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Design and optimization of a microfluidic-based inductor used as a multifunction-sensor

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Abstract: A planar miniaturized inductor has been designed in order to realize some transduction functions linked to the presence of fluids. Its electrical behavior has been studied for two liquids: Galinstan (an alloy of GALium INdium STANum) and salted water. Their presence between metallic armatures modifies the inductance value at a nominal frequency, chosen at 2GHz. By using a FEM software, the spatial distributions of magnetic field and surface current density in the entire device have been modelized for six arbitrary positions of these liquids in inductor microchannels. The geometrical aspects of the device have been studied and their influence examined for each liquid. We show that the inductor performances are influenced by the spiral width variations and the inter-turn distances of the coil. Considering the device as a sensor, we have evaluated the variations of two parameters: inductance and quality factors, which can respectively attain 664% (for Galinstan) and 175% (for salted water) from their nominal values.

Keywords: Variable inductor; sensor; micro-fluids

Zasnova in optimizacija mikrofluidne tuljave za večfunkcijski senzor

Izvleček: Zasnovana je bil planarna miniaturna tuljava, ki omogoča izvajanje nekaterih prenosnih funkcij, povezanih s prisotnostjo tekočin. Njeno električno obnašanje je bilo preučeno za dve tekočini: Galinstan (zlitina GALija INdija in STANija) in slano vodo. Njuna prisotnost med kovinskimi armaturami spremeni induktivnost pri izbrani nazivni frekvenci (2 GHz). S programsko opremo FEM so bile modelirane prostorske porazdelitve magnetnega polja in gostote površinskega toka v celotni napravi za šest poljubnih položajev teh tekočin v mikrokanalih tuljave. Preučeni so bili geometrijski vidiki naprave in njihov vpliv za vsako tekočino. Pokazalo se je, da na delovanje tuljave vplivajo spremembe širine spirale in razdalje med zavoji navitja. Če napravo obravnavamo kot senzor, smo ocenili spremembe dveh parametrov: induktivnosti in faktorjev kakovosti, ki lahko dosežejo 664% (za Galinstan) oziroma 175% (za slano vodo) svojih nazivnih vrednosti.

Ključne besede: spremenljiva tuljava; sensor; mikrofluidika

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1 Introduction

In the large domain of instrumentation, particularly those devoted to the high-frequency spectrum it is necessary to conduct studies in order to develop components, circuits and systems whose characteristics will be used for different applications. Among the passive electronic components, the inductor is largely used in the communication domains, particularly those developed by using microsystem technologies. The objective of this miniaturization is twofold: integration and parameterization of the different operating modes linked to a given application. In the field of RF applications, like those researched in embedded electronics, the need for continuously variable micro-nano devices is crucial [1-3].

In the continuity of our previous works on MEMS devices, particularly those using 'microfluidic technology ', we propose, by using FEM software, a modeling approach to design and optimize a variable micro-in-

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ductor. The inductance variations can be based on the dielectric properties of fluids and their positions in the inner channel constructed between the metallic armatures of the device. This choice, based on previously realized devices, will constitute the transducer element used not only in continuously variable electronic components, but also as a multifunction's sensor.

The choice of conductive liquid is important, especially for RF applications: 'metal' liquids are appropriate due to their high electrical conductivity, their held at high temperatures, supporting hence high electric power, and providing low losses. However, the high melting temperature of metals (~1000 °C for gold and ~660 °C for aluminum) presents a real obstacle prohibiting their exploitation in microfluidic systems. GALINSTAN (GALLium INdium STANum) has attractive characteristics: low melting temperature -19°C, high electrical conductivity σ = 3.46 106 S/m. Galinstan has become the most widely used metallic conductive liquid in radio-frequency applications such as: antennas, RF filters, and RF switches [4-10]. There are other possible alternatives to Galinstan, e.g. "Gallium-Indium-Tin (GaInSn) alloy", with similar properties and would presumably perform similarly to Galinstan. Other, low or non-conductive liquids like Ethanol and similar would not affect the behavior of the inductor very much and would therefore not be a good choice.

We have focalized our study on the behavior of a 6 turns coil inductor incorporating 3-turns microfluidic channels partially or totally filled with liquids [11-14].

Two liquids have been tested, saturated saline water (357 g/L), and Galinstan, chosen for their particular dielectric properties. By modifying their quantity present in the channels, the core permeability will be modified, given hence noticeable variations of the nominal value of inductance. Their presence and positions in the channel should modify the distributions of the magnetic field and electric current density, giving indirect information on the nature of the liquid, and/or the parts of the channel containing air or liquid and their spatial repartitions.

