Design of a Multi-Spiral Solenoidal Inductor for Inductive Power Transfer in Biomedical Applications

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Abstract: Inductive power transfer is the most common method for transferring power to implantable sensors inside human body. For good inductive coupling, the inductors should have high inductance and high quality factor. But the physical dimension of the receiver inductor cannot be large due to biomedical constraints. Therefore, there is a need for small size and high inductance, high quality factor inductors for implantable sensor applications. In this work, design of a multi-spiral solenoidal inductor for biomedical application is presented. The inductors are simulated and optimized for targeted application using a commercial electromagnetic tool, Sonnet. Parametric study of the multi-spiral inductor is investigated in terms of number of layers, metal spacing, and metal width. Finally, it is demonstrated that the proposed multi-spiral solenoidal inductor exhibits a better overall performance in comparison with the conventional spiral inductors for biomedical applications.

Keywords: Solenoidal, Multi-spiral, Inductor, Sonnet, Biomedical, PCB

1. Introduction

A wireless body area network based patient monitoring system is proposed for a comprehensive healthcare alternative [1]. This system provides early detection of abnormal conditions and prevention of serious consequences. In this system body sensors monitor various physiological phenomena (ECG, oxygen, temperature, motion, glucose, etc.) and send the data to a server computer which communicates with the central database through the internet. The data is monitored and stored in the central database and based on the sensor data proactive measures could be taken by healthcare providers. Some of the physical phenomena can be monitored by only placing implantable sensors inside the human body. The sensor electronics require power, but it is very dangerous to put a battery inside the human body as it can come in contact with the body fluids and can cause serious health risks. For this reason wireless power transfer concept come into play by which power can be supplied inside human body via this non-invasive method.

Inductive power transfer is the most common method of wireless power transfer to implantable sensors. In this method, two mutually coupled inductors work as an air core transformer to transmit or receive the power. For good inductive coupling, the implantable inductor should have high inductance (L) and high quality factor (Q). But the implantable inductors cannot be large due to biomedical constraints. Therefore, there is a need for high L and high Q inductors which occupy less physical area [2]. In this work, design of a multi-spiral solenoidal inductor for biomedical application capable of operating at 13.56 MHz ISM band is presented. Low frequency operation is advantageous due to biomedical restrictions. The inductors are simulated and optimized for targeted application using a commercial electromagnetic tool, Sonnet [3]. The effects of variation of the design parameters in terms of L, Q, and self resonance frequency (SRF) are presented in the following sections.

2. Design of Multi-Spiral Solenoidal Inductor

Spiral planar inductors are widely used in radio frequency applications. In this work, we use a multiple layer spiral inductor in a particular orientation to increase the total inductance value within the constraint of physical size limit of the inductor. The self inductance of a conductor is derived by Grover [4] as,

$$L_{self} = 2.l.\left\{ln\left(\frac{2.l}{w+t}\right) + 0.5 + \frac{w+t}{3.l}\right\} \tag{1}$$

where L_{self} is the self inductance, l is length, w is width, and t is the thickness of the inductor. In presence of mutual inductance (M), the total inductance can be calculated as [5],

$$L_{Total} = \sum L_{self} + \sum M_{+} - \sum M_{-} \tag{2}$$

where M_{+} is positive mutual inductance and M_{-} is the negative mutual inductance as illustrated in Fig. 1. From equations (1) and (2), it is evident that inductance can be increased if the length of the metal trace is increased and if the effective mutual coupling between metal lines works as positive coupling. This concept is utilized and expanded to design the multi-spiral solenoidal inductors. Figure 2(a) and 2(b) depict the top layer of the 4-layer inductor and the 3D view of the inductor, respectively.

