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Parallel-Branch Spiral Inductors with Enhanced Quality Factor and Resonance Frequency

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Abstract

In this paper, we present a cost effective parallel-branch spiral inductor with the enhanced quality factor and the resonance frequency. This structure is designed to improve the quality factor, but different from other fully stacked spiral inductors. The parallel-branch effect is increased by overlapping the first metal below the second metal with same direction. Measurement result shows an increased quality factor of 12 % improvement. Also, we show an octagonal parallel-branch inductor which reduces the parasitic capacitances for higher frequency applications.

Key words : Parallel-Branch Inductor, Quality Factor, Resonance Frequency.

Ⅰ. Introduction

Monolithic inductors are commonly used in radio frequency integrated circuits for wireless communication systems. The on-chip inductor is a critical device for the MMIC circuits such as voltage-controlled oscillators, impedance matching networks, and RF amplifiers.

Many works for on-chip inductor design techniques attempting to improve their performance have been proposed, including the use of higher conductivity metal layers to reduce the loss resistance of the inductor[1], multiple metallization layers in parallel to increase the effective thickness of the spiral inductor[2],[3], and thick oxide or floating inductors to isolate the inductor on the lossy substrate[4].

In particular, one of the most important characteristics of high performance inductor is its quality factor(Q), which is reduced due to parasitic components such as resistive losses and substrate coupling.

In order to increase the Q factor of on-chip inductor in silicon process, high Q inductor with patterned ground shied has been developed. That cuts off the path of the induced loop current in ground shield and reduces the loss due to the loop current[5],[6].

The present inductor processes use more than three metals, and require additional steps to fabricate. Therefore its process cost becomes high.

In this paper, a cost effective parallel-branch inductor has been proposed and developed in order to increase the Q factor of the conventional spiral inductor. This parallel-branch inductor is composed of only two metals. The presented parallel-branch inductor shows 12 % improvement in the Q factor with the same area as the conventional inductor. Also, we have improved the parallel-branch inductor for high frequency applications.

Ⅱ. Parallel-Branch Inductor

High Q on chip passive devices are required to meet the demanding requirements of RF circuits and to achieve the "system on a chip" integration levels.

Generally, Q factor of the thin film inductor formed on silicon substrate can be improved by the method for reducing the resistance of the metal line itself and the parasitic capacitance. The highest percentage improvement in inductor peak Q is achieved by reducing the series resistive losses of the spiral metal lines. To decrease the spiral metallization sheet resistance, other inductors use more than five metals and over than 4 um thick top metal.

This work has been developed as a performance enhancement of two metal spiral inductors in a cost effective inductor technology by the 0.5 um ETRI SiGe BiCMOS process. This process provides just two Al metal layers without any change in fabrication process and additional cost.

Inductors integrated in this work are used the Q factor enhanced parallel-branch spiral inductors. Our top metal thickness is 2 um. It has a little Q enhancement that the second metallization has more than 2 um thickness. In order to compare the Q factor characteristic between the inductor we proposed and the conventional one, we designed two inductors with the same diameter, trace width and turn number.

