High Performance Spiral Inductors Embedded on Organic Substrates for SOP Applications

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***Abstract*—This paper presents the design, measured data, and systematic analysis of spiral embedded inductors fabricated on standard organic substrates using low-cost, large-area MCM-L technology. Several configurations for inductors were investigated to optimize the inductor layout dimensions such as conductor width, number of turns, inner diameter, spacing between inductor and ground, and inductor area. A maximum Q of 100 was measured for a 3.6 nH inductor at 1.8 GHz on an organic substrate with a self resonance frequency of 10.6 GHz within an inductor core area of 0.72 mm^2. The effects of configurational variables on inductor characteristics such as quality factor, self-resonance frequency, and inductance will be discussed. High-Q inductors embedded on organic substrates can find numerous RF and microwave system-on-packge (SOP) applications, such as VCOs, IF/RF bandpass filters, LNAs, etc., in which IC chips are flip-chip mounted on the package substrate.**

I. Introduction

The demand for wireless and mobile devices requires integration, maintaining low cost, of passive components including inductors. Among the several technologies available for passive integration [1]-[4], the present paper studied systematically the spiral inductors embedded on organic substrate using MCM-L technology.

Over 150 different spiral inductors were designed and tested to characterize experimentally the factors of inductors such as inductance, quality factor, and self-resonance frequency as functions of such configurations as conductor width, number of turns, inner diameter, spacing between inductor and ground, and inductor area. This paper reports in detail the results of this investigation.

II. Inductor Design

The embedded spiral inductors fabricated in this study were designed with geometrical variations on FR-4 board that consists of two metal layers and one photo-via (4 mil diameter) layer. The cross-section of the test vehicle is shown in Fig.1. The inductors have a peripheral ground on the second metal layer and a floating ground below the substrate. The design variations of inductors are conductor coil width (W), spacing between inductor and ground (GV and GH), bridge width (B) connecting the inductor to the ground, number of turns, and inner diameter (C) as shown in Fig.2. Line spacing is fixed with 2 mil width.

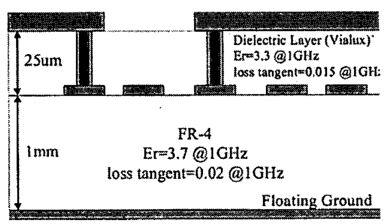

Fig. 1. Cross-section of the test vehicle

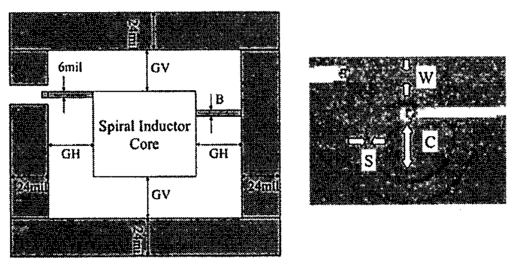

Fig. 2. Inductor Layout

III. Fabrication and Measurement

A 1mm thick, copper cladded (9μm) FR-4 organic substrate (epoxy-glass fiber composite) was used, as shown in Fig. 1. A 15μm thick photoresist dry film was laminated on the substrate (@ 75°C) using a vacuum pressure type laminator and then patterned. The first conductor coil layer was patterned by copper etching. The photoresist is then stripped off and a 25μm thick photosensitive dielectric epoxy dry film was laminated using a vacuum pressure type laminator to insulate the conductor coil layer. Photo-via openings were then formed

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through exposure to UV light, pre-baking in oven at 110°C for 1hr, developing in gamma-butyro lactone, and curing the dielectric polymer at 150°C (the maximum temperature used in this process) for 1.5 hr. The vias and the upper conductor lines were then formed through copper seeding by electroless plating followed by electrolytic copper plating into the photoresist mold made through lamination. For electroless copper plating, the surface of dielectric polymer was catalyzed through such process steps as swell, etch, neutralize, pre-catalyst, and catalyst. After plating, the photoresist was stripped off and the copper seed layer was wet-etched in micro-etch solution.

