A Fundamental 90-GHz CMOS VCO Using New Ring-Coupled Quad

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Abstract—A new circuit topology, named ring-coupled quad for millimeter-wave voltage controlled oscillator (VCO) design, is proposed. The proposed circuit topology provides higher open loop voltage gain than conventional cross-coupled pair. The layout of the proposed ring-coupled quad is fully symmetric without additional interconnection lines. A 90-GHz VCO using 90-nm CMOS process is implemented with this ring-coupled quad. This 90-GHz oscillator demonstrates a 2.5-GHz tuning range and higher than -20 dBm output power. The proposed ring-coupled quad is suitable for the realization of high frequency VCOs.

Index Terms—Cross-coupled, voltage controlled oscillator (VCO), millimeter-wave.

I. INTRODUCTION

VOLTAGE controlled oscillators (VCOs) are key components for wireless communication systems. Because of the rapid promotion of CMOS technology, it is possible to realize CMOS VCOs for millimeter-wave applications. The push-push topology is used to generate the millimeter wave signal using the second harmonic signal of VCOs [1]–[4]. Due to low device gain and high transmission line loss, the fundamental VCO is not easy to realize at millimeter-wave frequency. A four-stages amplifier to increase the open loop gain [5] and a special layout for cross-coupled pair to improve the loss of the interconnections and the circuit symmetry [6] have been reported.

In this letter, a new circuit topology, named ring-coupled quad, is proposed. This ring-coupled quad uses the four-stage common source transistors so that the voltage open loop gain is higher than conventional cross-coupled pair. Moreover, the layout of the ring-coupled quad can be fully symmetric and the loss of the interconnection is significantly reduced. A 90-GHz VCO using the proposed ring-coupled quad in a 90-nm CMOS process is implemented. The tuning range is 2.5 GHz and the output power is higher than -20 dBm. The experimental results show that the proposed ring-coupled quad is suitable for high frequency VCOs.

Manuscript received October 17, 2006; revised November 3, 2006. This work was supported in part by TSMC-NTU JPD and the National Science Council of Taiwan, R.O.C. under Projects NSC 94-2752-E-002-003-PAE, NSC 94-2219-E-002-006, NSC 94-2219-E-002-009, and NSC 94-2213-E-002-008 and by the National Chip Implementation Center of Taiwan.

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Digital Object Identifier 10.1109/LMWC.2006.890499

Fig. 1. Circuit schematic of (a) cross-coupled oscillators and (b) ring-coupled oscillators.

II. CONCEPT OF RING-COUPLED OSCILLATOR

Fig. 1(a) illustrates the schematic diagram of a conventional cross-coupled oscillator. It is composed of two common-source transistors (M_1 and M_2) and one resonator with load impedance (Z_{L1} and Z_{L2}). The open loop voltage gain from gate of M_1 to drain of M_2 can be expressed in terms of device transconductance (g_{m1} and g_{m2}) and Z_L

$$v_{d2}/v_{g1} = (-Z_{L1}(\omega)g_{m1})(-Z_{L2}(\omega)g_{m2}). \quad (1)$$

If the imaginary parts of Z_{L1} and Z_{L2} equal to zero, the phase of the open loop voltage gain is 0° and the signal is out of phase between each stages. When the real part of $1/Z_{L1}$ and $1/Z_{L2}$ are lower than the value of g_{m1} and g_{m2} , the magnitude of the open loop voltage gain is higher than unity and the oscillation condition is satisfied. Since the voltage of each stage is out-of-phase, the resonator can be realized as a pair of coupled lines and

Fig. 2. Schematic of the VCO using ring-coupled quad.

the load impedance (Z_{L1} and Z_{L2}) are equal to the odd mode impedance of the coupled line (Z_{rodd}).

Following the principle of a cross-coupled pair, the positive feedback can be realized with the four-stage common-source transistors. Fig. 1(b) illustrated the proposed ring-coupled oscillator. Four transistors are cascaded and four resonators are connected to the source and drain of each stage. The open loop voltage gain becomes

$$v_{d4}/v_{g1} = (-g_{m1}Z_{L1}(\omega))(-g_{m2}Z_{L2}(\omega)) \times (-g_{m3}Z_{L3}(\omega))(-g_{m4}Z_{L4}(\omega)). \quad (2)$$

Similar to (1), the signal is out of phase at each stage. The phase of the open loop voltage gain is zero while the imaginary part of the load admittance ($1/Z_{Li}(\omega)$, $i = 1, 2, 3, 4$) is zero. Since the real part of the load admittances are lower than the transconductance of the transistors, the magnitude of the loop gain is higher than unity. Because of the open loop gain in (2) due to four-stage cascade transistors, the magnitude of the loop gain is higher than the traditional cross-coupled pair. At higher frequency, the margin of the load admittance for oscillation condition is less due to the substrate loss. Since there are four-stage transistors, if the loop gain of one stage is lower, the other stages can cover the loss and ensure the oscillation condition.

Another important feature of using this proposed ring-coupled quad in VCO design is the symmetric layout. In the conventional cross couple pair, a cross junction is required to connect the gate and the drain of each transistor. As illustrated in the ring-coupled quad (Fig. 2), the four-transistors are connected in a ring, so that no additional lines are added in the layout and the parasitics of the interconnections are significantly reduced.

