Fully Embedded LTCC Spiral Inductors Incorporating Air Cavity for High Q-factor and SRF

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Abstract

In this paper, a new fully-embedded LTCC spiral inductor is proposed by incorporating an air cavity between the spiral and ground plane for high quality factor (Q-factor) and high self-resonant frequency (SRF). The disadvantage of fully embedded structure without an air cavity is the reduction of size efficiency in the RF system, since its structure needs a lot of layers to decrease parasitic capacitance between the spiral and ground plane for high Q-factor and SRF. The air cavity employed under the spiral reduces the shunt parasitic capacitance of the inductor, and results in high Q-factor and high SRF of the embedded inductors. The measured results of the optimized spiral inductor with the embedded air cavity show a maximum Q of 51 and SRF of 9.1 GHz, while those of the conventional spiral inductor describe a maximum Q of 43 and SRF of 8 GHz with effective inductance of 2.7 nH.

Introduction

Recently, multi-layer low temperature co-fired ceramic (LTCC) technology offers the potential for compact, high-performance and high-functionality implementation in RF/Microwave packaging applications. In addition to that, functional RF/Microwave modules require in general considerable amount of high quality factor (Q-factor) passive components to be integrated in monolithic microwave integrated circuits (MMICs). The off-chip passive components are packaged separately, and occupy a large chip area on the RF module. The inductor is one of the key passive components that determine the RF/Microwave module performance as well as total system size in RF module. For example, the noise figure of a LNA (low-noise amplifier), the phase noise of an oscillator and efficiency of a PA (power amplifier) critically depend on the Q-factor of the inductors employed. Therefore, many researche have focused on the design of high Q inductor with compact size.

Several achievements to improve the Q-factor have been reported on the inductors based on LTCC technology [1]-[3]. Helical inductors stacked vertically were reported to have Q-factor of 70, but the helical inductors need a lot of layers up to nineteen layers to decrease parasitic capacitance between spiral lines designed to obtain the high Q-factor [1]-[2]. Multi-layer inductors in the LTCC block also reveal high value of Q-factor as high as 60 [3], however, the placement of each spiral line of inductor restricts effective utilization of the space in the multi-layer RF System-in-package (SIP). Also, the above two inductor structures can be applied only to multi-turn inductor.

In this paper, we propose and implement a new structure of LTCC spiral inductor incorporating an air cavity between the spiral and ground plane. The performance of the devised spiral inductors has been evaluated in terms of the SRF, effective inductance, L_{eff}, and Q-factor for L- through C-band RF SIP applications.

Structure of LTCC Spiral Inductors with Air Cavity Incorporated

The inductors were designed using a low loss LTCC dielectric of 114μm thick per layer and silver conductor of 12μm thick. The relative permittivity and loss tangent of the employed dielectric have been assumed to be 7.4 and 0.001 at 10 GHz, respectively. The silver conductor has a conductivity of 6.2×10^{7} S/m. The spiral inductors with air cavity incorporated were fully embedded in a 5-layer LTCC block as well as those without air cavity [4], and each end of the inductors was connected through via holes to coplanar waveguide (CPW) pads on surface for on-wafer direct probing as shown in Figure 1, schematically.

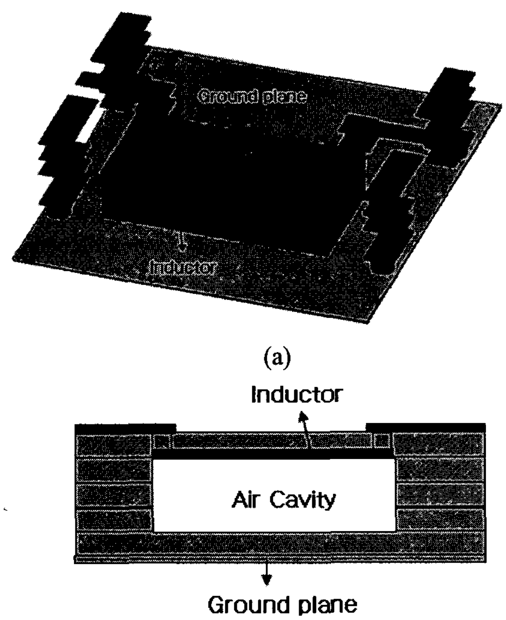

Figure 1. Structure of the fully embedded LTCC inductor with air cavity incorporated. (a) 3D-schematic view and (b) Cross-section of the overall spiral inductor.

The size of the outer rectangle of the inductor was designed to have $1500\text{x}750\mu m^2$ area with half turn of spiral. For air cavity structure, the inductor spiral was printed on backside of the uppermost layer with the ground plane at the first bottom layer. The electrical characteristics of the proposed inductor had been simulated and optimized using a 2.5 dimensional electromagnetic (EM) simulator. The standard line width of the spiral was 120μm.

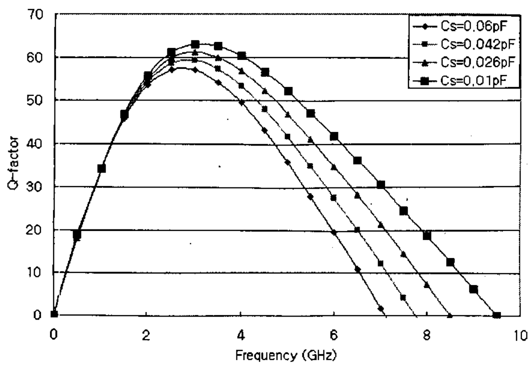

Figure 2. Q-factor of inductor as a function of the parasitic capacitance (C_S).

