Substrate Coupling Effect under Various Noise Injection Topologies in LC-Voltage Controlled Oscillator

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Abstract **— Impact of substrate noise coupling on a wideband VCO (5.6 to 7.5 GHz) was investigated using different noise injection topologies. Measured results indicated that IM2 increased by ~ 5 to 7 dB and IM3 by ~ 6 to 10 dB when the inductor guard ring floated. In addition, the noise at high frequencies still degraded the VCO performance even not injected directly to the substrate. The observed trends were modeled and explained by a simple physical-based resistive network together with the oxide layer capacitors successfully.**

Index Terms **— RF CMOS, VCO, Noise coupling**

I. INTRODUCTION

In recent years, the explosive growth of wireless communication applications has led to strict demands on a high integration level for multiple circuit functions in a single chip. One major challenge for the chips including many circuit blocks is the noise coupling effect through the Si substrate. Among these circuits, the most vulnerable block is the RF circuitry, especially the high-frequency voltage-controlled oscillator (VCO), which is the heart of a phase-locked loop. Several papers have been published to discuss the impact of substrate noise on the VCO characteristics [1]-[4], which provide useful information about the origin and modeling of the noise coupling effect. In this work, a further investigation using various noise injection topologies is conducted including different distances, different ground/signal pads connections, and the effect of the inductor guard ring grounded/floated under a wide frequency range. In addition, a physical-based substrate model is established using a simple resistive network, which also provides a quantitative analysis for substrate noise coupling effect.

This paper first introduces the VCO circuit topology and various noise injection configurations in section II. Section III presents the measured spurs (IM2 and IM3) generated from the injected noise signal. Section IV describes the modeling for substrate noise coupling effect. Section IV concludes this work.

II. DESIGN OF VCO AND INJECTION PADS

A. VCO circuit topology

As shown in Fig. 1, the VCO circuit consists of a complementary cross-coupled pair and two pairs of switches for a wide tuning range from 5.6 GHz to 7.5 GHz. The circuit was implemented by a standard 0.18-μm CMOS technology with one poly layer and six metal layers (1P6M). The source follower was adopted as the output buffer. The measured phase noise is -128 dBc/Hz at 1MHz offset with a carrier frequency of 7.3 GHz, and the VCO core power dissipation is 15.5 mW under a 1.8 V power supply.

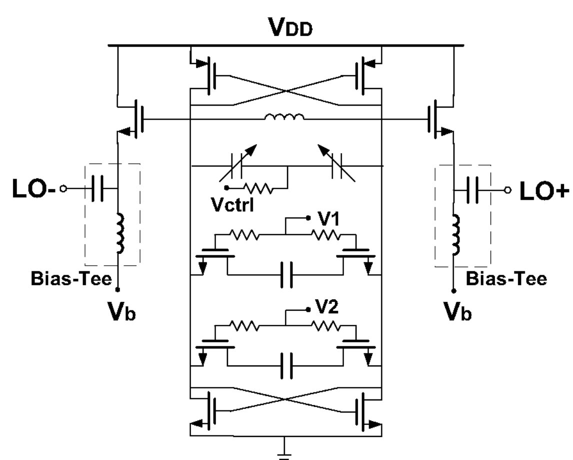

Fig. 1. VCO circuit topology.

B. Various noise injection conditions

The designed injection pads vary in four different topologies as shown in Fig. 2. A sinusoidal signal is injected into the chip to imitate the noise coupling effect in a real chip. The VCO circuit is placed at the center, while the ground-signal-ground (G-S-G) injection pads are on both sides of the chip. The injection pads are named from port 1 to port 4 from the right side to the left side. Port 1 and port 2 are designed to compare the coupling effect of different noise injection distances. The distances of port 3 (293 μm) and port 4 (443 μm) to the core circuit are identical to those of port 2 and port 1, respectively, while the signal pad of port 3 is connected to the metal layer only (Metal 6) to compare with those connected to the p+ substrate region for the other three ports. The ground pads of port 4 are connected directly to the overall circuit ground via both the top metal layers and the p+ substrate region underneath, while the ground pads for the other three ports are floated (Metal 6 only). In addition, the guard ring of the spiral inductor is designed such that the ground can be removed by the laser cutter as indicated by the three small circles in the figure. The purpose is to investigate the significance of the guard ring on substrate noise coupling in the VCO, which consumes a large additional area on the chip as can be seen in the figure.