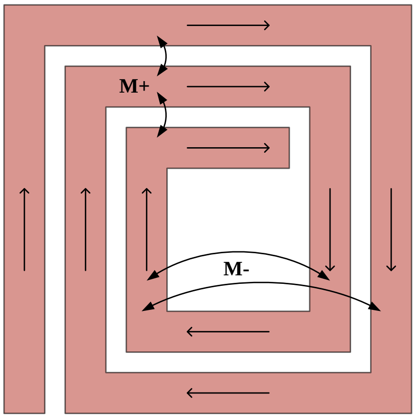
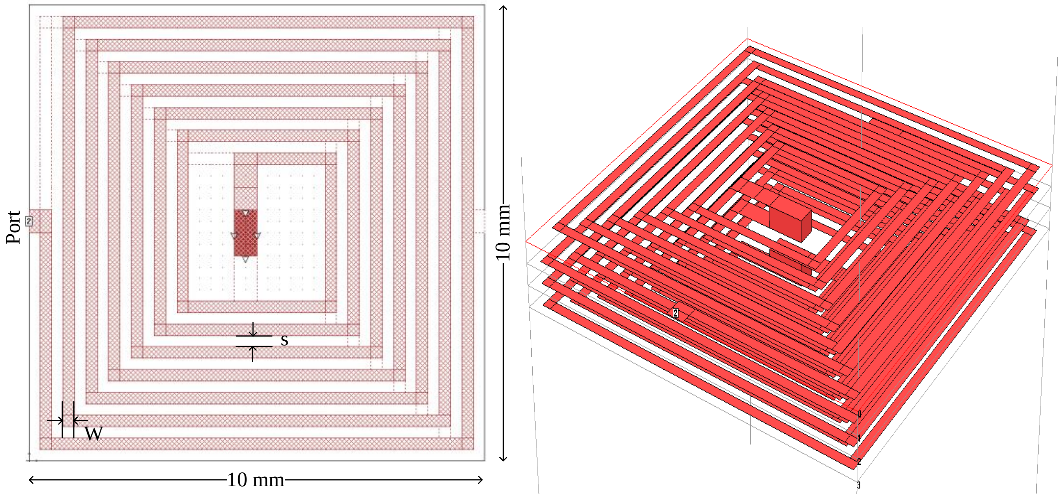


Fig. 1. Positive and negative mutual inductance in a planar spiral inductor.



(a) (b)

Fig. 2. (a) Top view of the designed 4 layer inductor (b) 3-D view of the designed inductor.

3. Simulation Results

A. PCB Inductor Design

The inductor is designed and simulated using Sonnet. For the simulation, the structure of a commercial 4 layer PCB is assumed with FR-4 as the substrate material and copper as the metal layer. For physical constraints, the size of the inductor is fixed to 10 mm x 10 mm. The inductors are simulated up to 100 MHz, considering the application for biomedical systems. L and Q can be calculated from the admittance parameter as follows,

$$L = \frac{Imag\left(\frac{1}{Y21}\right)}{2.\pi.f} \tag{3}$$

$$Q = \frac{|Imag\,(Y_{11})|}{Re\,(Y_{11})} \tag{4}$$

Figure 3 demonstrates L and Q of inductor over a frequency range. This inductor shows promising performance in terms of L and Q particularly in the low frequency range, which is desirable for biomedical applications. Current densities of the designed inductor are shown for 17.75 MHz and 90.25 MHz in Fig. 4(a) and Fig. 4(b), respectively. Current crowding effect is obvious in Fig 4(b). The design is summarized in Table 1.