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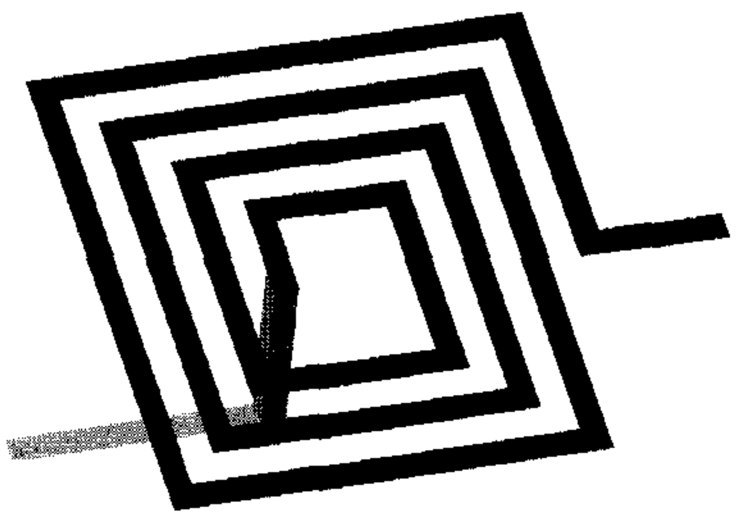
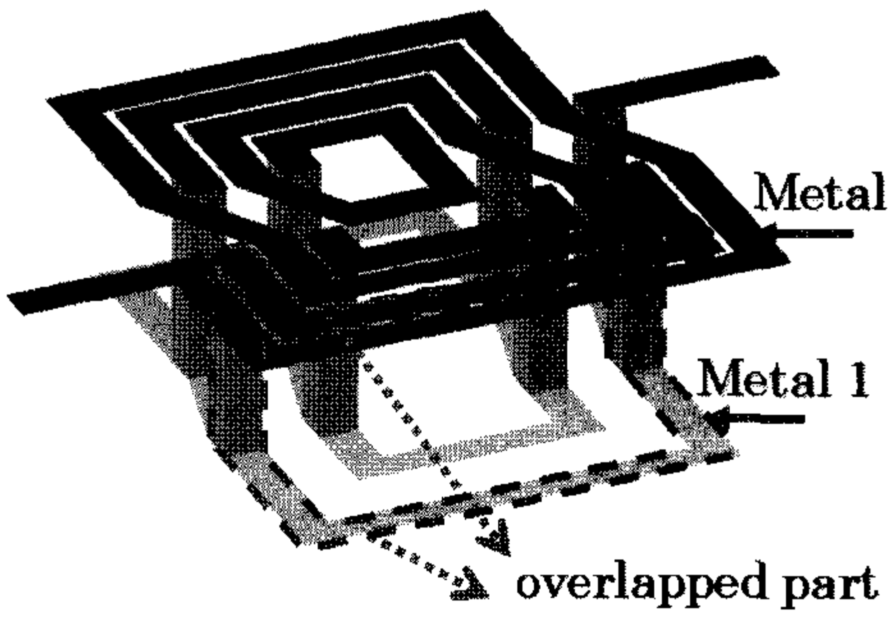


(a) The conventional inductor



(b) The parallel-branch spiral inductor

Fig. 1. Schematic diagrams.

Fig. 1 shows the structures of the conventional spiral inductor and parallel-branch spiral inductor. Both are squared spiral inductors having silicon dioxide of 1 um thick as an insulating layer. Substrates used in our processes have a medium substrate resistivity. Due to the interaction of the electric and magnetic fields of the spiral inductor with the substrate, parasitic substrate currents can be established in the substrate material. Parasitic currents that occur from the electric field interaction with the substrate will cause power losses in the inductor lowering Q[7].

The upper metal strip of the conventional inductor is connected only once with the lower one through just one via but, in case of parallel-branch inductor is connected with the lower one through several vias to arrange two metals in parallel. The parallel-branch inductor strip starts at the upper metal, branches off in the upper and lower metal strips. The inserted lower metal strips have same direction. By branching off the two metals in parallel with the same direction, mutual inductance is maximized and parasitic capacitances between lower metal and substrate are caused. Therefore, the Q factor of parallel-branch inductor is enhanced and the frequency of the peak Q factor f_{QMAX} is possible to be tuned. The structure of presented parallel-branch inductor is different from fully stacked spiral inductor[8]. The inductor has 10 um metal width and 2 um metal space.

The inductance and Q factor of the inductors are derived from scattering(S) parameters measured within the frequency range of 0.5~10.5 GHz by HP 8510C network analyzer after several post processing such as de-embedding and parameter transformation. As for the Q factor, we have adopted the usual definition as $Q=-\mathrm{Im}(Y_{11})/\mathrm{Re}(Y_{11})$.

