C-band Oscillator Using High-Q Inductors Embedded in Multi-Layer Organic Packaging

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ABSTRACT — **We present C-band oscillators with external high-Q inductors: wire-bond inductors and embedded inductors in a Multi-Layer Organic (MLO) board fabricated by a thick-film MCM-L technology. The phase-noise performance of oscillators are compared with the oscillator using on-chip inductors. Inductors are designed to obtain high quality factor in C-band. The phase-noise performance of the oscillator with on-chip inductors measures –108 dBc/Hz at 600 KHz offset frequency, and that of the oscillator with external inductors shows –113 dBc/Hz at the same offset. Using MLO inductors, the phase-noise is better than the oscillator with on-chip inductors and comparable to the oscillator with wire-bond inductors. To our knowledge, this is the first C-band oscillator using inductors embedded in the multi-layer organic packaging technology. This is also the first report comparing the performance of oscillators using three different inductor technologies: on-chip integration, wire-bonding, and multi-layer organic packaging technology.**

I. INTRODUCTION

In recent years, the rapid growth of the mobile communications market in C-band has resulted in an increased demand for the C-band wireless technology. A prime example includes the low phase-noise oscillators, which are the critical circuit block in all wireless communication transceivers. The phase-noise performance of oscillators is one of the most important figure-of-merits in the wireless transceiver because it affects dynamic range, selectivity, and sensitivity of a receiver. The phase-noise performance of LC-oscillators is mainly dependent upon the quality factor (Q) of inductors used in the resonators. Hence, a lot of different technologies have been presented for high-Q inductors. There has been active research on the oscillator design using the wire-bond inductors [1]. In Recently, high-Q inductors, fabricated by multi-layer technologies such as Low Temperature Co-fired Ceramic (LTCC) [2], Multi-Layer Organic (MLO) [3], and thin-film multi-layer Multi-Chip-Module (MCM) technology [4], have been reported, and a few papers on the oscillator with these high-Q inductors are published [5,6,7].

In this paper, three oscillators using inductors, made by different technologies, are presented. One is the oscillator using on-chip inductors, another uses wire-bond inductors, and the last uses MLO inductors. These oscillator circuits are implemented by GaAs MESFET process. The wire-bond inductors are carefully designed and implemented to achieve the oscillation frequency in C-band. MLO inductors are optimized with IE3D simulator to obtain the maximum Q-value in C-band. The 3 metal-layer organic process is used to fabricate embedded inductors. The measured Q-value of wire-bond, and MLO inductor are around 40 and 75 , respectively in C-band. The phase-noise performance of the oscillator with MLO inductors is compared with that of the oscillators with on-chip and wire-bond inductors.

II. EMBEDDED HIGH-Q INDUCTOR DESIGN IN MULTY-LAYER ORGANIC PACKAGING

Multi-layer organic packaging, in which inductors are embedded, represents a thick-film MCM-L technology suitable for System On Package (SOP) application. Three metal-layers are used and thick-film organic material is laminated between the metal layers. The second and the third layer are used to make inductors. In inductor design, there are many design freedoms including the shape, the width of layer, the space between layers, the number of turn, the inner radius of the inductor, and the distance from ground plane to the inductor.

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In this work, the circular type inductor is chosen as shown in Fig. 1. To simplify the design, the number of turn and the width is fixed at 1 turn, and 3 mils, respectively. We vary the radius (r) of inductor to obtain target inductance. The inductance of 1.2 nH is designed with the radius (r) of 20 mils. MLO inductor shows the maximum Q-value of 80 at 6 GHz. Fig. 2 shows the quality factor and the inductance value of MLO and wire-bond inductor used in the resonator.