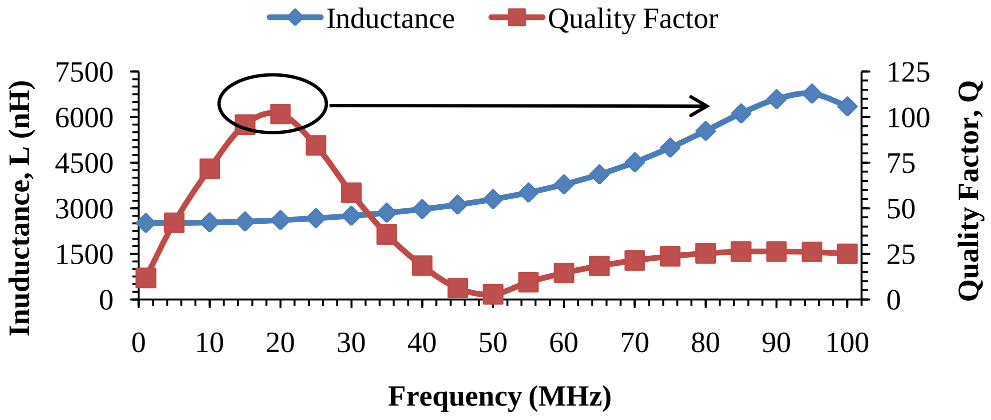
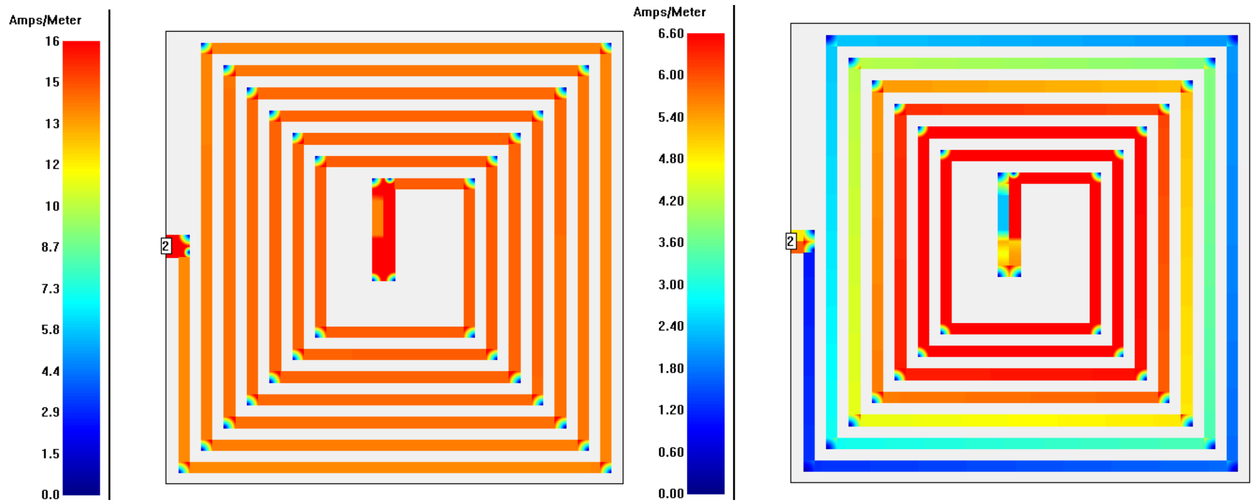


Fig. 3. Inductance and quality factor of the proposed inductor.



(a) (b)

Fig. 4. Current distribution of the top layer of the inductor at frequency (a) 17.75 MHz and (b) 90.25 MHz.

Table 1: Summary of the proposed design

Parameter	**Value**
Size	10 mm X 10 mm
Metal spacing	0.25 mm
Metal width	0.25 mm
Number of layer	4
Self resonant frequency	48.25 MHz
Inductance, L (13.56 MHz)	2546.5 nH
Quality factor, Q (13.56 MHz)	89.8504
Peak quality factor, Q_{peak}	102.59 @ 18.75 MHz
Peak inductance, L_{peak}	6775.19 nH @ 95 MHz

B. Variation of Physical Parameters

The effects of variation of design parameters (number of the metal layers, spacing of the metal traces, and width of the metal trace) are presented in the following sections.

a. Variation of number of metal layers

Inductors have been designed for the number of metal layers varying from 1 to 4 and the results are shown in Fig. 5. Inductors in multiple PCB layers are oriented in such a way that they keep a solenoidal structure and mutual coupling between metal lines are constructively added to the overall inductance value. From Fig. 5, it is evident that as the number of metal layers is increased the inductance value is increased, while the self resonance frequency is decreased. If we increase the number of metal layers, the effective length of the inductor is increased resulting in an increase in the inductance (see equation 1). Increment of the number of layers, also, increases the parasitic capacitance value thereby reducing the self resonance frequency.