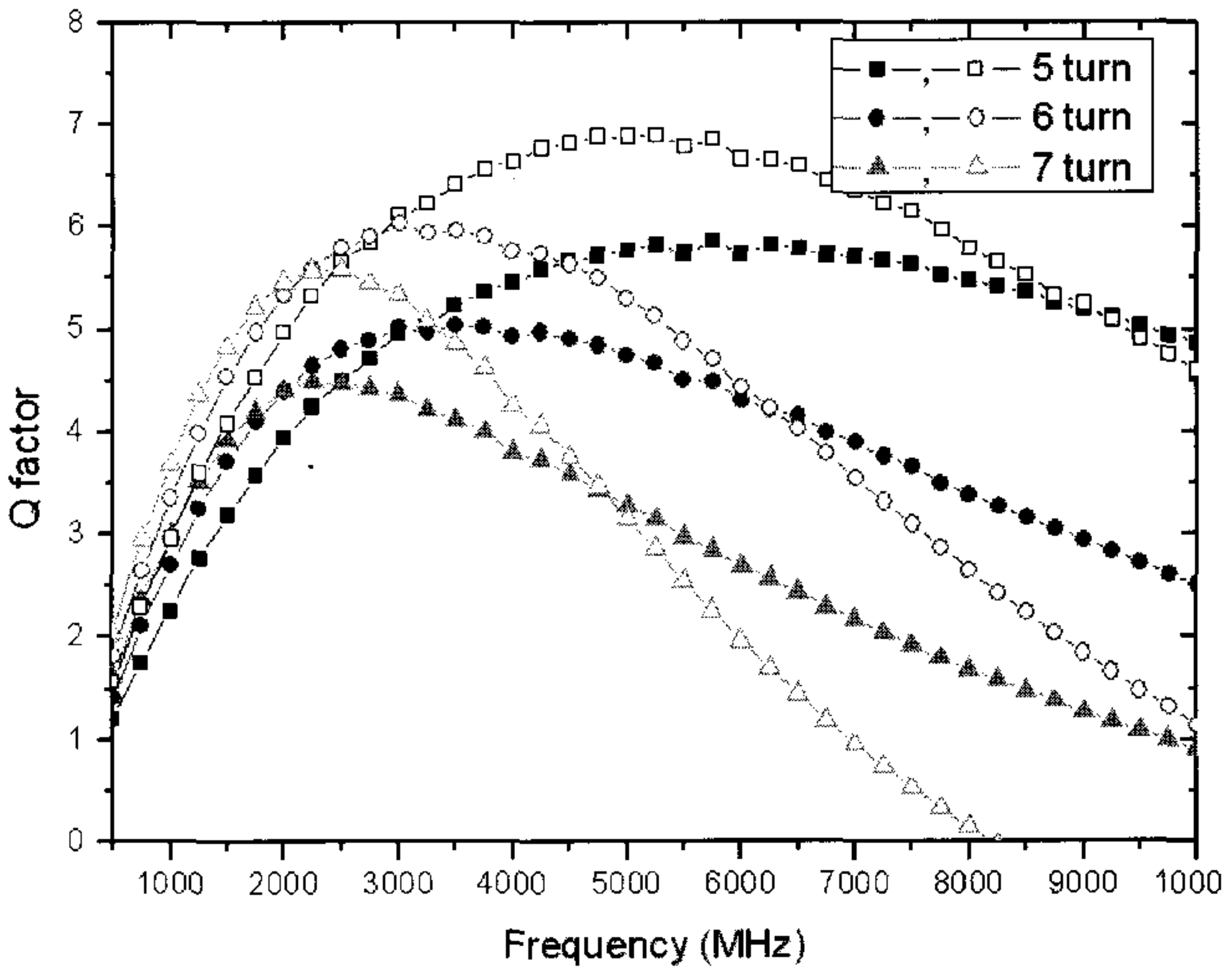


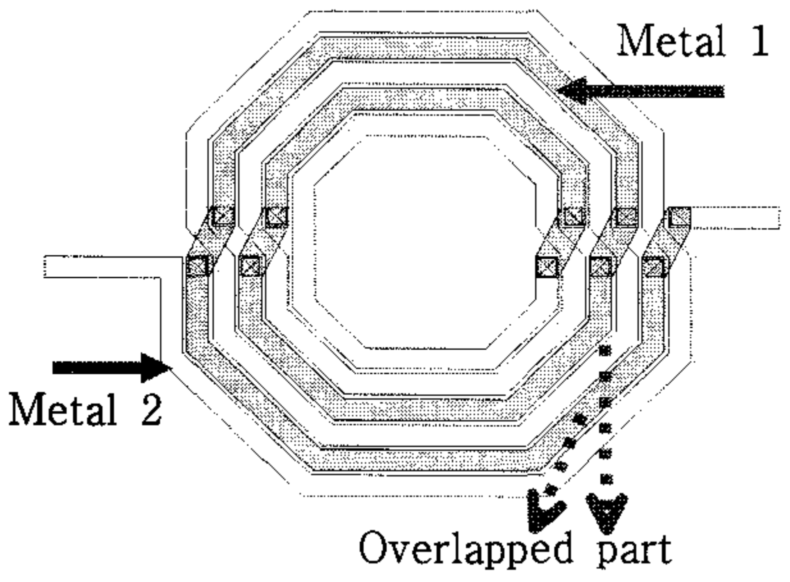
Fig. 2. Q factors versus frequency for the parallel-branch inductor (vacant) and the conventional spiral inductor with 30 um inner dimension (solid).

Fig. 2 shows the Q factor variation of the conventional and the parallel-branch spiral inductor along the frequency. The presented parallel-branch inductor has 12 % improved Q factor with the same area as the conventional inductor. That results stem from the self and mutual inductance of the inserted lower metal and the decrease of resistance values.

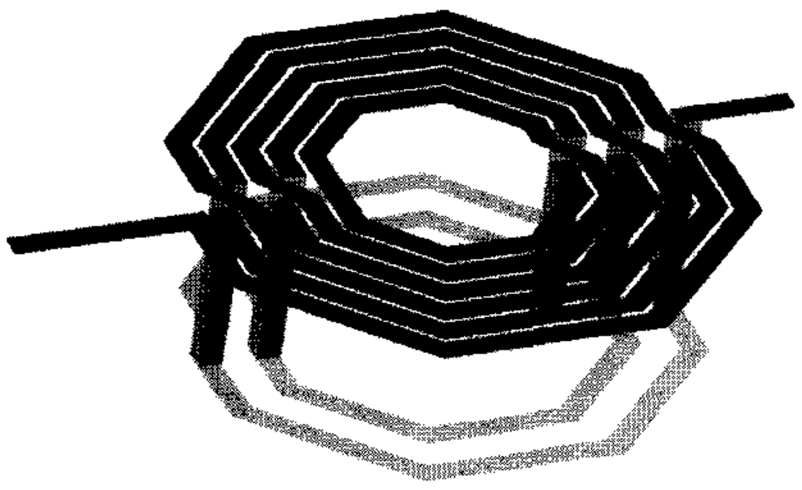
Ⅲ. Octagonal Parallel-Branch Inductor

According to the necessity of the RF communication system which becomes more and more broadband, we have developed an octagonal-parallel branch inductor. The parallel-branch inductor has some drawbacks. In spite of the higher Q factor, the resonance frequency and the f_{QMAX} are shorter than the conventional inductor, because of the overlapped metals. Particularly the self-resonant frequency of the 7-turned parallel-branch inductor is decreased down to 8 GHz, showing that more capacitive reactance is generated than the conventional one in a large inductor. We qualitatively understand that this result is attributed to the additional lower strip that induced more parasitic capacitance into the silicon substrate.

The top-view and 3D structure of the octagonal parallel-branch spiral inductor are shown in Fig. 3. The octagonal-parallel branch inductor is designed to decrease the series resistance and series capacitance of the parallel branch inductor. The high Q factor and the resonan-



(a) The plane viewed inductor



(b) The 3D octagonal parallel-branch spiral inductor

Fig. 3. Structure diagrams.

ce frequency are related to the reduction of the series resistance and the series capacitance, respectively.

Fig. 4 shows the Q factor changes according to the frequency of the parallel-branch and the octagonal parallel-branch spiral inductor with 100 um inner dimension. In spite of the relatively large-scale inside diameter, the octagonal parallel-branch inductor has very good performance of Q factor. Within the group of inductors with the same number of turns, we have obtained the improvements of the Q factor, resonance frequency and f_{QMAX} by reducing the resistance values and the parasitic capacitances. The Q factor improvements of the octagonal parallel branch inductor have as large as 24 % and 12 % at conventional inductor and parallel-branch inductor, respectively.

