Available online at www.sciencedirect.com
SCIENCE DIRECT®
Solid-State Electronics 48 (2004) 1643–1650
SOLID-STATE ELECTRONICS
www.elsevier.com/locate/sse

Characterization of symmetrical spiral inductor in 0.35 μm CMOS technology for RF application

T. Hui Teo [a,*], Yeung-Bun Choi [a], Huailin Liao [a], Yong-Zhong Xiong [a], Jeffrey Shiang Fu [b]

[a] *Integrated Circuit and System Laboratory, Institute of Microelectronics, 11 Science Park Road, Singapore Science Park II, Singapore 117685, Singapore*

[b] *School of Electrical and Electronics Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore*

Received 7 November 2003; received in revised form 5 April 2004; accepted 5 April 2004
Available online 30 April 2004

The review of this paper was arranged by Prof. S. Cristoloveanu

Abstract

Characteristics of symmetrical spiral inductor in differential mode is studied and optimized in this work. The characteristics of interest include inductor value, quality factor, peak frequency and self-resonance frequency. Both single-layer and double-layer inductor using top metals are characterized. Inductor excited in differential mode and single-ended mode are characterized for comparison. The optimized symmetrical spiral inductors are fabricated in standard digital 0.35 μm CMOS process. Experimental results show 60–100% improvement of quality factor and peak frequency, meanwhile 10–20% improvement of self-resonance frequency by exciting the symmetrical spiral inductors in differential mode compared with single-ended mode. To further validate the characterized inductor, the differential spiral inductors are adopted in optimizing low power and low phase noise fully integrated 2.4 GHz voltage-controlled oscillator (VCO). The designed VCO achieved phase noise of more than −105 dBc/Hz at 100 kHz offset with approximately 4.5 mA at 3.0 V supply.

Keywords: CMOS; Differential mode; RF; Single-ended mode; Symmetrical spiral inductor; VCO

1. Introduction

Low-cost CMOS process, such as 0.35 μm technology is attractive for radio frequency application up to 2.4 GHz. The limitation of this process is its low quality on-chip inductor. In order to extend the use of 0.35 μm in this frequency range, quality factor of the on-chip inductor should be improved. Multi-layer inductor is one of the methods commonly adopted for this purpose [1]. Differential mode on-chip inductor is also suggested, [2] to improve the quality factor. However, there is still lack of extensive study on these two methods with sufficient experimental data.

Differential circuit such as VCO excites the symmetrical spiral inductor in differential mode. In such case, the characteristics of the spiral are different from the single-ended and need to be considered for circuit optimization. In this work, we have designed two sets of symmetrical spiral inductor in single-layer metal and double-layer metal to verify and compared their characteristics in both differential and single-ended mode. The dc inductance of these inductors is in the range of 2–8 nH with 0.4 nH per step, which covers the practical implementation in giga hertz range. The experiment results imply the optimize use of the symmetrical spiral inductor in this process. High performance VCO can be

* Corresponding author. Tel.: +65-67705323; fax: +65-67745754.
E-mail address: teehui@ime.a-star.edu.sg (T.H. Teo).
URL: http://www.ime.a-star.edu.sg.

0038-1101/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2004.04.004

designed and optimized with these characterization results.

This paper is organized as follows. In Section 2, analysis of the symmetrical spiral inductor is briefly discussed. Characterization of the inductor is presented in Section 3. Fully integrated VCO design is then presented with measured results in Sections 4 and 5. It is followed by conclusion in Section 6.

2. Analysis

The quality factor of the spiral inductor is defined as the ratio of the energy stored in the inductor to the energy dissipated in the parasitic components. It can be estimated by dividing imaginary with real part of the input impedance of the two-port network of spiral inductor. Physical model of the spiral inductor in Fig. 1(a), [3] is employed for discussion. It is a simplified π-network.