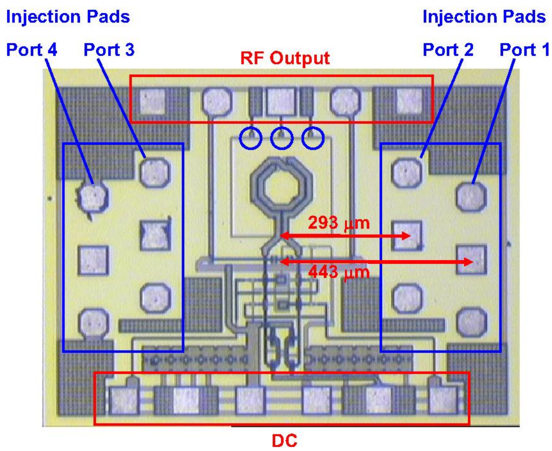

Fig. 2. Chip micrograph.

III. Measured Results

Fig. 3 shows the IM2 and IM3 spur powers versus the noise frequency at three VCO operation frequencies of 5.6, 6.4, and 7.2 GHz as low, middle, and high bands, respectively, where the injected signal is via port 4 with a power level of 25 dBm and a frequency range of 10 to 500 MHz (IM2) and 50 to 300 MHz (offset frequency of IM3). As can be seen, the spur power increases with the operation frequency of the VCO, while reduces with the injected signal frequency for IM2 and the offset frequency for IM3. These trends can be explained by the equations shown below [6]:

$$IM2 = \alpha_2 A_0 A_n \cos(\omega_0 \pm \omega_n)t \tag{1}$$

$$IM3 = \alpha_3 A_0^2 A_n \cos(2\omega_0 \pm \omega_n)t \tag{2}$$

where α_2 and α_3 are the nonlinear coefficients of the circuit; A_0 and A_n are the amplitudes of the carrier and the injected noise, respectively; and ω_0 and ω_n represent the frequencies of the carrier and the injected noise. Since the output power of the VCO increases with the operation frequency in this design, the IM2 and IM3 products also increase with the VCO operation frequency.

The reduced IM2 and IM3 as the noise frequency and offset frequency increasing can be attributed to the reduced nonlinear coefficients α_2 and α_3 as the difference between the carrier and the noise frequencies increases.

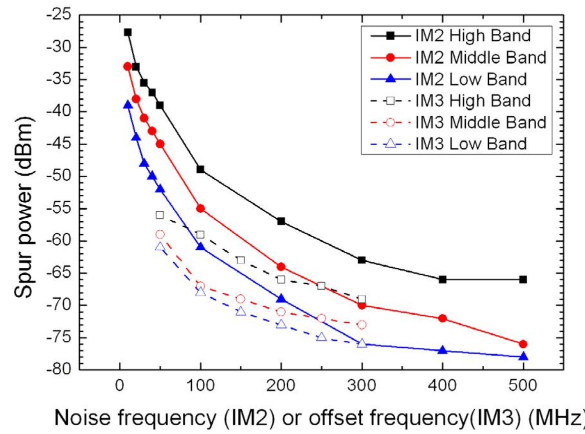

Fig. 3. IM2 and IM3 spur powers with noise signal injected in three different VCO operation frequency bands.

Fig. 4 shows the IM2 generated with a 20 MHz noise injected (VCO operates at 6.4 GHz) as a function of the noise power under both inductor guard ring grounded/floated. As can be seen, the spur power with the noise injected via port 2 is higher than that via port 1 due to a shorter distance to the main VCO circuit. In addition, compared the injection through port 4 and port 1 with the same distance to the core circuit, the ground connection to the overall circuit can effectively reduce the spur power. As the guard ring removed by the laser cutter, an increased spur power of ~ 5 to 7 dBm was observed in all the cases.

Fig. 5 shows the IM3 generated from a noise of 20 MHz offset (VCO operates at 6.4 GHz) as a function of the noise power under both inductor guard ring grounded/floated. A similar trend was observed compared with the IM2 results. For example, the highest spur results from the injection of port 2, and the spur level of port 4 is lower than that of injected from port 1. With the guard ring floated, the IM3 spur power increases by ~ 6 to 10 dBm. Both IM2 and IM3 reveal the importance of the properly grounded guard ring for the inductor in a LC VCO to prevent noise coupling effect. In addition, the results suggests that IM3 spurs are more sensitive to different noise injection conditions, while the spur levels are in general lower than IM2.

