Embedded Ferrite LTCC Inductors

Andrea Marić[1*], Goran Radosavljević[2], Nelu Blaž[1], Walter Smetana[2], Ljiljana Živanov[1]

[1] University of Novi Sad, Faculty of Technical Sciences, Department of Electronics, Trg Dositeja Obradovića 6,
2100 Novi Sad, Serbia, Telephone: + 381 21 485 2543, Fax: + 381 21 475 0572
[2] Vienna University of Technology, Institute of Sensor and Actuator Systems, Gusshausstrasse 27-29, A-1040 Vienna,
Austria, Telephone: +31 58801 36616, Fax: +431 58801 36695
* e-mail: amaric@uns.ac.rs

Abstract

This paper presents for the first time one realization of simple planar inductor realized inside the stack of ferrite LTCC (Low Temperature Co-fired Ceramic) tapes. Presented inductor is one layer square spiral fabricated in the LTCC technology. In order to point out benefits of implementation of ferrite material on inductor inductance, the same inductor geometry was fabricated between two dielectric LTCC tapes. Commercially available LTCC material (both ferrite and dielectric) were implemented for the realization of proposed inductors. Designed structures were characterized and obtained experimental results show that even implementation of a very thin layer of ferrite material around inductor lines drastically increases its inductance. For the same inductor design that occupies the same chip area the inductance enhancement over 11 times is achieved. In addition this enhancement is followed with maintenance of good performance of the inductor.

Index Terms - *LTCC technology, ferrite inductors, inductance improvement, high performance*

1. Introduction

In the days of modern integrate circuit technology and wireless industry, one of the key requirements of the availability of small, cost efficient, high performance, high power electronic circuit and components. Almost all of these modules demand the incorporation of high inductance and good performance passives with high packaging potential [1]-[3]. Since all passive components (inductors, transformers, capacitors etc.) occupy large chip area, their fabrication on the top of the chip must be avoided. Moreover, in cases when high inductances need to be achieved the chip area becomes an even more important issue.

As a promising approach to answer the abovementioned requirements, implementation of the LTCC (Low Temperature Co-fired Ceramic) technology for the fabrication of micro-sized inductors and transformers with good performances has on more than one occasion been appreciated as an excellent solution [4]-[10]. It offers the possibility of embedding all cumbersome components inside the substrate, as well as different ways of design optimization in order to achieve better performance. The benefits of LTCC technology, such as the parallel manufacturing process with high yield and low cost, wide variety of commercially available materials for component fabrication, quick rounds in prototyping, environmental stability, compact structures, integration, etc., are well known.

Ferrite inductive components are widely used in filters, power supplies units, to suppress high frequency noise in electronic circuits, they represent efficient and cost effective solutions for suppression of electromagnetic interference in a computers, cellular phones, digital communication equipment, televisions, VCRs etc. [11]-[13]. Their applications in higher frequency range (over 100 MHz) are growing rapidly.

Presented research is conducted with regard to enhance inductance of LTCC inductors implementing ferrite material for their fabrication. Combination of commercially available ferrite and dielectric material has been used for inductor fabrication. Implemented combination of the substrate material has never been used in this manner, to the best of the authors' knowledge. An extensive investigation of material properties and determination of optimal fabrication parameters has been conducted prior to inductor fabrication. Designed structure is characterized and obtained results are compared with properties of the same design that was fabricated on dielectric substrate. Inductance increase of over 11 times has been achieved with implementation of only several thin ferrite tape layers around inductor conductive lines. In addition, chip space used for inductor fabrication is preserved and achieved inductor performance is maintained at good level.

After a short introduction, design concept of both inductor structures is presented in Section 2. This is followed with detailed fabrication procedure in the Section 3 and followed with obtained experimental results in the Section 4. Short summary of obtained results is given in Section 4 of this paper.

2. Basic Design of Proposed Inductors

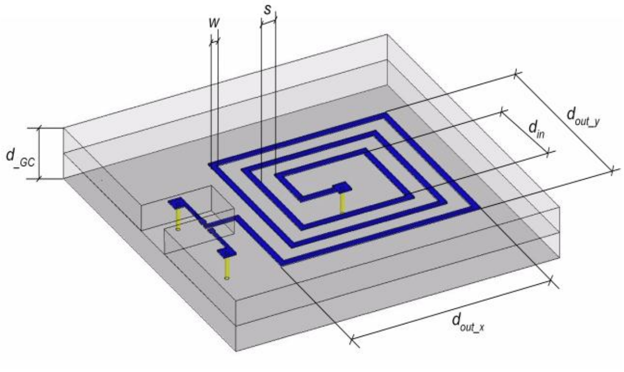
Considered structure is a one port square spiral inductor, embedded inside two different substrate stacks. The spiral consists of three 200 µm wide turns of 10 µm thick conductive segments. The first configuration includes fabrication of inductor inside the stack of dielectric tapes, while the second includes sandwiched inductor in combined ferrite-dielectric stack. Values of relevant geometrical parameters of designed inductors are stated in Table 1.