In this network, L_s, R_s, C_s, C_p and R_p represent the desired inductance, series resistance, feed-forward capacitance, substrate capacitance and resistance of the symmetrical spiral inductor, respectively. The symmetrical spiral inductor is a fully symmetrical network. Hence, the single-ended, Z_{se} and differential, Z_{diff} input impedance can be estimated by

$$Z_{se} = \frac{1}{Y_{11}}, \tag{1}$$

$$Z_{diff} = \frac{2}{(Y_{11} - Y_{21})}, \tag{2}$$

where $Y_{11} = Y_{22}$, $Y_{12} = Y_{21}$, Y_{11}, Y_{12}, Y_{21} and Y_{22} are the Y-parameters of the two-port network. It is equivalent to reduce the substrate capacitance by half but increase the substrate resistance by a factor of two in the differential mode input impedance. The equivalent circuit of the differential symmetrical spiral inductor is depicted in Fig. 1(b). In other words, the substrate losses are greatly reduced. The quality factor in both cases are simplified as

$$Q_o = \frac{\omega \cdot L_s}{R_s}, \tag{3}$$

$$Q_{se} = Q_o \cdot \frac{1 - \left(\frac{R_s^2}{L_s} - \omega^2 \cdot L_s\right) \cdot (C_p + C_s)}{1 + \frac{R_s}{R_p} \cdot \left[1 + \left(\frac{\omega \cdot L_s}{R_s}\right)^2\right]}, \tag{4}$$

$$Q_{diff} = Q_o \cdot \frac{1 - \left(\frac{R_s^2}{L_s} - \omega^2 \cdot L_s\right) \cdot \left(\frac{C_p}{2} + C_s\right)}{1 + \frac{R_s}{2 \cdot R_p} \cdot \left[1 + \left(\frac{\omega \cdot L_s}{R_s}\right)^2\right]}, \tag{5}$$

with ω is the radian frequency, L_s, R_s, C_s, R_p and C_p represent the components as shown in Fig. 1. Q_o is the quality factor due to conductance losses only. Q_{se} and Q_{diff} are the single-ended and differential quality factor, respectively, which take into the substrate losses. In extreme case, when $L_s \gg (C_p + C_s)$, $C_p \gg C_s$ and $R_p \gg R_s$, the quality factor can be further simplified as (6) and (7), which are only taken care the low-frequency effect.

$$Q_{se} = Q_o \cdot (1 - \omega^2 \cdot L_s \cdot C_p), \tag{6}$$

$$Q_{diff} = Q_o \cdot \left(1 - \omega^2 \cdot L_s \cdot \frac{C_p}{2}\right). \tag{7}$$

By inspecting (6) and (7), we expect an improvement in maximum quality factor and peak frequency of the differential mode spiral inductor by at least 40%. For spiral inductor with small inductance, the peak frequency happens to be at high frequency. At these frequencies, the second term of the numerator in (4) and (5) is much larger than one and cannot be neglected. Hence,

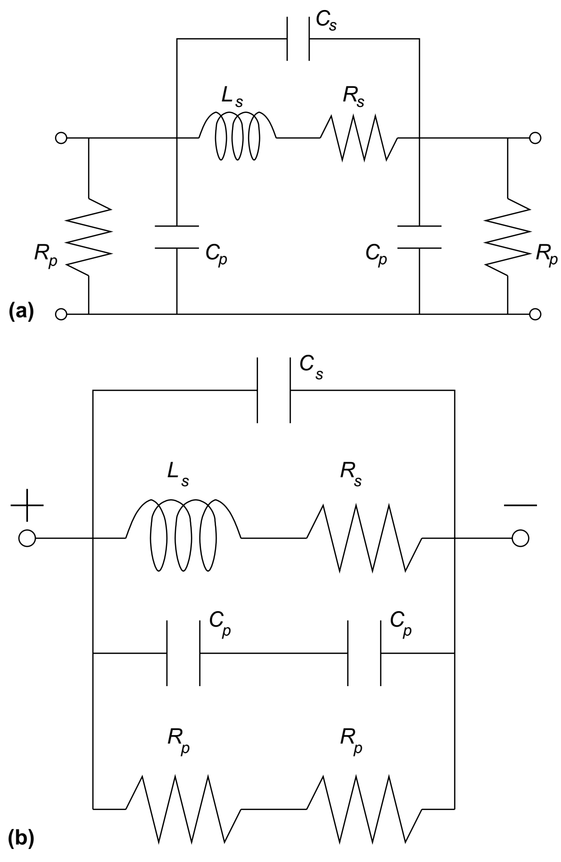

Fig. 1. Simplified equivalent circuit of symmetrical spiral inductor: (a) single-ended, (b) differential.