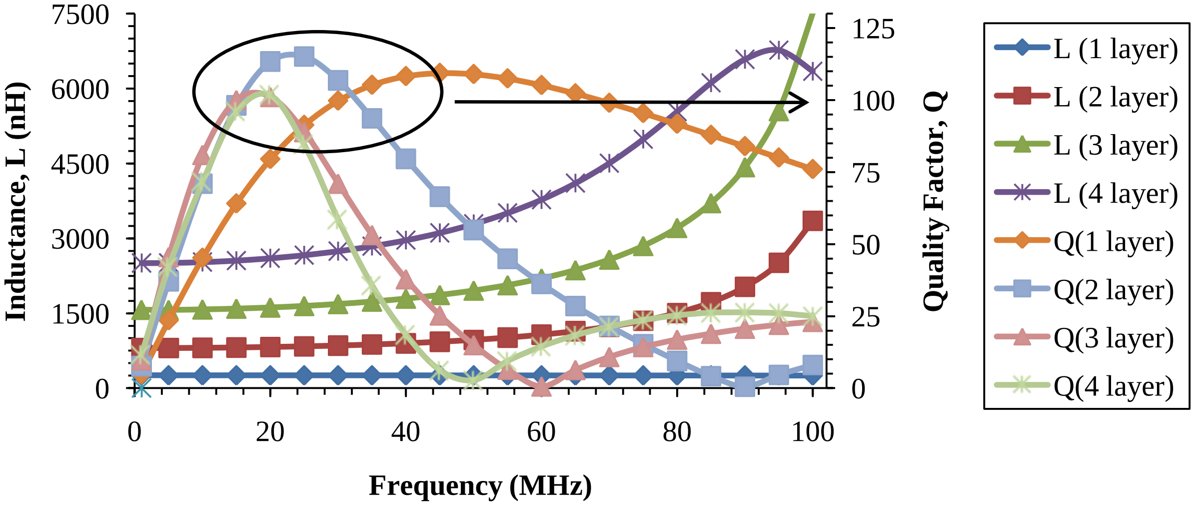


Fig. 5. Effect of variation of number of metal layers on inductance and quality factor. Both metal spacing (s) and width (*w*) are kept at 0.25 mm.

b. Variation of metal spacing (s):

The spacing (s) between metal traces, also, changes the effective inductance and quality factor. The effect of the change in metal spacing from 0.25 mm to 0.75 mm is illustrated in Fig 6. As the metal spacing is increased, the inductance is decreased while the SRF is increased. When the metal spacing is increased, the effective length of the total conductor is decreased and as a result inductance is decreased. Similarly, increase in metal spacing reduces the parasitic capacitance and consequently increases the SRF.

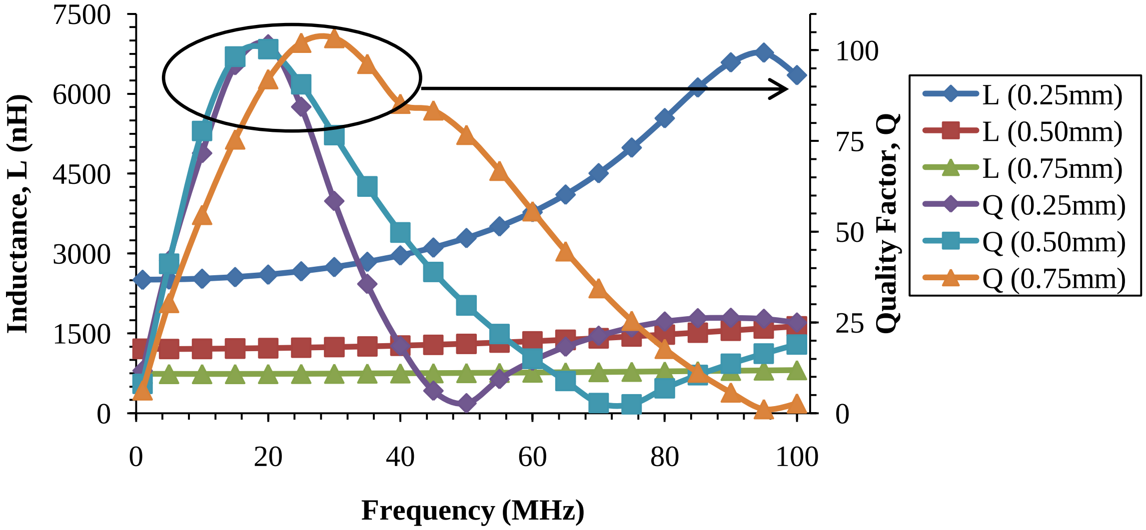


Fig. 6. Effect of variation spacing (s) between metal traces on inductance and quality factor. Metal width (w) is kept at 0.25 mm in a 4 layer design.