Table 1. Relevant geometrical parameters of inductor

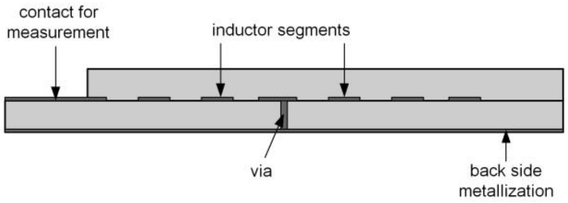
w [µm]	200
s [µm]	500
d_{in} [µm]	215
d_{out_x} [mm]	6.05
d_{out_y} [mm]	5.20
$d_{\_GC}$ [µm]	520
$d_{\_ferrite}$ [µm]	580
t [µm]	10
N	3

w – line width, s – spacing between adjacent conductive segments, d_{in} – inner dimension, $d_{out\_x,\ y}$ – outer dimension along x/y direction, t – line thickness, N – number of windings

Design of the inductor embedded inside the dielectric stack consider sandwiching conductive spiral segments between two 260 µm dielectric tapes (thickness after firing), as demonstrated in the schematic presentation in Fig. 1. The spiral is placed on the top of the base tape and is covered with protective top layer which hosts outlets for approach to measurement contacts.



(a)



(b)

Fig. 1. Schematic presentation of dielectric inductor stack (a) 3D view and (b) cross-section

The ferrite inductor includes placement of the conductive segments on the top side of the second ferrite tape in a four ferrite layer stack. In order to meet the requirements of the LTCC technological process used for inductor fabrication, ferrite stack is enclosed within two protective dielectric tapes from both sides (top and bottom). The corresponding 3D and cross-section representation of the ferrite inductor design is depicted in Fig. 2.

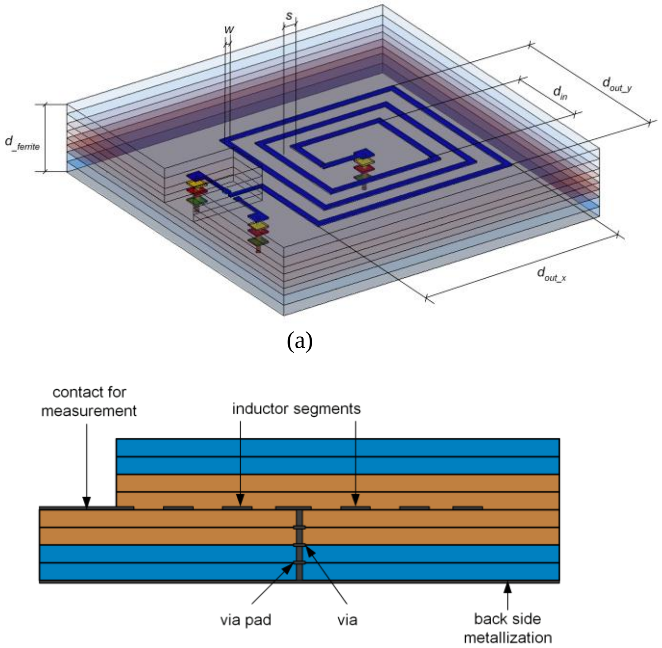


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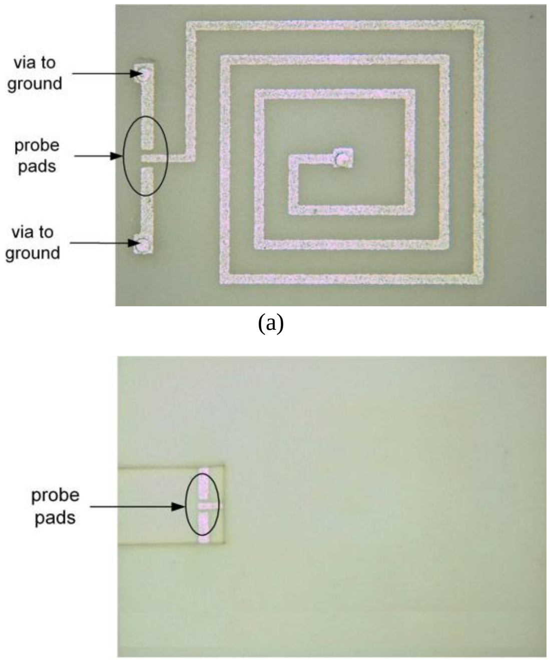
Fig. 2. Schematic presentation of ferrite inductor stack (a) 3D view and (b) cross-section