Fig. 5 reports the Q factors of the parallel-branch and the octagonal parallel-branch spiral inductor which have turn count like Fig. 4. From the data in this figure, we also have improved the Q factor, resonance frequency and f_{QMAX}. The Q factor improvement of the octagonal parallel branch inductors with 150 um inner dimension are more than 10 %.

We have applied the π-typed nine-element model to the parallel-branch and the octagonal parallel-branch inductors in order to point out what component of inductors enhances the Q factor and resonance frequency as shown in Fig. 6[9],[10]. Series inductance(L_{ind}), series resistance(R_s), series capacitance(C_f) between the upper and the lower metal strips, and the parasitic elements pertinent to the substrate and silicon dioxide layer are considered. The parasitic elements are characterized by the capacitance of silicon dioxide($C_{OX1,2}$) and the resistance and the capacitance of silicon substrate ($R_{si1,2}$ and $C_{si1,2}$). In Table I, we compare the extracted parameters of parallel-branch inductor and octagonal parallel- branch inductor. As a result the octagonal parallel-branch inductor has lower resistance value and parasitic capacitances than those of the parallel-branch type. That implies that the octagonal parallel-branch inductor enhances the Q factor, resonance frequency and f_{QMAX} by mainly reducing the series resistance and parasitic capacitances of the inductor without degradation of the inductance values.