On another hand, in order to assure the inclusion of the device as an active element of an RF circuit, we choose to operate at 2 GHz (resonant frequency of the microfluidic inductor). A frequency conversion, by means of a passive resonator containing the liquid-based inductor, allows to use it in applications associating tuning/sensing or quality factor.

2 Microfluidic inductor as a sensor

2.1 Variation principle

The projected device is based on a miniaturized coil used as a micro-sensor. Its schematic principle is represented in Fig. 1: it has a dual system of channels in which a microfluid can circulate, occupying partially or totally the space between metallic plots, called 'spiral 1' and 'spiral 2'.

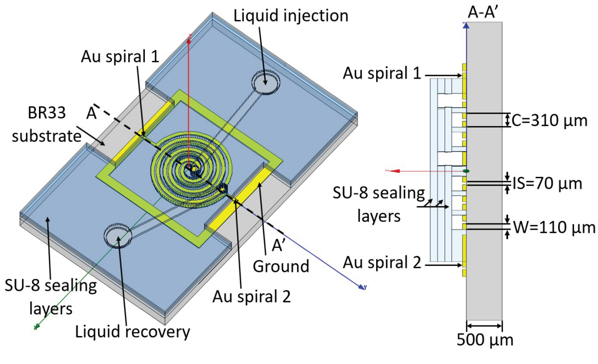


Figure 1: A five-turns MEMS microfluidic inductor: (a) 3D view perspective (b) cross-section.

The particular dielectric properties of fluids and their positions in the channel (between 'injection hole' and 'exit hole') will be chosen according to the device's intended use. As can be seen in equation (1), the intrinsic value of the inductance L is affected not only by its dimensions (length l, number of spires N, and surface S) but also by the permeability μ_r of the fluid present in the channel:

$$L = \mu_0 \mu_r N^2 S/l \tag{1}$$

The dielectric properties of liquid and air in the channel modify the electrical behavior of the inductance. Also, by aging on the fluid circulating or positioned in different parts of the channel, it will be possible to use the device as a sensor not only to detect the presence or absence of fluids/air, but equally to indicate the respective position of each of them.

Consequently, the electric current distribution in spirals is affected by the presence or absence of liquid between the channel.

2.2 Design characteristics

The cross-section of the device (Fig. 1(b)) shows different elements constituting the inductor: spiral-shaped channels designed by using the photosensitive polymer SU8 [14,15], with gold electrodes; these elements are disposed on a dielectric glass substrate Borofloat 33 [14,15]. This insolating support is used instead of common substrate for its good RF characteristics such as a low relative permittivity ε = 4.6 and an almost zero dielectric loss (tanδ = 0.0037); the choice of Au for metallic lines is based on its resistance to corrosion and its high electrical conductivity (σ = 41.106 S/m). Furthermore, the liquid is in direct contact with the inductor core, therefore, we use Deionized water before new measurements in order to clean microfluidic channels from some saltwater residual parts.

3 Theoretical approach

Used as a sensor, this passive electrical component will be necessary in physical contact with liquid samples [15-18]. In order to predict its electrical behavior or its performances for a particular use, it is necessary to study some parameters like the magnetic field distribution and current density in the channel for a particular liquid, Galinstan (σ = 3.46 10^6 S/m) [21-23].

3.1 Spatial distribution of magnetic field lines

We have studied the spatial distribution of the magnetic field for six Galinstan positions in the channel: different results obtained at 2 GHz excitation frequency are reported in Fig. 2.

As shown in Fig. 2 (a), when the microfluidic channel is empty, magnetic field lines cover the entire coil surface with an almost uniform distribution. The insertion of conductive liquid between inductor turns will gradually and continuously change the magnetic field distribution. The first position presented in Fig. 2 (b) shows the absence of magnetic field lines in the inductor center. With Galinstan displacement from POS1 to POS6, the field lines will be canceled on the entire surface occupied but their level increases more near the ground (Fig. 2(e-f)). When the channel is completely filled with Galinstan, Fig. 2 (g) shows that the magnetic field is completely removed from the winding; it is maximum elsewhere.

3.2 Surface electric current density

We also studied the change of electric current density on the micro-inductor caused by the Galinstan displacements. The results are summarized in Fig. 3 for six positions.