Since the shunt parasitic capacitance (C_S) existing unintentionally between the spiral and the ground plane degrades the SRF and Q-factor, the spiral inductor was implemented by enforcing air cavity between the spiral and ground plane to reduce this parasitic capacitance. The parasitic capacitance, C_S for the LTCC inductors with air cavity incorporated and conventional structure are calculated as 0.01pF and 0.06pF, respectively. The simulated Q-factors of the LTCC inductor as a function of frequency for the different values of the C_S are shown in Figure 2. It is found that a C_S decreases from 0.06pF to 0.01pF while the other conditions remained constant, the Q-factor and SRF increase from 57 to 63 and from 7 GHz to 9.4GHz, respectively.

Characteristics of Fabricated Inductors

The LTCC blocks composed of 5 layer dielectrics were fabricated using commercial green sheets and metal pastes. The spiral inductors with air cavity incorporated and conventional structure are fully embedded in a same LTCC block for comparison.

Figure 3 shows surface and X-ray photograph of the fabricated inductor incorporating air cavity underneath the spiral. To apply an air cavity to the conventional structure, the inductor spiral was realized at the bottom of the uppermost layer with the ground plane below the first bottom layer. The input/output ports of the 2-port inductor were extended to the CPW pads with low-loss transition on the surface for on-wafer direct probing.

Figure 4 shows the Q-factor of the fabricated half turn spiral inductor with air cavity incorporated together with conventional inductor structure. As predicted from the simulation shown in Figure 2, the spiral inductor incorporating an air cavity has higher Q-factor and SRF. The spiral inductor incorporating air cavity shows maximum Q of 51 with L_{eff} of 2.63nH at Q_{max} and SRF of 9.1 GHz, while the conventional inductor has maximum Q of 43 with 2.74nH and SRF of 8 GHz. This is attributed to the lower values of the parasitic capacitance, C_S of the spiral inductor incorporating an air cavity than that of the conventional spiral inductor. The parasitic capacitance, C_S of the spiral inductor incorporating an air cavity has been extracted from circuit model as 0.06pF showing the improvement of SRF and Q-factor than that of convetional spiral inductor estimated as 0.09pF. It is thought that the difference between the extracted values (0.06pF) of the parasitic capacitance and the calculated one (0.01pF) for the inductor incorporating an air cavity is due to the increased spiral area, fringing effect in addition to the thinned dielectric around the spiral during lamination process and mismatch between the inductor spiral and air cavity.

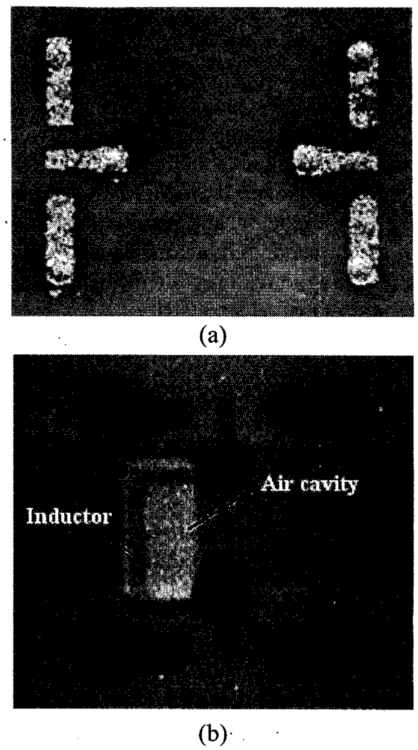

Figure 3. (a) Surface and (b) X-ray photograph of the fabricated LTCC inductor with an air cavity incorporated.

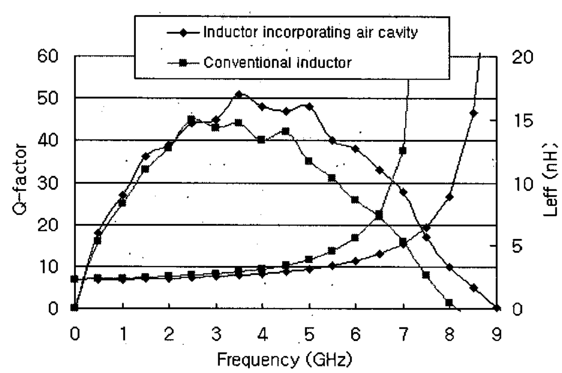

Figure 4. Q-factor and L_{eff} of the inductors with an air cavity incorporated and conventional structure.

Conclusions

We have devised a new fully embedded LTCC spiral inductor placing an air cavity underneath for high density and high frequency RF system integrations. With same dimension and numbers of turns, the spiral inductor with an air cavity incorporated has better performance than conventional spiral inductor. It means that the characteristics of the spiral inductor incorporating an air cavity has been improved 14% in SRF and 19% in Q-factor compared to that of the conventional spiral inductor.

References

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