3. Fabrication Procedure

Both inductor stack configurations were fabricated applying the conventional LTCC technology, implementing structuring of tapes by means of laser micro-machining, metalizing, laminating and co-firing the stack of LTCC tape layers. All processing parameters were adopted to meet the requirements of optimal values for each type of the used materials.

For realization of the dielectric inductor, Ceramtec GC tape was used [14]. The dielectric constant of implemented tape is around 7.5 at frequency of 1 MHz. Conductive segments were applied in the screen-printing procedure, using Heraeus TC7306A paste, while interconnecting vias were formed with stencil printing of Heraeus TC7304A via fill paste. Uniaxial lamination of the collated layers was performed with the load of 1700 kg at temperature of 75 °C for 3 minutes. The sintering was preformed in a belt furnace, at 900 °C peak temperature and 80 minutes totals firing cycle. Printed inductor lines in green state, as well as the top view of the sintered stack are presented in Fig. 3.

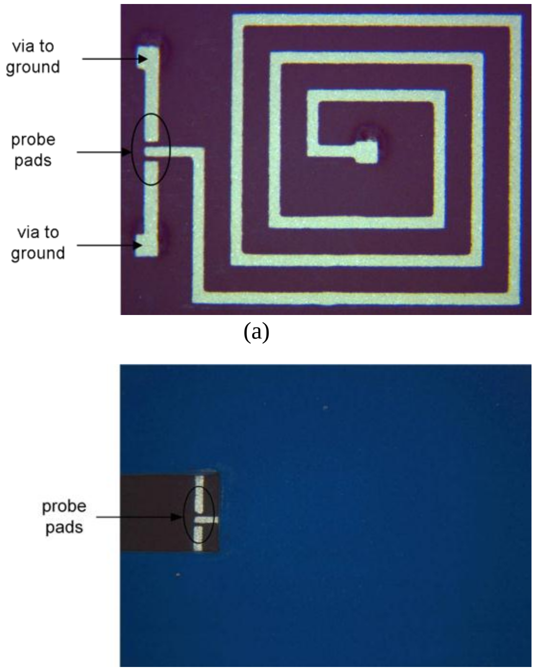


(a)

(b)

Fig. 3. Ceramtec GC inductor (a) inductor in green state and (b) fired inductor.

The ferrite stack was formed from four 70 µm thick ferrite ESL 40011 tapes, supported with two 100 µm thick ESL 41020 dielectric layers (dielectric constant of 7.5 at 1MHz frequency) from the top and the bottom [15]. Inductor was printed using silver ESL 903B paste on the top of the second ferrite tape, placing it in the middle of the stack. ESL 902 paste was implemented for via filling. Recommended lamination force of 1900 kg was applied in duration of 3 minutes, at lamination temperature of 75 °C. Firing of the ferrite sample was performed in a box furnace, at peak sintering temperature of 885 °C and 10 h and 10 min duration of the total cycle. The top view of the printed inductor and also the fabricated sample is presented in Fig. 4.



(a)

(b)

Fig. 4. Ferrite inductor (a) inductor in green state and (b)fired inductor.

4. Experimental Characterization

Fabricated inductors were designed with intention of using high frequency measurement equipment for their characterization. Therefore, to enable the measurement inductors were accommodated with adequately designed probe pads on one side of the layout and connection to the back-side metallization on the other. The measurement set–up implemented for the characterization comprised Süss MicroTec PM5 RF probe station, Agilent vector network analyzer VNA E5071B, high frequency interconnecting cables and coplanar ground-signal-ground Cascade Microtech APC50-GSG-250 probe. Prior to the measurement process, the measuring system was calibrated on impedance characterization substrate 101-190 calibration substrate, implementing SOL (Short Open Load) calibration method. Obtained S-parameters for both inductor structures are given in graphs of Fig. 5.