III. MMIC PROCESS AND THE 90-GHZ VCO

The process used in this VCO is TSMC 1P9M CMOS technology, with an f_T of 160 GHz and an f_{max} of 142 GHz. In order to reduce the loss of the transmission line in CMOS process, the thin film microstrip line is adopted [7]. There are nine metal layers in this 90-nm CMOS process. Metal 1 is used for the ground and the top metal is used for the signal line. A pair of coupled thin-film microstrip lines are used as the resonator which has a odd-mode characteristic impedance of 65.5 Ω and odd-mode attenuation of 560 dB/m. Breaking point A in Fig. 1(a) and (b), the voltage or the current transfer function is simulated by the image parameter method [8]. Fig. 3 shows the simulated transfer functions of oscillators in

Fig. 3. Simulated loop gain of the proposed ring-coupled VCO and the cross-coupled VCO.

Fig. 4. Circuit schematic of the realized VCO using ring-coupled quad.

 Fig. 5. Chip photo of the realized VCO using ring-coupled quad with a chip size of 620 $\mu\text{m} \times 550 \mu\text{m}$.

Fig. 1(a) (v_{d2}/v_{g1}) and (b) (v_{d4}/v_{g1}) with the same device size (four-fingers and 16- μm gate width) and equal resonators. All the parameters and coupling effects are considered in the simulation via full-wave EM solver [9]. The simulated results show that the ring-coupled VCO has higher loop gain than the cross-coupled VCO. Fig. 4 illustrates the complete circuit schematic of the VCO. Four transistors are connected as a ring, while the gate and drain of each transistor are connected to a resonator separately. Because the voltage of the drain and gate of each device are differential, each end of the resonators is virtual short. Therefore, the dc bias lines are connected to the end of the resonators without influencing the radio frequency (RF) performance of VCOs. The output voltage is sampled

Fig. 6. Oscillation frequency and output power versus tuning voltage.

Fig. 7. Output spectrum of the VCO.

by a 0.05-pF capacitor from the drain of M_1 . The sampled voltage is amplified by a common source buffer amplifier. The frequency is tuned by the V_{dd} of the VCO [V_{dd} (VCO)]. To fix the bias condition of the buffer amplifier, the 0.05-pF capacitor blocks the dc level of the V_{dd} of the VCO and the gate voltage of the buffer amplifier. The V_{dd} of the VCO [V_{dd} (VCO)] and the buffer amplifier [V_{dd} (Buffer)] are fed separately. Fig. 5 is the chip photo of the realized VCO with a chip size of $620 \mu\text{m} \times 550 \mu\text{m}$. The area of the cross-coupled quad is only $33 \mu\text{m} \times 33 \mu\text{m}$.

IV. MEASUREMENT RESULTS

The circuit was measured via on-wafer probing. The RF output pads of the chip were connected to the WR-10 waveguide by a W-band RF ground-signal-ground (GSG) probe. The loss of the waveguide and the probe is estimated to be 2 dB. The output signal of VCO was down-converted to IF by the harmonic mixer HP11970W and measured using spectrum analyzer 8565EC.

The drain voltage of the VCO is tuned from 0.6 to 1.45 V for frequency tuning. The drain and gate voltages of the buffer amplifier are both 0.8 V and the gate voltage of the buffer amplifier is 1.1 V. Fig. 6 shows the oscillation frequency and output

TABLE I
COMPARISON OF THE REPORTED FUNDAMENTAL CMOS
VCO OVER 90 GHz OPERATION FREQUENCY

Ref.	Process	Freq. (GHz)	P _{out} (dBm)	Phase Noise (dBc/Hz @ 10 MHz offset)	P _{DC} (mW)
[5]	90 nm	103.9	-65	110	30
[6]	130 nm	88.5~90.1	-14 ~ -18	104 ~ 106	15.75 ~ 7.5
This Work	90 nm	90~92.5	-12 ~ -20	107.1 (90 GHz)	87.2 ~ 14

power versus drain voltage of the oscillator [V_{dd} (VCO)] in Fig. 4. The frequency can be tuned from 92.5 to 90 GHz which gives 2.5-GHz tuning range. The output power is higher than -20 dBm over the entire tuning frequency. Fig. 7 illustrates the measured output spectrum when tuning voltage is 1.18 V. The phase noise at 10-MHz offset is -107.1 dBc/Hz. Table I lists the reported fundamental VCO over 90-GHz operation frequencies. Although the over 100-GHz operation frequency was demonstrated in [5], the output power is very low. Compared with [6], this work presents comparable output power and wide tuning range performance.

V. CONCLUSION

A new circuit topology of ring-coupled quad is proposed. It can provide a higher open loop voltage gain than the conventional crossed-coupled pair and the symmetrical layout can be achieved via this design approach. A 90-GHz VCO with 90-nm CMOS process is implemented with the proposed ring-coupled quad. The tuning range is 2.5 GHz and the output power is higher than -20 dBm. The experimental results reveal that this ring-coupled quad is suitable for high frequency VCO design.

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