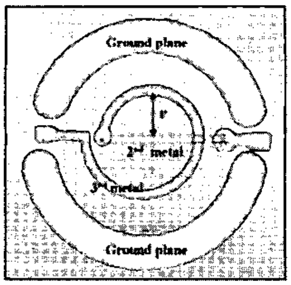

Fig. 1. Photograph of the fabricated circular type Multi-layer Organic inductor

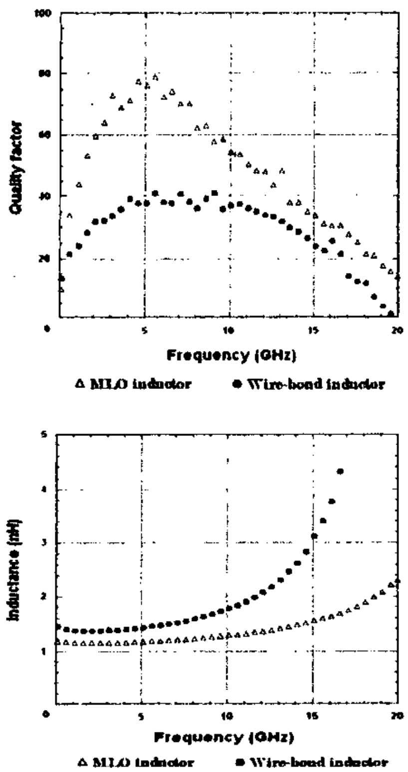

Fig. 2. Measured quality factor and inductance of MLO and wire-bond inductor as a function of frequency

III. OSCILLATOR CIRCUIT DESIGN

The TriQuint 0.6 μm GaAs MESFET process is utilized to design and implement the oscillator circuit. Fig. 3 is the circuit schematic of the oscillators, and Fig. 4 shows a photograph of an oscillator with pads for wire-bonding to connect external inductors with the oscillator circuit.

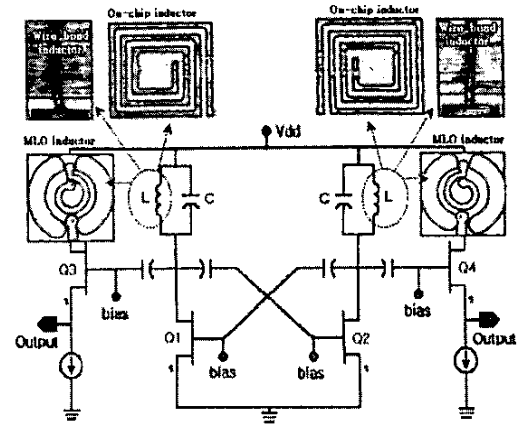

Fig. 3. Schematic of oscillator circuit

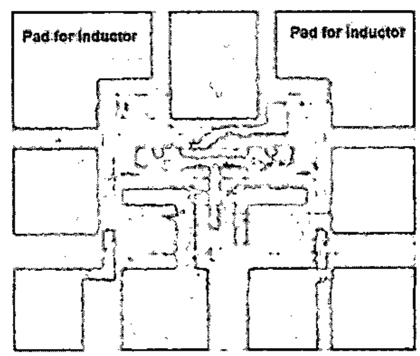

Fig. 4. Photograph of oscillator circuit with pads for external inductors

To reduce the 1/f noise up-conversion, the cross-coupled differential topology with the capacitive coupling feedback was used [8]. Cross-coupled transistors (Q1 and Q2) form a positive feedback to provide a negative resistance to cancel the loss in the LC-resonators. The positive feedback is obtained through capacitors (Cf). These capacitors take roles of suppressing the 1/f noise up-conversion as well as dc-blocking in order to bias cross-coupled transistors. The LC-resonator at the drain consists of an inductor (L) and a capacitor (C). In this work, on-chip, wire-bond, and MLO inductors are used for the inductor (L) of the resonator. Q3 and Q4 form buffers capable of driving 50Ω. The gates of all MESFETs in the design are biased with high value resistors.

IV. RESULTS

On-wafer measurements of oscillation frequency, output power, and phase-noise were performed using an Agilent 8563E spectrum analyzer. The phase-noise performance was measured across the offset frequency range from 100 KHz to 1 MHz. Fig. 5 shows the oscillation frequency and the phase-noise performance of the oscillator with on-chip inductors. The phase-noise is –108 dBc/Hz at the offset frequency of 600 KHz. The oscillator with wire-bond inductors shows the phase-noise performance of –113.5 dBc/Hz at the same offset as shown in Fig. 6.