The S-parameters of inductors were measured using an HP8720ES network analyzer and Cascade Microtech ground-signal-ground microwave probe. Network analyzer calibration was done using short-open-load calibration standards. The one-port S-parameters were recorded from 0.1 up to 10 GHz. Inductance values were measured at the frequency showing the maximum quality factor.

IV. EXPERIMENTAL RESULTS

A. Inductor Size

Fig. 3 shows the variations of the maximum quality factor, inductance, and self-resonance frequency as a function of inductor outer diameter (or inductor size). The one-turn inductors with three different conductor coil width (2, 4, and 6 mil) were designed and tested respectively. As inductor size increases, the maximum quality factor and the self-resonance frequency decrease because longer coil has higher series resistance and larger area occupied by inductor induces larger substrate parasitics (or losses). The inductors with wider conductor coil show significantly higher Q-factor owing to lower series resistance. On the other hand, self-resonance frequencies are little affected by coil width. The inductance increases linearly with inductor outer dimension because the self-inductance of a conductor coil with a rectangular cross-section area is directly proportional to the coil length. For the present study, the mutual inductance between two parallel coils can be negligible because the flat orthogonal coils with side-by-side configuration have little mutual coupling and further the coil-to-coil spacing is as large as 2 mil.

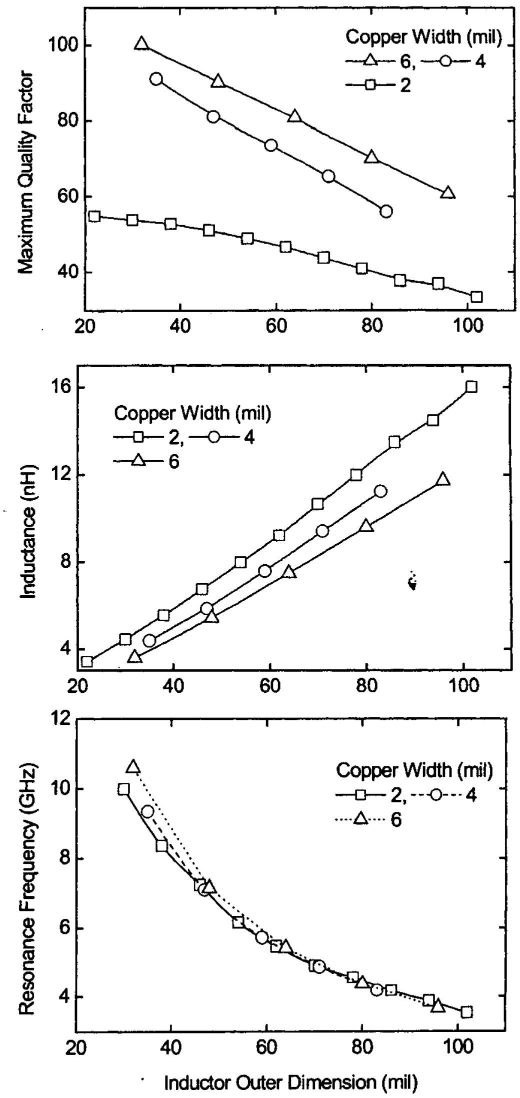

Fig. 3. Variations of maximum quality factor, inductance, and self-resonance frequency versus inductor outer diameter (or inductor size). Spacing between turns = 2 mil, and 1 turn.

B. Conductor Coil Width

Figure 4 shows the variations of maximum quality factor, self-resonance frequency, and inductance as a function of conductor coil width. The 2 mil width conductor is regarded as a lower dimensional limit for low-cost and large area fabrication process in MCM-L technology using organic substrate. As the conductor width increases from 2 mil up to 4 mil, the Q factor increases owing to lower series resistance of the coil, whereas the inductance decrease. The conductor coils with smaller cross-section area, in general, have a larger inductance value because they generate more magnetic flux external to the coils.