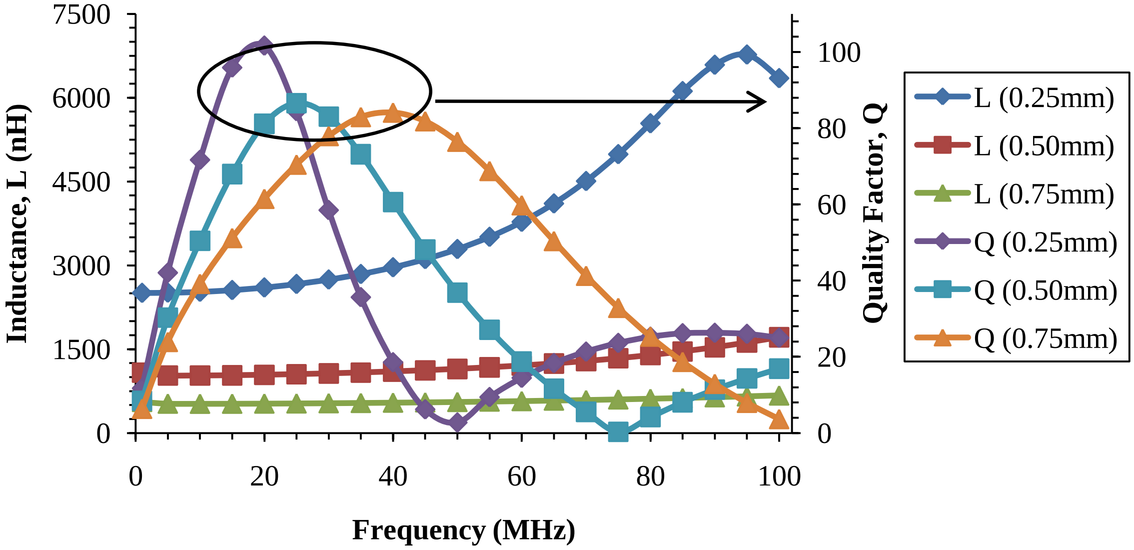


Fig. 7. Effect of variation metal width (*w*) on inductance and quality factor. Metal spacing (s) is kept at 0.25 mm in a 4 layer design.

c. Variation of metal width (*w*):

The variation of metal width (*w*), also, changes the effective inductance and the quality factor of the inductor. The results for the change in the metal spacing from 0.25 mm to 0.75 mm are shown in Fig 7. It is obvious from the figure that as the metal width is increased, the inductance is decreased and the SRF is increased. When the metal width is increased, the effective length of the total conductor is decreased and, as a result, inductance is decreased. Similarly, increase in metal width reduces the parasitic resistance and consequently increases the SRF. The change in SRF due to variation of the design parameters are summarized in Table 2.

Table 2: Effect of variation of design parameters on self resonance frequency (SRF)

Variation of number of layer	Layer	1	2	3	4
	SRF (MHz)	207	89.5	59.5	48.25
Variation of metal spacing	Spacing (mm)	0.25	0.5	0.75	-
	SRF (MHz)	48.25	72.5	96.5	-
Variation of metal width	Width (mm)	0.25	0.5	0.75	-
	SRF (MHz)	48.25	75.25	105	-

4. Conclusions

For implantable biomedical sensor applications, there is an acute need for high inductance and high quality factor inductors with reduced area for inductive power transfer. In this paper, we propose a design of a multi-spiral solenoidal inductor. Multiple inductors of different levels are oriented in such a way that the mutual couplings of the inductors are added together increasing the effective inductance. Although the self resonance frequency is reduced in this scheme, it is still within the range of biomedical applications. The effect of the variation of various design parameters (e.g. number of layers, metal spacing, and metal width) on inductance, quality factor, and self resonance frequency of multi-spiral inductor is also investigated. The designed inductor exhibits inductance of 2546.5 nH and quality factor 89.85 at 13.56 MHz. Peak quality factor of 102.59 is achieved at 18.75 MHz and self resonance frequency is found to be 48.25 MHz. This proposed inductor is suitable for inductive coupling in wireless inductive power transfer.

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