When the inductor is empty (Fig. 3 (a)), the electric current density is maximum at the inductor center. On the other hand, the current value is low in the last coil turn and it is almost zero at the ground. This result explains the presence of magnetic field lines in inductor winding and its absence next to the ground when it is empty (Fig. 2 (a)). For the first position of Galinstan (Fig. 3 (b)), we notice that the current density is almost zero in the area occupied by the conductive liquid. This result shows that the Galinstan penetration decreases the inductor current path surface: consequently, the inductance value decreases. Also, this result corroborates the cancellation of magnetic field lines observed in Fig. 2 (b). In Fig. 3 we can observe that if the penetration of the fluid is continuing from POS2 to POS6, the current distribution decreases more and more in the parts occupied by Galinstan.

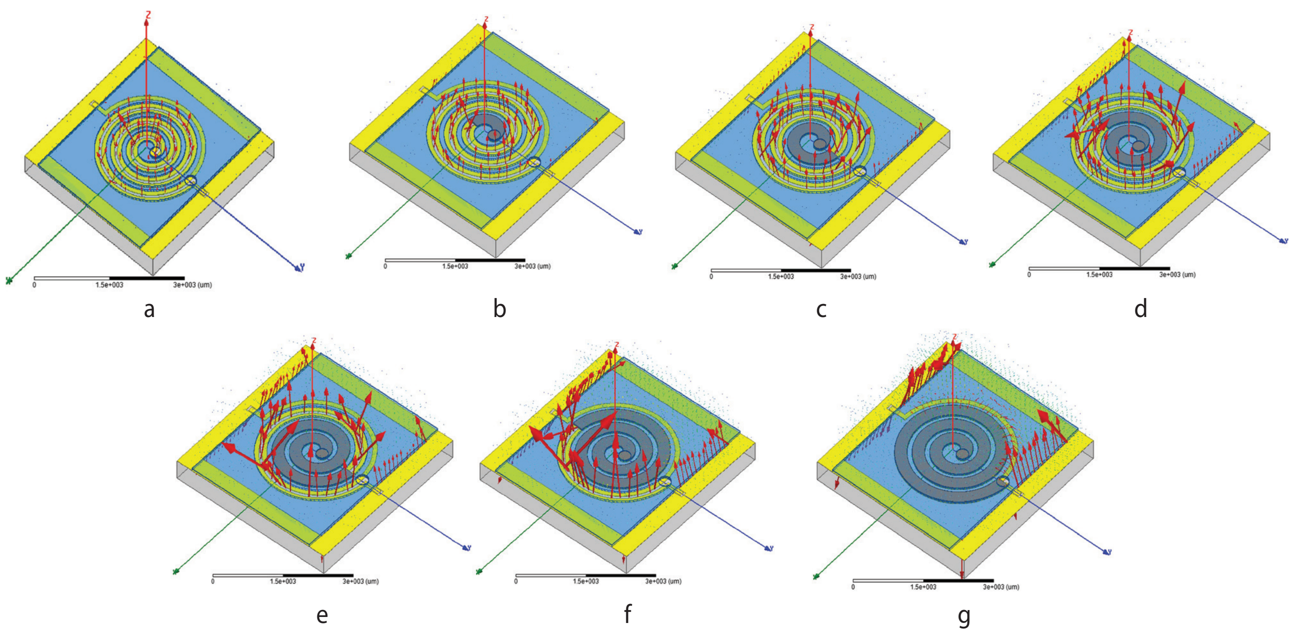


Figure 2: Magnetic field lines distribution for six arbitrary positions of Galinstan in the inductor channel: (a) no liquid (b) POS1 (c) POS2 (d) POS3 (e) POS4 (f) POS5 (g) POS6.