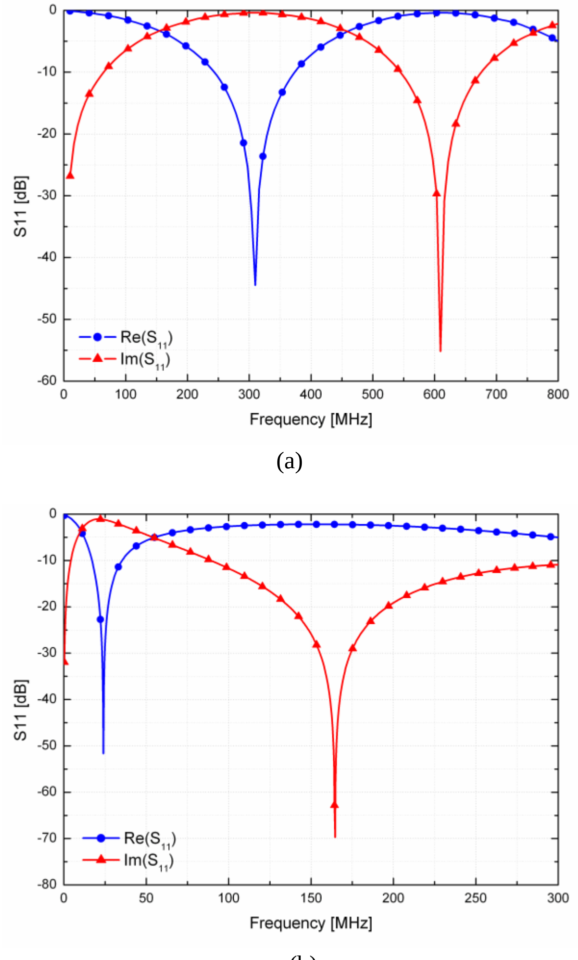


Fig. 5. Measured S-parameters vs. frequency (a) Ceramtec GC inductor and (b) ferrite inductor.

In order to exclude influence of the contacting pads on inductor's performance, de-embedding of parasitic effects was performed. Taking into consideration that the frequency range of interest is below 1 GHz, only an open dummy was implemented for de-embedding process. Presented measured S-parameters were converted to corresponding Y-parameters, de-embedded and introduced to following expressions in order to obtain inductance L and quality factor Q (Q-factor) values

$$L = \mathrm{Im}(1/Y_{11})/(2\cdot\pi\cdot f)\,, \tag{1}$$

$$Q = -\,\mathrm{Im}(Y_{11})\,/\,\mathrm{Re}(Y_{11})\,, \tag{2}$$

where *f* stands for frequency.

Obtained inductances and Q-factor values for both inductor structures are presented in graphs of Fig. 6 and Fig. 7.

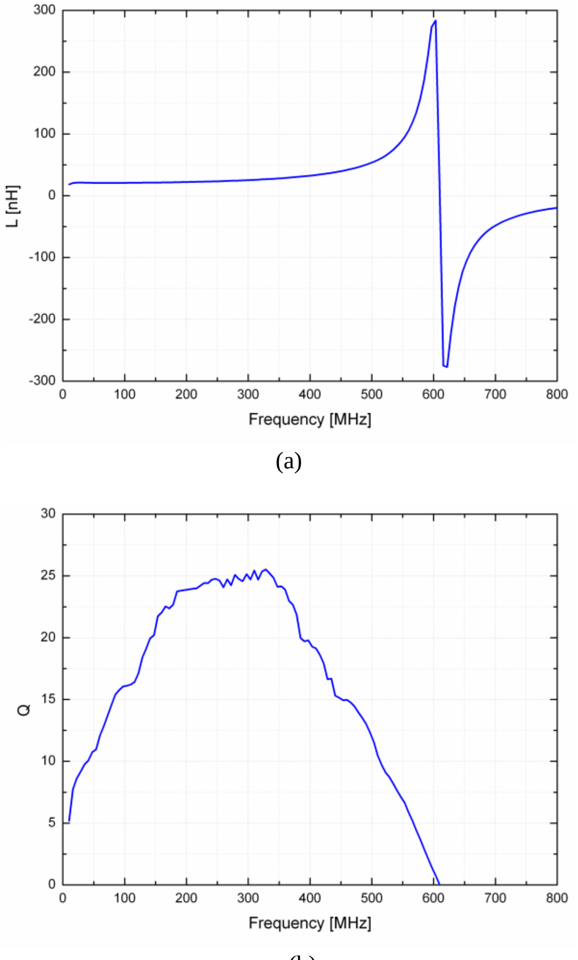
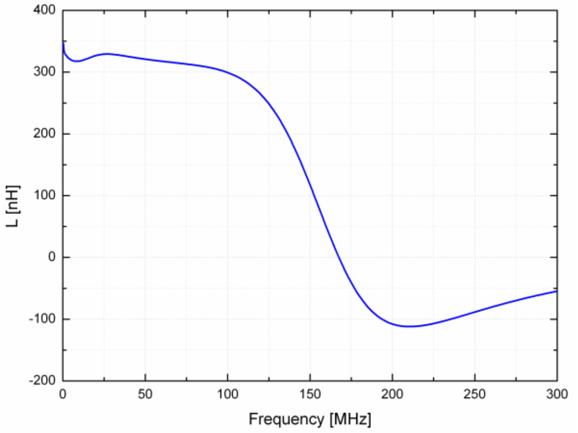
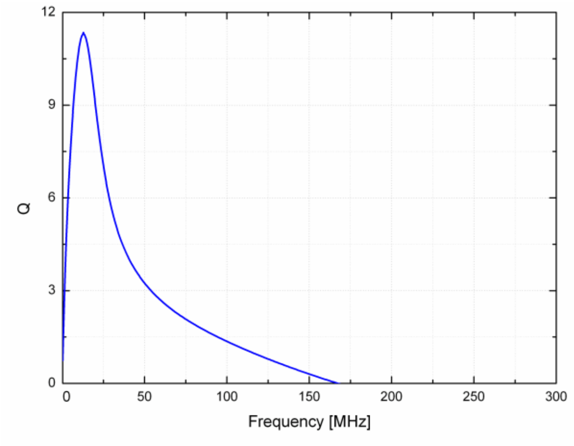