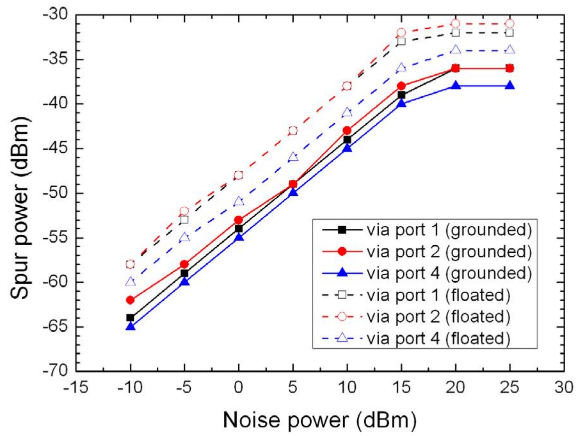

Fig. 4. IM2 spur power vs. noise power with a 20 MHz noise injection under the inductor guard ring grounded/floated. The VCO operates at 6.4 GHz.

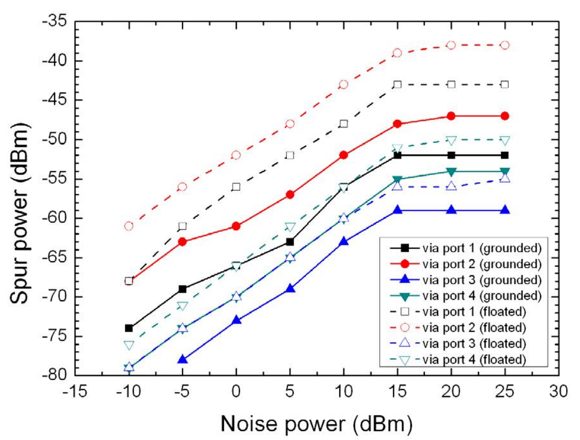

Fig. 5. IM3 spur power vs. noise power with a noise of 20 MHz offset injection under the inductor guard ring grounded/floated.

IV. Modelling of Substrate Noise Coupling Effect

Fig. 6 shows the physical-based substrate model for the noise coupling effect in this study. The small figures indicate the modelling approach for various noise injection configurations via the G-S-G probing pad, where C_{ox} describes the capacitance corresponding to the SiO_2 layer underneath the metal layers, and $R_{sub\text{-}pad}$ models the equivalent substrate resistance seen by the injected noise signal returning back to the ground pad. The noise signal propagates from the pad to the core VCO circuit can be modelled by a simple resistive network as also shown in the figure. The body terminal of each transistor is connected to the noise source in series with a lumped resistor, and the spiral inductor is connected in the same manner. Note that a small resistor $R_{sub\text{-}grd}$ is inserted between the spiral inductor and ground to model the effect of the guard ring.

In the VCO circuit investigated here, three possible paths exist for the injected noise signal loop through the substrate. The first path is the noise power flowing via the substrate and returns back to the injection ground pad, where the effect is modelled by $R_{sub\text{-}pad}$. For the second path, the noise power flows through the substrate and injects into the body of the MOSFETs. In addition, the noise power can flow through the substrate and inject into the spiral inductor to affect the VCO spurs. Note that C_{ox} is added underneath the ground pads for port 1, 2, and 3, and also for the signal pad of port 3 since these pads are floated on top of the SiO_2 layer, while the pads connected to $R_{sub\text{-}pad}$ corresponding to a direct link to the p+ contact region of the substrate.

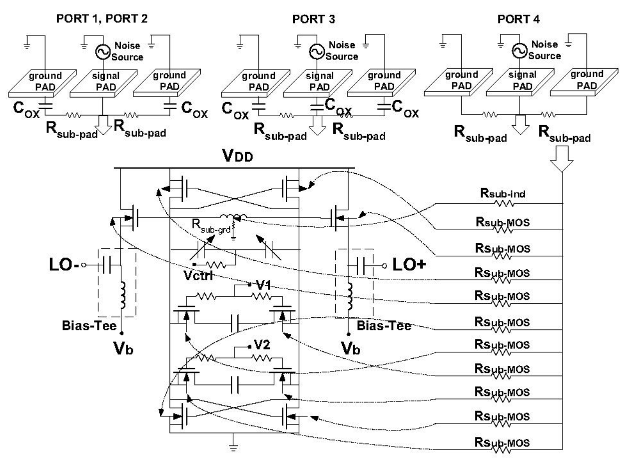

Fig. 6. Equivalent circuit model for noise coupling effect in the VCO.