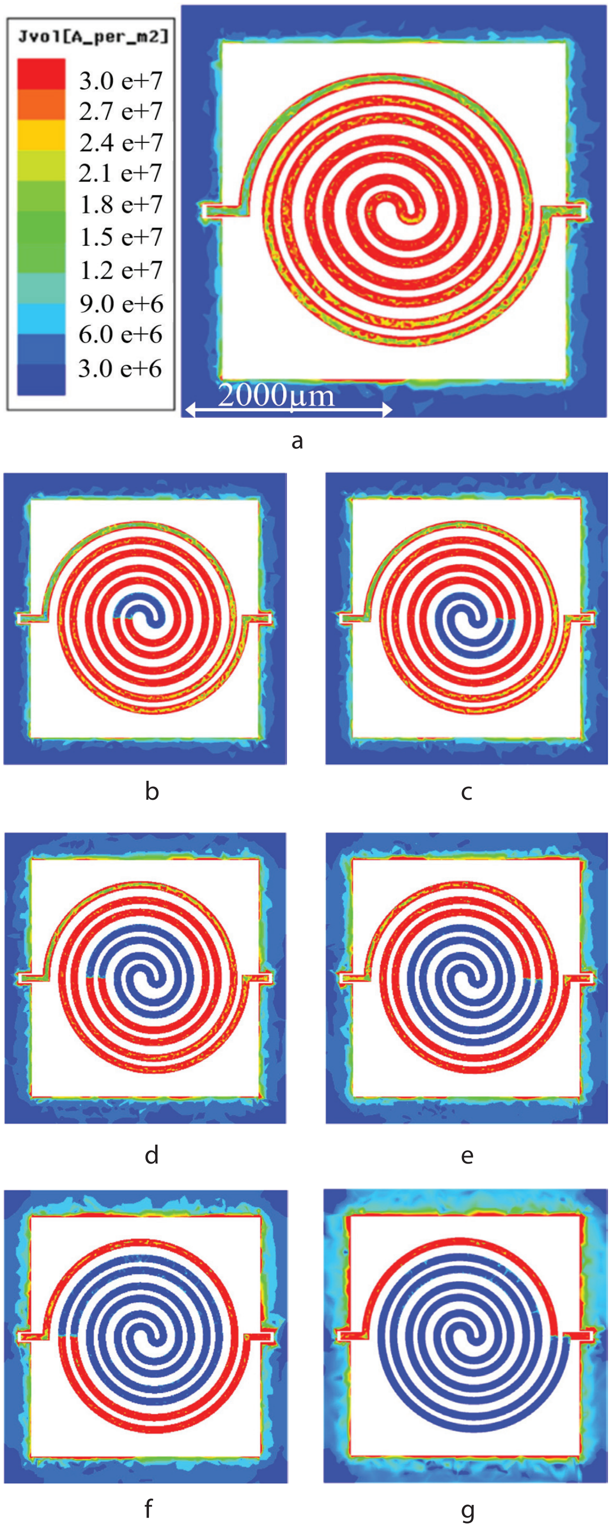


Figure 3: Distribution of the electric current density for the six positions of Galinstan in the channel: (a) no liquid (b) POS1 (c) POS2 (d) POS3 (e) POS4 (f) POS5 (g) POS6.

4 Principal performances indicators

We also checked the double spiral geometric parameters variations and study their effects on the inductor performances when the microchannel is empty and when it is completely filled with Galinstan. We have applied our model to another liquid, salted water (σ = 75 S/m, when saturated), in order to study the device performances. We have varied the inter-spacing "IS" (Fig. 1(b)) from IS = 10 µm to IS = 70 µm with a step of 10 µm; and at each value of IS we change spiral width, from W = 10 µm to W = 110 µm.

4.1 Inductance value variations

For each geometric value (couple of parameters IS and W), we calculated the difference between the inductance value when it is empty and when it is fully filled with respectively Galinstan and salted water. The principal results giving the inductance variations are represented in Fig. 4: the tuning range is calculated at 2 GHz frequency.

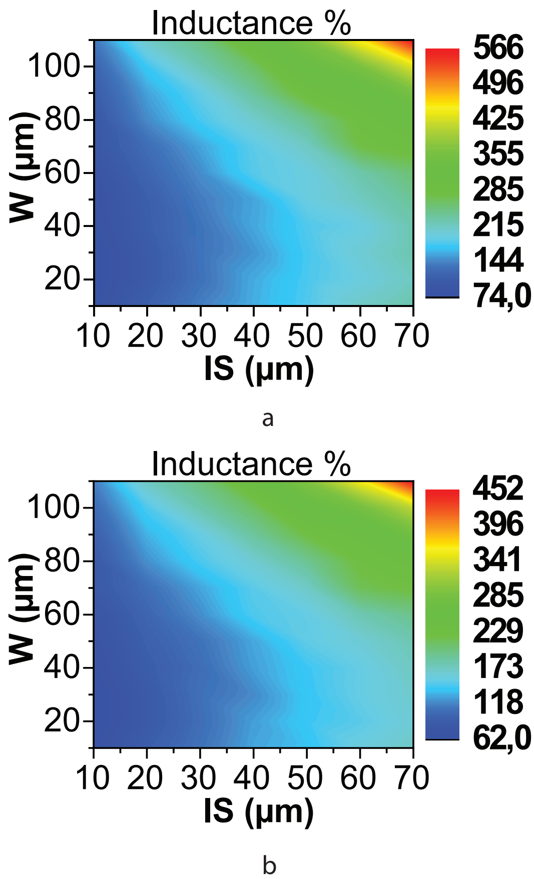
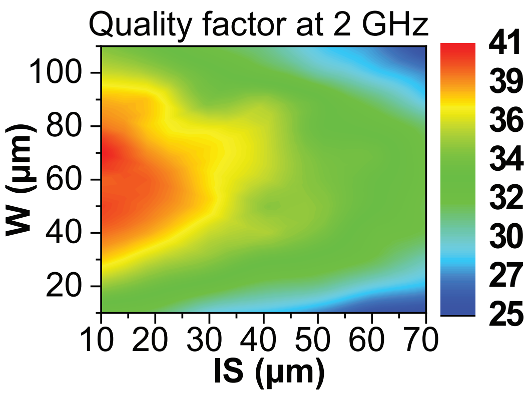


