of the printed inductive coil by keeping the number of turns constant. This can be practical visualized by the sample 1 and sample 2 from the Table 2.

2) Hypothesis 2:

Hypothesis 2 can be confirmed from the experimental data measured in the Table 1. The series resistance and quality factor (Q factor) is highly influenced by the thickness of the printed conductive traces. The improvement in both of the factors is visualized when the conductive traces are multi –layer printed. This fact is clearly visible in the data for the sample number 7 in the Table 1 having highest quality factor (Q factor) of 8.3642 and least series resistance 6. 87 ohms associated with it. The improvement of series resistance and associated quality factor of more than 50 % is visible with the experimental results. This improvement can be linked with the increase in the thickness/active area of the printed traces (0. 7 micrometer) in the multi-layer printing process in comparison to single layer printing (0. 35 micrometer).

B. *Implications & Limitations:*

The fabrication of printed inductive coil using a low cost off the shelf printer is possible in conjunction with sliver conductive ink and flexible substrate. The inductance value achieved was an average value of 787. 14 nH (Nano Henry) with an average series resistance of 32 Ohms. This low cost-desktop printers in conjunction with the conductive nanoparticle inks can serve as an alternative for high –end & costly industrial printers for rapid prototyping of the printed flexible electronic. The research explores the various cost effective fabrication methods which could effectively lead into cost effective printed flexible electronics fabrication. The result of the research indicates room of improvement of the effective inductance and reduction of the series resistance when compared to the conventional copper based inductive coil. The stability of the measurement is a concern with the values fluctuating due to the influence of the electronic noise and cable connecting the printed inductive coil also coming as add-on to the measurement. This aspect can be improved by improved measurement techniques and also improved quality of the printed inductive coil. The sensitivity of the printed inductive coil is also questionable for improvement. Fabrication of printed inductive coil using ferromagnetic particles to improve electrical properties will be option and can be imparted as the future work. The limitation also includes quality factor (Q factor) achieved by this fabrication process being less than 8 which is far below the acceptable rate for the application of the conventional RFID application. The fabricated printed inductive have lesser/smaller inductance when compared to the arts mentioned in the literature (L= 2. 82 µH) [12]. This is due to the limitation of printing the more than two layers of conductive traces with the current printer. The Higher resistance associated with printed inductive coil is due to the printer resolution which is limited to 600 * 1200 dpi [3]. The thickness of the printed inductive coil is also restricted to 0.7 µm (micrometer) due to the restriction of the print head. This can be improved with the fabrication using a professional inkjet printer with 5 axes movement (e.g. LP 50 Pixdro printer [14]). The improvement of the inductance by integrating ferromagnetic material as described in the literature [13] could be for seen as future work of this research.

V. Conclusion

In summary fabrication of low sensitive inductive coil in conjunction low cost circuit printer is possible on flexible substrate [2]. The improvement of quality factors, inductance and series resistance associated with the printed inductive coil can be imparted as the future work. The experimental results indicate that the fabricated printed inductive coil cannot be employed in the conventional RFID (radio frequency identification) due to its higher series resistance and smaller quality factor. The integration of mentioned flexible printed electronic circuity can open up a new window for development in low cost electronics. The high cost associated with current printed electronics process is closely linked with the high cost of high end printers and proposed method with low cost printers can be alternative to reduce the cost. The study also points to the room for improvement of quality associated with low cost printers to compete with high end inkjet printers to reduce the cost related to flexile electronic printing.

Acknowledgment

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