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An optimized 2.4 GHz VCO circuit design and simulation with high-Q MEMS LC-tank

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Abstract

This paper focuses on design of high-performance MEMS LC-tank circuit for use in CMOS voltage controlled oscillators (VCO) operating at 2.4 GHz. The high-Q air suspended inductor has been designed by inductance of 2.87 nH using MEMS technology to reduce the resistive loss and the substrate loss. A MEMS two-gap tunable capacitor has been designed. The DC voltage is 2.5 V which is applied to the plates and the results of 2.04 pF could be achieved. The pull-in voltage has been optimized to achieve low phase noise, low power consumption VCO. Through this optimization, less phase noise ($-117.7\,dB_c$/Hz at 100 KHz) and lower power consumption (11 mW) have been obtained.

Keywords: MEMS LC Tank; VCO; Inductor; Varactor; Q Factor

1. Introduction

In order to fulfill the needs of low cost and low power wireless telecommunication systems, the design of the wireless systems should be optimized. Looking at an integrated transceiver, the most critical point is mixing and modulation of signals. In most of the systems an input of mixer will be stimulated by a periodic signal, so an oscillator will be needed. The most used using oscillator in transceivers is voltage controlled oscillator (VCO) which can control the frequency of oscillation by an input voltage.

VCOs need some kind of frequency-selective or tuned circuit in a feedback configuration to generate sinusoidal output. Tuned oscillators usually place switched-capacitor circuits, LC circuit, RC circuit or crystal into a feedback loop when the loop gain should become positive and equal to unity [1]. An LC oscillator has been used more frequently because of the advantages of using in RF, sinusoidal output and ability to improve the specification of LC-tank. An LC-tank contains inductor and varactor which is a device whose reactance can be varied in a controlled manner, in this case, DC bias voltage.

The performance of a VCO can be evaluated by some specification such as oscillation frequency, phase noise, and power consumption. The most important factor which causes a low power and low noise oscillator is quality factor of inductor and varactor of LC-tank which is defined as $L\omega/R$ for inductor and $1/\omega R_c C$ for capacitor. The Q of inductor has been improved due to many researches on it [2–7]. Among those investigations using MEMS technology is the best solution to design an inductor with high-Q factor. The reasons for low factors are thin metal layers (ohmic loss) and high substrate coupling (eddy-current loss) in standard

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silicon processes. MEMS techniques have been developed to reduce the substrate loss.

On the other hand an important parameter which causes limitation of operation for varactors is the pull-in effect that causes the movable plate of varactor stick to the fix plate and stop tuning. Due to this problem, there have been different structures to realize high-performance varactors. Movable dielectrics, two parallel plates and double-air-gap are the most popular structures to increase the Q factor of varactor and overcome the pull-in voltage effect [8–11]. Therefore the phase noise of VCO can be reduced by using MEMS passive elements when the power consumption still remains low [12,13]. The inductance and capacitance of LC-tank are calculated from the resonance frequency equation ($f = 1/2\pi\sqrt{LC}$).

This paper proposes designing of high-performance MEMS LC-tank circuit for use in complementary metal-oxide semiconductor (CMOS) VCO operating at 2.4 GHz. The expected inductance and capacitance are 2.8 nH and 2 pF, respectively. The high-Q air suspended inductor has been designed using MEMS technology to reduce the resistive loss and the substrate loss. Low-resistivity material has been used. A MEMS two-gap tunable capacitor, which can be operated in low voltage, has been designed. The variable capacitor has been designed using two parallel plates (one fixed, one movable). The capacitor can be varied by applying low voltage to variable plate. The pull-in voltage has been optimized to achieve low phase noise, low power consumption, and a wide frequency tuning range for VCO. It can be noted it is desirable to evaluate the device prior to fabrication especially where the characteristic of device material and dimensions have a major influence on the performance of the overall system. To achieve this goal, a simulation tool is essential to reduce the number of trials for improving the production yield and optimizing the device. To the best of the authors' knowledge, this work has been reported the lowest value for phase noise by keeping the power consumption low.

2. VCO circuit design

Cross-coupled pair VCO which is shown in Fig. 1 is the best topology for RF oscillator circuit. It has large voltage swing, symmetric structure, and differential output. These circuits can be easily integrated with baseband CMOS digital circuits. The LC-tank two NMOS transistors which have been used in the circuit are coupled in positive feedback to provide a negative resistance. The minimum power supply needed for operating this circuit is $V_{D,sat\ PMOS}+V_{GS\ NMOS}$. The dimensions of the transistors are very important to minimize the noise. The ratio of NMOS and PMOS transistors has been optimized for reducing the flicker noise. The actual NMOS transistor widths have been determined for thermal noise reduction. We have used ratio for NMOS to PMOS transistors to be about 1:2.5. This is the best ratio reported on the literature review [12].

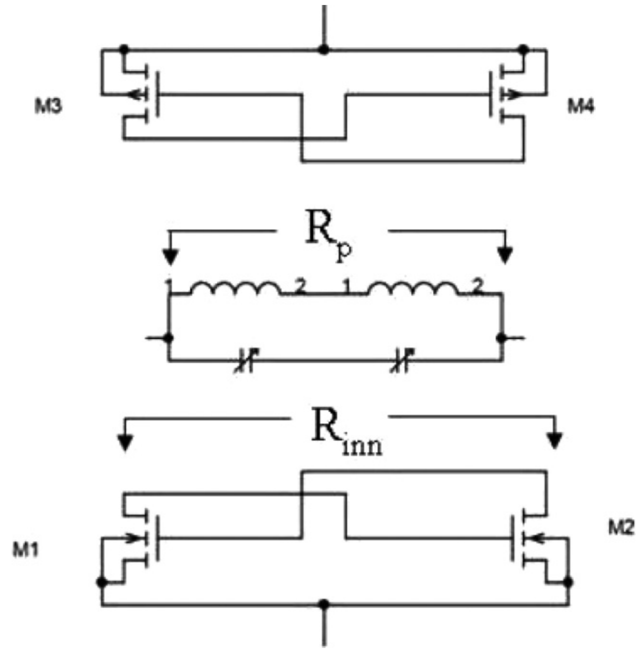

Fig. 1. VCO circuit with positive and negative resistance.

One role of an active part of the oscillator circuit is to compensate for the losses in the LC-tank for a stable oscillation. Fig. 1 shows the positive and negative resistance between active part and LC-tank circuit. The cross-coupled pair has a negative resistance around $-2/g_m$. If all losses in the LC-tank are equal to R_P, then for the oscillation to start the negative resistance should be equal to the positive resistance. The minimum value of transconductance (g_m) of cross-coupled transistors for oscillation is obtained from the condition that

$$2/g_m \geqslant R_p \tag{1}$$

where R_P is loss of the resonator and is given by

$$R_p = Q2\pi f L \tag{2}$$

L is the inductance, f is the frequency, and Q is the resonator quality factor which could be improved using MEMS technology. The g_m of the transistor is given by

$$g_m = \frac{I_D}{Vgs - V_T} = \left[2K'\frac{W}{L}I_D\right] \tag{3}$$

where I_D is the DC bias current.

The dimensions of the transistors of active part have been computed and it is given as

$$\frac{W}{L} = \frac{g_m^2}{2KI_D} \tag{4}$$

Based on those equations the Q factor of resonator directly has efficiency on the design of VCO. This effect will be