Fig. 6. Measured results for Ceramtec GC inductor (a) inductance and (b) Q-factor vs. frequency.



(a)



(b)

Fig. 7. Measured results for ferrite inductor (a) inductance and (b) Q-factor vs. frequency.

The corresponding measured values of relevant inductors parameters are summarized in Table 2.

Table 2. Relevant measured results

	L @ f_{Qmax} [nH]	Q_{max}	f_{Qmax} [MHz]	SRF [MHz]
Ceramec GC inductor	26.75	25.52	328.43	616
Ferrite inductor	319.76	11.35	12.97	167.7

f_{Qmax} – Q-factor maximum frequency, Q_{max} – Q-factor maximum, *SRF*– self resonant frequency

It is evident that from the presented results that implementation of different material type affects drastically on inductors performance. Inductor fabricated inside dielectric substrate offers higher quality factor and wider useful frequency range (higher self resonant frequency). However, advantage of ferrite material properties on the inductance of fabricated component is substantial. Inductance of 319.76 nH at Q-factor maximum frequency of 12.79 MHz is achieved with only 240 µm thick ferrite stack. Quality factor maximum of ferrite inductor is 11.35 and this value is relatively high, taking in consideration losses in ferrite material and very small thickness of used ferrite. Achieved inductance value of Ceramtec GC dielectric inductor at Q-factor maximum frequency of 328.43 MHz is 26.75 nH. Q-factor maximum value of 25.52 is achieved at frequency of 328.43 MHz. It can be seen that quality factor of dielectric inductor is also acceptable, having in mind the corresponding inductance value, material losses and distance of the inductor from the backside metallization (260 µm). Comparing inductance values of the ferrite and dielectric inductor at Q-factor maximum frequency it is obvious that increase of inductance over 11 times is achieved with implementation of ferrite material. This is very important in applications where high inductance values high performances are required on a limited substrate area.

5. Conclusion

Investigation of different material properties on performance of integrated LTCC inductors are presented in this paper. Advantages of involving the ferrite material in incensement of LTCC inductors are demonstrated. Investigated design is a three turn square spiral inductor embedded inside two different LTCC sack configurations. One is realized between two dielectric LTCC tapes, while the other one is sandwiched in the middle of the ferrite stack of LTCC tapes. Such ferrite substrate configuration has not yet been realized in the LTCC technology, to the best of the author' knowledge. The obtained experimental results indicate increase of inductor inductance over 11 times, only by fabrication of planar inductor between four thin (55 µm thick) ferrite tapes. In addition, achieved value of the inductor quality factor is relatively high having in mind material properties and present losses. According to the presented results it can be concluded that proposed ferrite inductor can offer high inductance (around 320 nH) and good performance (over 11 Q-factor) for the applications in the frequency range up to 167.7 MHz. In addition, presented inductor is an embedded structure and therefore enables mount of other components over the inductor diminishing chip size in which it is integrated in.

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