The self-resonance frequency is little affected by conductor width.

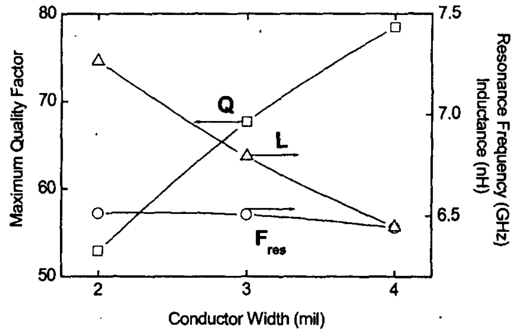

Fig. 4. Variations of maximum quality factor, inductance, and self-resonance frequency versus conductor coil width.

C. Inner Diameter

Fig. 5 shows the variations of the maximum quality factor and self-resonance frequency as a function of inner diameter for inductor with conductor width = 6 mil, spacing between turns = 2 mil, and 2 turn.

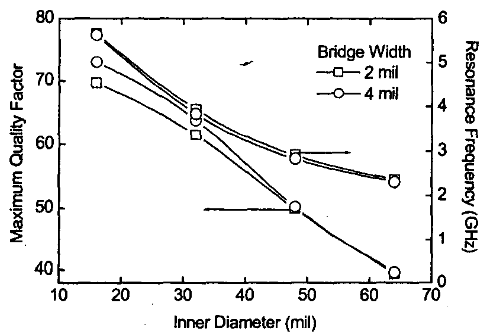

Fig. 5. Variations of maximum quality factor and self-resonance frequency versus inner diameter of inductor core

As inner diameter increases, the maximum quality factor and self-resonance frequency decrease owing to increased series resistance and substrate parasitics. The substrate parasitics evoked from substrate capacitance is approximately proportional to the area occupied by the inductor. Inductors with two different bridge width (2 and 4 mil) were tested, respectively. The inductors with wider bridge (4 mil) showed a little higher quality factor than those with 2 mil bridge, especially for those with smaller inner diameters, owing to the lower series resistance. On the other hand, the wider bridge (4 mil) showed slightly lower self-resonance frequency than those with 2 mil bridge. Wider bridge induces higher overlap capacitance between over-pass bridge and spiral coils as well as reduces series resistance of inductor as a whole. It is believed from the results that the series resistance is significant for maximum quality factor, whereas the overlap capacitance is dominant for self-resonance frequency. The photomicrographs of the measured inductors in Fig. 5 is shown in Fig. 6.

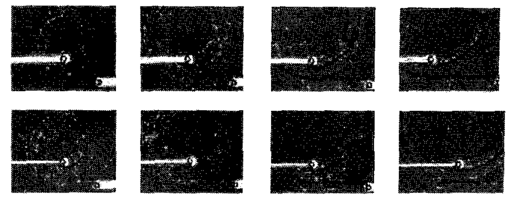

Fig. 6. Inductors with different inner diameter and bridge width. First row : bridge width = 4 mil, second row : bridge width = 2 mil.

D. Number of Turns

Fig. 7 shows the variations of the maximum quality factor, inductance, and resonance frequency as a function of the number of turns. The inductors with different inductor areas were also designed and tested, respectively. As the number of turns increases, the maximum quality factor decreases owing to increased parasitic capacitance and increased RF resistance due to eddy currents, and the inductance increases approximately as (the number of turns)^2, and the self-resonance frequency decreases owing to higher parasitic capacitance.

E. Spacing between inductor and ground

Fig. 8 shows the variations of maximum quality factor, inductance, and self-resonance frequency as a function of spacing between inductor and ground. Two sets of inductors were designed. For one set of inductors, x-axis spacing between inductor and ground (parallel direction with that of bridge) is varied and y-axis spacing is fixed. For the other set, the situation is reversed. As the spacing between inductor and ground increases, the maximum quality factor and resonance frequency decrease, and the inductance increases to some extend. Especially, the effect of spacing on the quality factor is more significant for the inductors that the spacing varied along with bridge direction (x-axis) than those the spacing varied along with y-axis.