To simplify the model parameter extraction procedure, a pure resistive network was employed for the substrate network. In addition, since the distance from the pad to each active component of the core circuit is similar, the substrate resistance $R_{sub\text{-}MOS}$ can be approximated to be identical. Also, the equivalent resistance $R_{sub\text{-}ind}$ is smaller compared with the substrate resistance connected to the MOS owning to a large area of the inductor [7]. The C_{ox} can be estimated from the layer physical structure. Based on the spur levels of various injection configurations, most of the parameters can be determined directly, while optimization was also employed for a better agreement between the measured and modelled results. Table I summarizes the parameter values used in the model.

TABLE I: SUBSTRATE MODEL PARAMETERS

Injection PADs	C_{OX}	25 fF
	$R_{sub\text{-}pad}$	50 ohm
$R_{sub\text{-}ind}$	Port 1,4 (443μm)	200 ohm
	Port 2,3 (293μm)	50 ohm
$R_{sub\text{-}MOS}$	Port 1,4 (443μm)	4000 ohm
	Port 2,3 (293μm)	1000 ohm
$R_{sub\text{-}grd}$		1 ohm

Examining the values in Table I, as can be seen, a larger resistance is essential to model the noise injected from port 1 (port 3) compared with that from port 2 (port 4), which can be well understood since the substrate resistance increases with the distance between the noise source to the core circuit. With a higher substrate noise resistance, a less amount of noise is injected into the circuit, thus the spur levels of noise injected via port 2 is higher than that via port 1 for both IM2 and IM3.

Compared the results of noise injected from port 2 with that via port 3, one can see that IM2 was too low to be observed for port 3, and the IM3 level of port 3 is substantially lower than that of port 2. The observed results can be explained by the equivalent circuit model. The only difference between the noise injection topology from port 2 and port 3 in the model is an additional C_{ox} placed underneath the signal pad, which provides a relatively large impedance for the injected noise at low frequencies. However, the impedance reduced when the injected noise frequency increases as in the case of IM3. As a result, the IM3 can be observed when noise injected via port 3, while is not detectable for IM2.

In addition, compared the noise injection through port 1 and port 4, one can see that both the IM2 and IM3 levels are lower for the later case. According to our model and the above mentioned different noise injection paths, the lower spur level can be attributed to a higher amount of injected noise flows directly back to the ground pad instead of interfering the core VCO circuit. Since there is no additional C_{ox} blocked in the noise signal return path compared with other cases.

With the guard ring of the spiral inductor floated, the path connected to ground with a small resistor $R_{sub\text{-}grd}$ is removed. As a result, the spur level increases owing to more noise injected to the circuit instead of bypassing via the ground. Fig. 7 shows the measured and modelled IM3 with a noise of 20 MHz offset injection under the inductor guard ring floated. Excellent agreement was obtained based on the proposed physical-based substrate model. For other cases, the model also predicts the spurs levels within 5-dB accuracy.

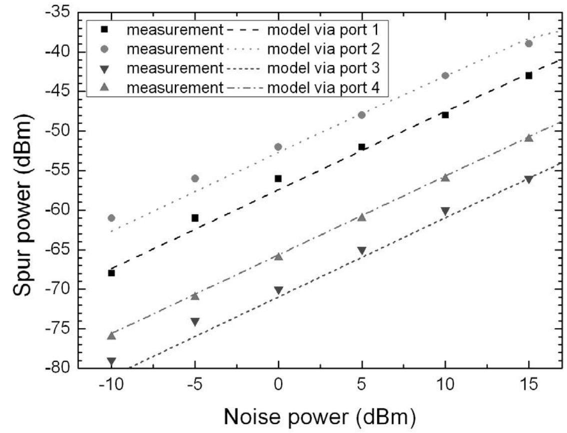

Fig. 7. Measured and modelled results for IM3 as a function of the injected 20 MHz offset signal under the inductor guard ring floated.

V. CONCLUSION

The effect of substrate noise coupling was investigated on a wideband LC-VCO using various noise injection topologies. It was found that the ground connection for both the injection pads and the guard ring of the VCO can reduce the noise coupling level. With the guard ring floated, IM2 increased by ~ 5 to 7 dB, and IM3 increased by ~ 6 to 10 dB. In addition, a physical-based equivalent circuit model was established, which explained the observed trend via various injection configurations successfully.

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