Figure 4: Tuning range parameters versus geometrical parameters of the inductor when the channel is fully filled with: (a) Galinstan (b) salted water.

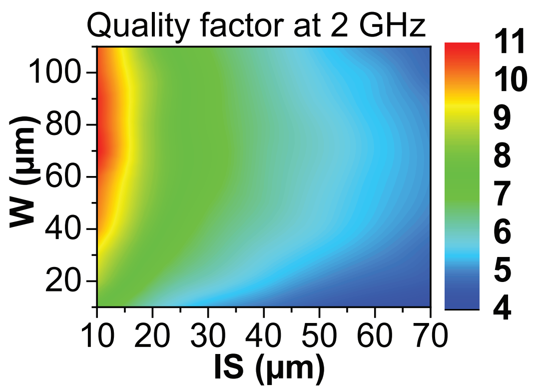
Fig. 4 shows that the maximum tuning range is obtained for IS = 70 µm and W = 110 µm regardless of liquid. In Fig. 4 (a) we note that the tuning range is comprised between Tr = 74 % and Tr = 566 % leading to a large sensitivity of 664.8 % for Galinstan. From Fig. 4 (b), the tuning range is comprised between Tr = 62 % and Tr = 452 %, for a sensitivity of 629 % when the inductor is fully filled with salted water. These results demonstrate the large tunability of the inductor and its high sensitivity to geometric variations for these two liquids.

4.2 Quality factor variation

The quality factor represents the ratio between total coil energy and dissipated energy during one cycle, we have evaluated it at 2 GHz. The results are reported in Fig. 5. for the two liquids:



a



b

Figure 5: Quality factor of the inductor and its dependence on geometrical parameters "IS" and "W" when the microchannel is fully filled with: (a) Galinstan (b) salted water.

Fig. 5 (a) shows that the presence of Galinstan induces a high-quality factor for the device: it can reach Q = 41 at 2 GHz. Nevertheless, the red region area decreases and is affected by the parameter IS until a value of 30 µm. By comparing the effects of the two liquids, we observe that the quality factor values are comprised between Q_{min} = 25 and Q_{max} = 41 and between Q_{min} = 4 and Q_{max} = 11 respectively for Galinstan (Fig. 5 (a)) and salted water (Fig. 5 (b)). Quality factor values provided by salted water are significantly higher sensitive (175%) than those obtained with Galinstan (64%). We can conclude that the quality factor parameter could categorize liquids and demonstrate the multi-sensing behavior of the microfluidic inductor. Hence, the high electric conductivity liquid allows a significant improvement for the microfluidic inductor quality factor, which is moreover an essential parameter for RF applications.

5 Conclusion

An inductor based on microfluidic actuation has been studied in order to be used as a multifunctional device, able to be included in an embedded electronic circuit. It has been designed to allow the displacement of fluids, Galinstan and salted water, between the frames of a spiral coil. We have shown that their electrical (or dielectric) properties can modify not only the electromagnetic distribution in the channel, but also the influence of geometrical parameters of the channel on them: each of these aspects makes it is possible to foresee a use as a sensor for different liquids and their characteristics.

On the first hand, it has been shown that the metallic liquid Galinstan influences the magnetic field distribution and therefore the total energy stored in the coil.

Another liquid, salted water, has been tested in the model: its presence modifies the electric field distribution and consequently the coupling between two spirals of the microfluidic inductor.

The global results reveal that the electrical performances of this device are influenced differently not only by the nature of fluids or their positions in the channel, but also by the geometrical parameters of the device. This opens up the prospect of using it as a multifunctional sensor that can be integrated into an instrument circuit operating at RF frequencies.

6 Conflict of Interest

The authors declare that there is no conflict of interest for this paper. Also, there are no funding supports for this manuscript.

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