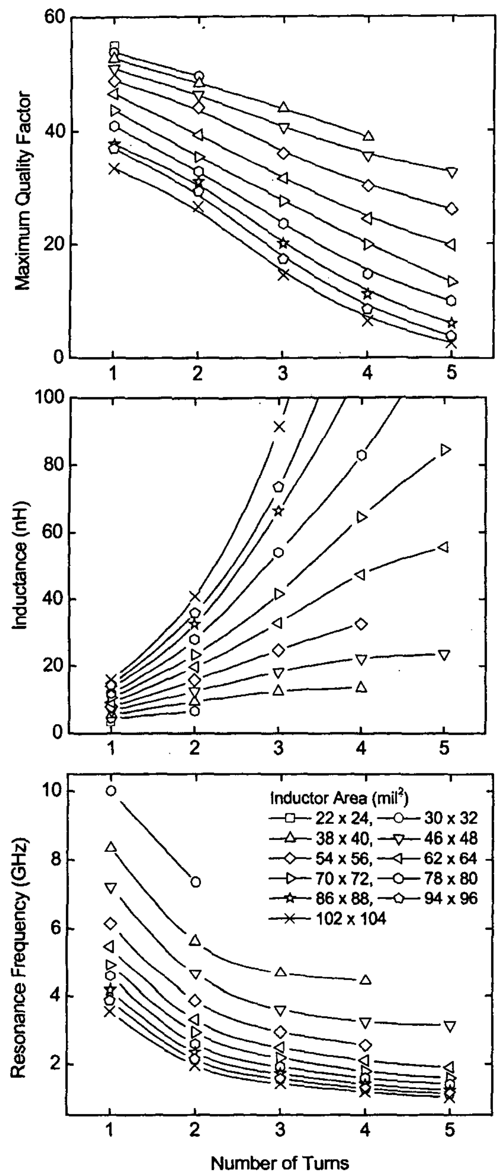

Fig. 7. Variations of maximum quality factor, inductance, and self-resonance frequency versus number of turns.

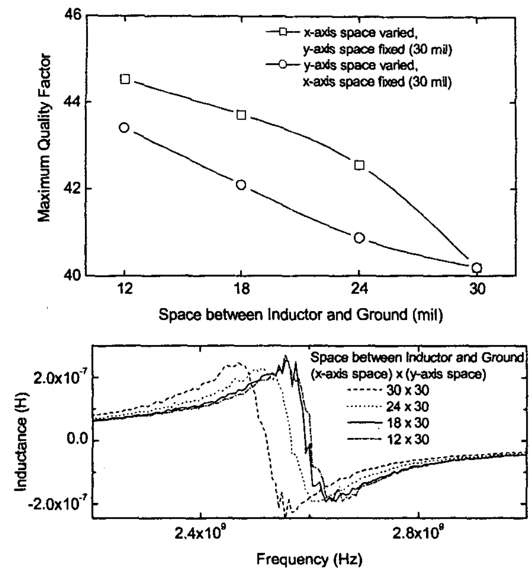

Fig. 8. Variations of maximum quality factor, inductance, and self-resonance frequency versus space between inductor and ground.

V. Conclusion

Planar spiral embedded inductors with various configurations were designed and fabricated on organic substrate using low-cost and large-area (12 inch) MCM-L process, measured, and analyzed. In this study, a maximum Q of 100 was measured for a 3.6 nH inductor at 1.8 GHz on an organic substrate with a self resonance frequency of 10.6 GHz within an area of 0.72 mm^2. For a inductor with higher Q factor, smaller inductor area, larger conductor width, smaller inner diameter, smaller number of turns, and smaller spacing between inductor and ground are required. The use of high Q inductors developed in this study for SOP application will result in improved RF performance, smaller substrate size, and lower cost.

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