# Enhancement of Broadband Performance for On-Chip Spiral Inductors With Inner-Patterned-Ground

<table>
<thead>
<tr>
<th>Journal:</th>
<th><em>Microwave and Optical Technology Letters</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>MOP-07-1445</td>
</tr>
<tr>
<td>Wiley - Manuscript type:</td>
<td>Research Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>23-Nov-2007</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Shi, Jinglin; Institute of Microelectronics Sun, Sheng; NTU Xiong, Yong Zhong; Institute of Microelectronics Yeoh, Wooi Gan; Institute of Microelectronics</td>
</tr>
<tr>
<td>Keywords:</td>
<td>on-chip spiral inductor, CMOS, Inner-Patterned-Ground (IPG), quality factor (Q)</td>
</tr>
</tbody>
</table>
Enhancement of Broadband Performance for On-Chip Spiral Inductors with Inner-Patterned-Ground

Jinglin Shi\textsuperscript{1}, Sheng Sun\textsuperscript{2}, Yong Zhong Xiong\textsuperscript{1}, Wooi Gan Yeoh\textsuperscript{1} and Kiat Seng Yeo\textsuperscript{2}

\textsuperscript{1}Institute of Microelectronics, Singapore, 117685, \textsuperscript{2}Nanyang Technology University, Singapore 639798

Corresponding author: Tel: (65) 6770-5418, Fax: (65) 67745754, Email: jinglin@ime.a-star.edu.sg

\textbf{ABSTRACT} — A set of on-chip spiral inductors with novel inner-patterned-ground (IPG) is presented in this paper to enhance the broadband performance. By grounding the simple center metal cross, the IPG structure, an additional inner ground path is formed, the input impedance of the spiral inductor is reduced at the higher frequency range. Compare with conventional inductors, the quality factor (Q) of the IPG inductors increases by 15-30\% over the frequency range of 15 to 35 GHz. The IPG inductors can be modeled based on a simple lumped equivalent circuit. The extracted inductance and quality factors are verified by on-wafer measurement up to 50 GHz.
Introduction: Silicon On-Chip spiral inductors have been widely used in radio frequency integrated circuits (RFICs) for wireless communication systems such as wireless local area networks, personal handsets, and global positioning systems. Monolithic inductors have drawn tremendous research effort over the past decades, especially in recent years. A lot of modeling approaches have been reported in recent years [1-3]. But only a few work has been done on the novel design of the spiral inductor structure itself [4-6].

The FCC has opened up 22 – 29 GHz for ultrawideband vehicle radar systems [7]. Consequently, a lot of research work published on 24-GHz range 24GHz blocks or transceivers [8-9]. In this paper, a novel inner-patterned-ground (IPG) structure is proposed for the design of broadband spiral inductors. The enhancement of quality factor over the frequency range 15 GHz – 35 GHz has been achieved compared to the conventional inductors. The resultant performance is verified by measurement based on standard 0.18μm CMOS technology.

Inductor Design: A set of inductors with and without IPG structure is fabricated using standard 0.18μm CMOS technology (substrate resistivity 10 O–cm). Fig. 1a and Fig. 1b show the die photo of the conventional spiral inductor and the IPG inductor respectively, fabricated using standard CMOS process technology with six layers of metal TiW/Al-1% Si/TiW interconnects. The inductors have an inner diameter of 40 μm and 50 μm, a metal winding width of 5 μm, a metal winding spacing of 5 μm and 2 turns. The IPG inductor has a metal cross, ie. the IPG structure inside the inductor coil which consists of metal 1 to metal 6 together with vias. The width of the cross bar is 3 μm, the distance from the edge of the sign to the inductor inner edge is 5 μm. The cross sign is connected to the ground bar through metal 1.

Due to the implementation of the IPG structure, the magnetic field and the electric field to the substrate are modified. At low frequency, the performances of the two sets of inductors are the same. As frequency increases, the electric field to the silicon substrate is partially changed to the IPG.

Fig. 2 shows the equivalent circuit for the inductors. The dash box refers to the equivalent circuits of
the conventional inductor based the concept as in [10], where R2 and L2 account for high frequency effect. The port 1 to port 2 coupling capacitance is omitted due to the calculated value is less than 1 f using the method described in [11]. The IPG provides one additional path to ground which is modeled by series C3, R3, and L3. For simplicity and clarity, we use _CON and _IPG for type 1a inductor in Fig. 1a and type 1b inductor in Fig. 1b through this paper.

**Experimental Results and Discussions:** The fabricated structures were measured using an HP8510C network analyzer, a Cascade probe station and Cascade infinity GSG probes from 100MHz to 50.1GHz and de-embedded with the open structure. The inductance and quality factor are calculated by Eqs. (1) and (2) with the Y-parameters converted from measured de-embedded S-parameters

\[
L = \frac{\text{Im}(1/Y_{11})}{\omega} \quad (1)
\]

\[
Q = \frac{\text{Im}(1/Y_{11})}{\text{Re}(1/Y_{11})} \quad (2)
\]

Fig. 3 shows the extracted inductance values for these inductors. The inductance of the novel inductor with IPG increases faster than that of the conventional inductor as the frequency goes up.