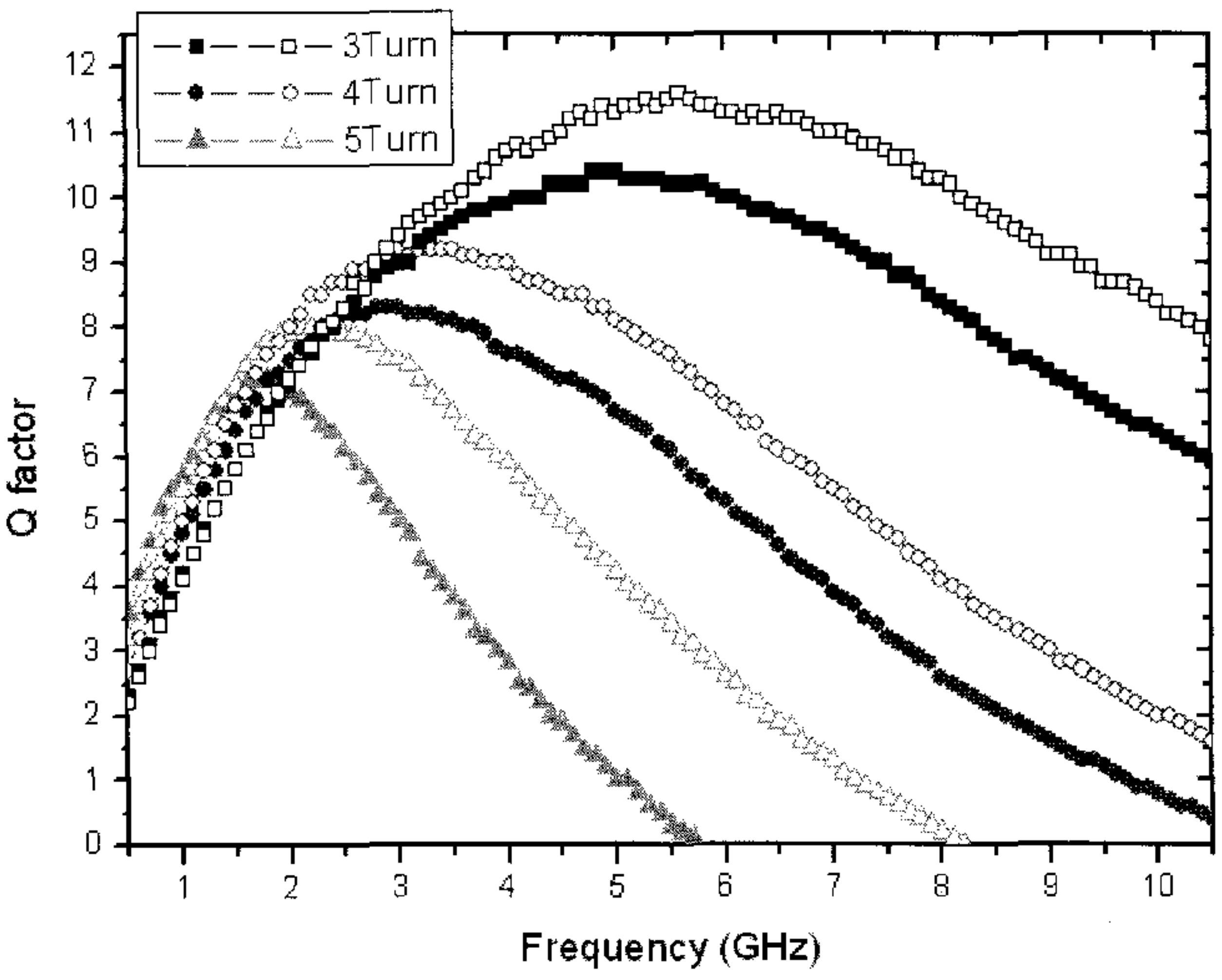


Fig. 4. Measured quality factors for the octagonal parallel-branch inductor (vacant) and the parallel-branch spiral inductor (solid) with 100 um inner dimension as a function of frequency.