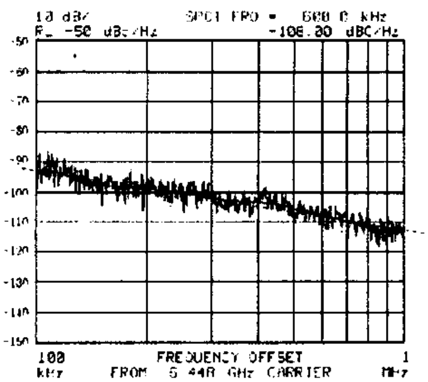

Fig. 5. Measured phase-noise performance of the oscillator using on-chip inductors

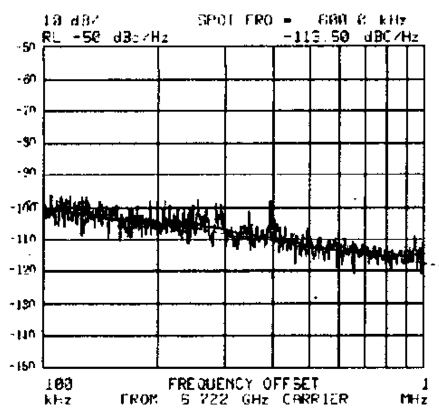

Fig. 6. Measured phase-noise performance of the oscillator using external inductors

Due to higher quality factor, the oscillator with wire-bond inductors shows 5~6 dB phase-noise improvement over the oscillator using the on-chip inductors across the offset frequency range between 100 KHz and 1 MHz. However, even though the wire-bond inductors have the high quality, they are not thought to be a good candidate to replace the on-chip inductors because of the difficulty in controlling the inductance value of wire-bond. Using the MLO inductors (Q: 80 at 6 GHz) which have higher quality factor than wire-bond inductors (Q: 40 at 6 GHz), the oscillator shows phase-noise performance comparable to the oscillator using wire-bond inductor. In spite of the comparable phase-noise performance, MLO inductors are better choice than wire-bond inductors because of the improved accuracy of the inductance value controlling, which is critical in oscillator design.

V. PHASE-NOISE ANALYSIS

As the quality factor of inductors in the resonator increases, the phase-noise performance improves. However, the extent of improvement in the phase-noise is not directly proportional to the quality factor. The phase-noise of oscillators depends not only on the inductor quality, but also on the resistance in parallel with the resonator. The phase-noise can be formulated by [1]

$$L\{\Delta f\} = \frac{kT \cdot R_{eff} \cdot [1+A] \cdot \left(\frac{\omega_0}{\Delta\omega}\right)^2}{V^2 / 2} \quad (1)$$

$$R_{eff} = R_L + R_C + \frac{1}{R_p \cdot (\omega_0 \cdot C)^2} \quad (2)$$

k : boltzman constant　ω_0 : oscillation frequency
T : temperature　$\Delta\omega$: offset frequency
A : noise factor　V : signal voltage
R_L : series resistance in inductor
R_C : series resistance in capacitor
R_p : parallel resistance with the resonator
C : capacitance in the resonator

When using MLO inductors, even though the resistance in the inductor (R_L) goes extremely small, the parallel resistance with the resonator (R_P), which composes the third term in the equation (2), limits the phase-noise performance and makes it saturated.

IV. CONCLUSION

C-band oscillators, using inductors implemented by different technologies: on-chip integration, wire-bond, and

MLO packaging, are presented and compared in terms of the phase-noise performance. Inductors are designed to obtain maximum quality factor around the oscillation frequency in C-band. The phase-noise of the oscillator using MLO inductors is better than that of the oscillator using on-chip inductors and comparable to that of the oscillator using wire-bond inductors.

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