Fig. 4 shows the extracted quality factors of these inductors. The quality factors (Q) increase 15-30% from 20-35 GHz. It increases more for the 50 um diameter inductor than the 40 um diameter inductor. From these figures, we can conclude the IPG has effect on both the inductance and quality factor at higher frequency range. The equivalent circuit values of the conventional and novel inductors are tabulated in Table I and II respectively. In Table II, R1, L1, R2 and L2 are omitted because they are the same as in Table I.

Fig. 5 shows the extracted inductance and quality factor from the circuit model (_C) and measurement data (_M) for the 50 μm inductor. The circuit simulation data show good agreement with the measurement data.

Fig. 6 shows the input impedance of the inductors. The impedance of the novel inductor is flatter than that of the conventional inductor at higher frequency range which further confirms that IPG improves
the inductor performance.

**Conclusion:** In this paper, novel spiral inductors with IPG were designed, fabricated and characterized experimentally. The improvement of the quality factor is obvious and it would benefit broadband applications without any extra cost.
REFERENCES


Fig. 1. Die photos of the conventional and novel inductor (1a: conventional, 1b: inductor with IPG)

113x72mm (96 x 96 DPI)
Fig. 2. Equivalent circuits of the conventional and IPG inductors (dash line box is a simplified circuit model for the conventional inductor).

212x106mm (96 x 96 DPI)
Fig. 3. Extracted inductance of the two sets inductors with inner diameters of 40 µm and 50 µm. Legend: ■ - D40_CON - □ - D40_IPG - ▲ - D50_CON - △ - D50_IPG

152x120mm (96 x 96 DPI)
Fig. 4. Extracted quality factor of the two sets inductors with inner diameters of 40 μm and 50 μm. Legend: - ■ - D40_CON - □ - D40_IPG - ▲ - D50_CON - △ - D50_IPG

160x117mm (96 x 96 DPI)
Fig. 5. Comparison of inductance and quality factor of measured and modeled the inductor with inner diameter 50 μm. Legend: - ■ - D50_CON_M - □ - D50_CON_C - ▲ - D50_IPG_M - △ - D50_IPG_C

174x122mm (96 x 96 DPI)
Fig. 6. Comparison of input impedances of the conventional and IPG inductors with inner diameter of 40 µm and 50 µm. Legend: - ■ - D40_CON - □ - D40_IPG - ▲ - D50_CON - △ - D50_IPG

142x101mm (96 x 96 DPI)
### TABLE I  Equivalent Circuit Values for Conventional Inductors

<table>
<thead>
<tr>
<th>Ind_con</th>
<th>$R_1$(ohm)</th>
<th>$L_1$(pH)</th>
<th>$R_2$(ohm)</th>
<th>$L_2$(pH)</th>
<th>$C_{ox1}$(fF)</th>
<th>$C_{S1}$(fF)</th>
<th>$R_{S1}$(ohm)</th>
<th>$C_{ox2}$(fF)</th>
<th>$C_{S2}$(fF)</th>
<th>$R_{S2}$(ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D40</td>
<td>4.4</td>
<td>580</td>
<td>3</td>
<td>80</td>
<td>13</td>
<td>1</td>
<td>280</td>
<td>14</td>
<td>2</td>
<td>250</td>
</tr>
<tr>
<td>D50</td>
<td>5.6</td>
<td>690</td>
<td>3.2</td>
<td>80</td>
<td>14.2</td>
<td>2</td>
<td>220</td>
<td>15</td>
<td>2.5</td>
<td>200</td>
</tr>
</tbody>
</table>
TABLE II  Equivalent Circuit Values for Inductors with IPG

<table>
<thead>
<tr>
<th>Ind_nov</th>
<th>$C_{ox1}$ (fF)</th>
<th>$C_{S1}$ (fF)</th>
<th>$R_{S1}$ (ohm)</th>
<th>$C_{ox2}$ (fF)</th>
<th>$C_{S2}$ (fF)</th>
<th>$R_{S2}$ (ohm)</th>
<th>$C_3$ (fF)</th>
<th>$R_3$ (ohm)</th>
<th>$L_3$ (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D40</td>
<td>11</td>
<td>10</td>
<td>130</td>
<td>13</td>
<td>10</td>
<td>100</td>
<td>3</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>D50</td>
<td>12</td>
<td>10</td>
<td>110</td>
<td>14</td>
<td>10</td>
<td>95</td>
<td>3</td>
<td>2.5</td>
<td>10</td>
</tr>
</tbody>
</table>