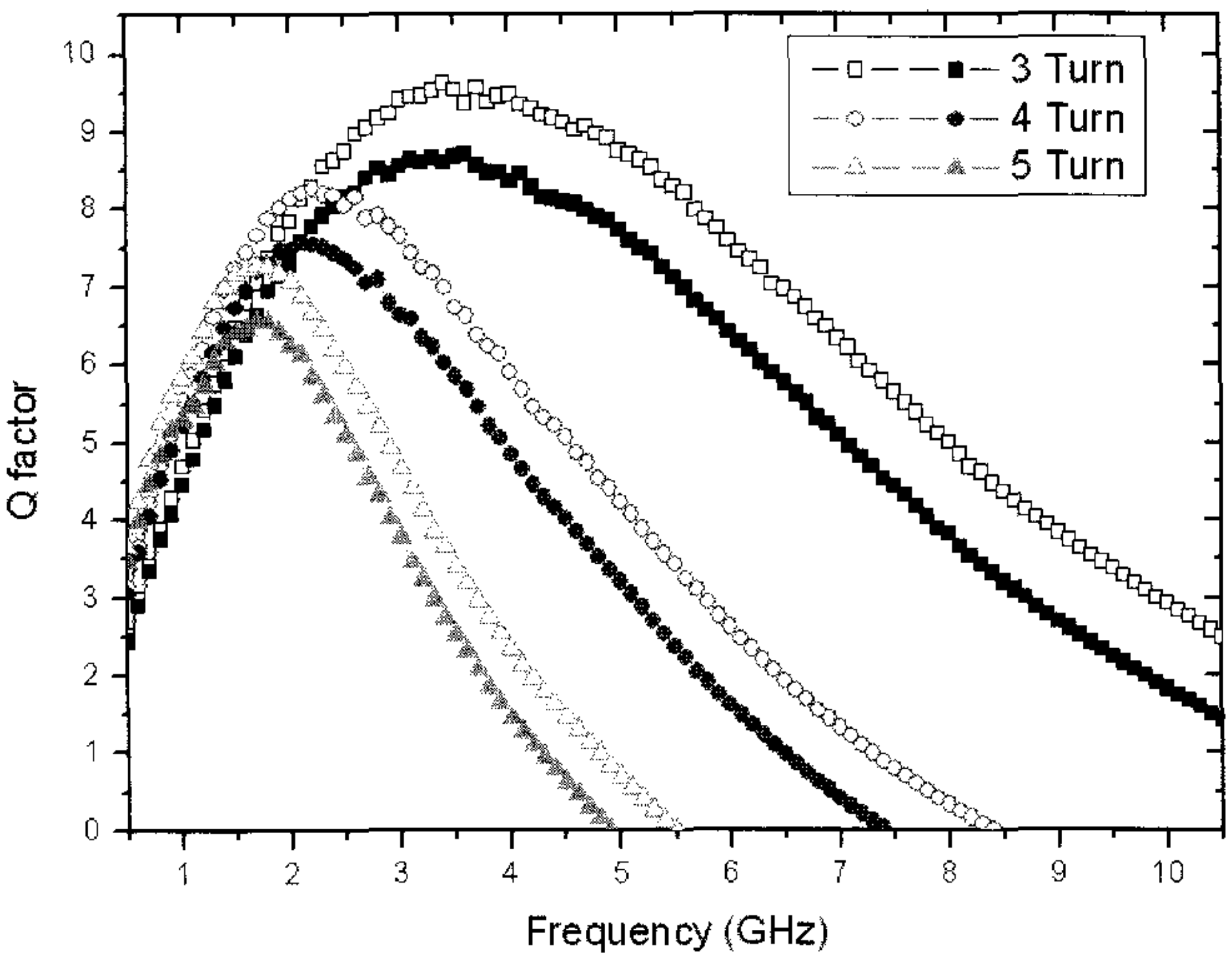


Fig. 5. Measured quality factors for the octagonal parallel-branch inductor (vacant) and the parallel-branch spiral inductor (solid) with 150 um inner dimension as a function of frequency.

Table 1. The comparison of the extracted parameters between square and octagonal parallel-branch inductors.

Type / Parameters	Parallel-branch inductor (Inner dimension : 100 um)			Octagonal parallel branch inductor (Inner dimension : 100 um)			Octagonal parallel branch inductor (Inner dimension : 150 um)		
Turn	3	4	5	3	4	5	3	4	5
L_{ind}(nH)	1.5	2.6	4.2	1.4	2.5	3.9	2.1	3.8	6.0
R_s(Ω)	2.2	2.2	2.6	2.1	2.1	2.1	2.0	2.0	2.1
C_f(fF)	13.3	43.7	66.7	9.8	35.9	60.5	23.2	53.4	80.0
C_{ox1}(fF)	143	180	222	130	149	173	138	179	256
C_{ox2}(fF)	148	187	300	148	179	252	163	248	373
R_{si1}(fF)	838	516	434	915	595	465	482	393	362
R_{si2}(fF)	426	334	301	485	397	330	365	286	260
C_{si1}	27.8	43.9	76.6	21.9	30.1	56.5	34.7	68.1	114.4
C_{si2}	12.8	27.5	57.5	9.3	21.6	42.7	25.2	51.8	94.1
Q_{MAX}	10.4	8.3	7.2	11.5	9.2	8.1	9.6	8.3	7.3
f_{QMAX}(GHz)	4.9	3.0	2.1	5.4	3.5	2.1	3.4	2.2	1.7

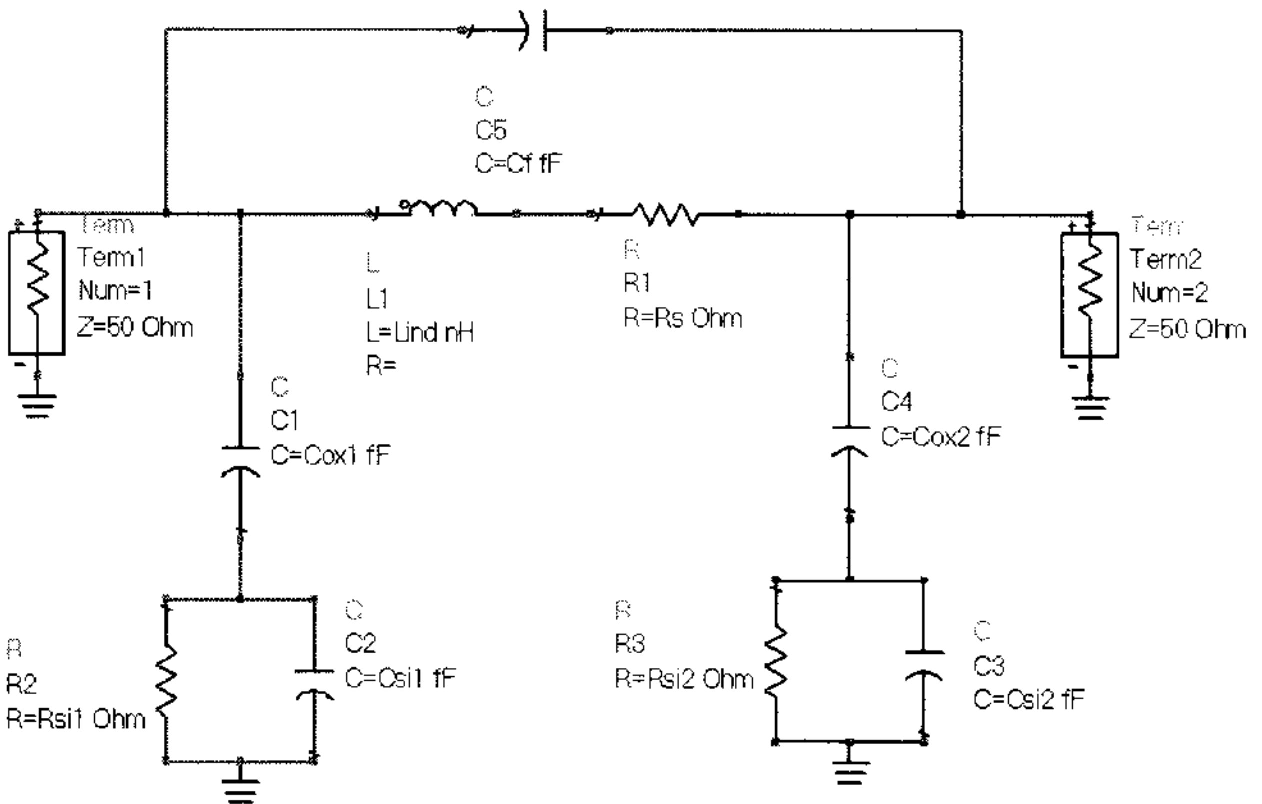


Fig. 6. Equivalent circuit model for an inductor.

Ⅳ. Conclusion

In this work cost effective inductor structures were presented to enhance the *Q* factor of the conventional spiral inductor. The parallel-branch inductor was suggested without any change in fabrication process and additional cost. As a result the *Q* factor of the parallel-branch inductor was greatly enhanced by structurally and in turn electrically branching metal strip without loss of inductance. Also, we showed the octagonal parallel-branch inductor that had the improved *Q* factor and the resonance frequency. The improved performances were explained to the value of the reduced series resistance and parasitic capacitance. The octagonal parallel-branch inductor had an improved *Q* factor over a wide frequency range.

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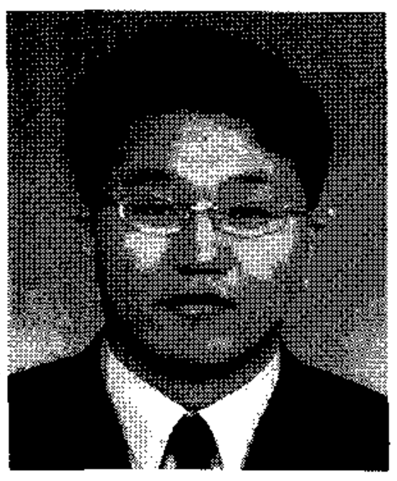

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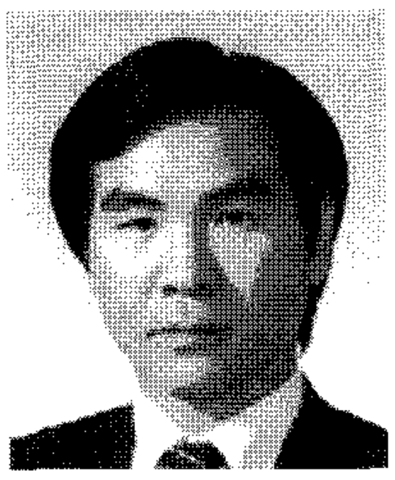

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