

# An X-Band CMOS Quadrature Balanced VCO

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**Abstract** — A new quadrature balanced voltage controlled oscillator (B-VCO) is presented. The quadrature and single B-VCO with identical components are implemented in 0.18  $\mu\text{m}$  CMOS technology. The quadrature B-VCO has lower phase noise, higher oscillation frequency and higher figure of merit (FOM) than the single B-VCO. The measured phase noise values of the single and quadrature VCO are  $-114.83$  and  $-116.67$  dBc/Hz at the offset frequencies of 1 MHz at the center frequency of 10.21 and 10.81 GHz respectively. Both VCO cores consume about 8.8 mA from a 1.8 V supply. The FOM of 183 and 185 dB are achieved in the quadrature and single VCOs respectively.

**Index Terms** — Quadrature, Balanced, CMOS, VCO, Current switching, Transformer

## I. INTRODUCTION

Cross-coupled oscillators have been used in CMOS process due to their ease of implementation [1][2]. Although they have reliable start-up and differential output, Cross-coupled VCO is inferior to balanced VCO in high frequency VCO [3]. The balanced VCO consists of two identical Colpitts VCOs.

A Colpitts VCO has been used most commercially because the VCO has superior cyclostationary noise properties and can achieve low phase noise. But, a single ended Colpitts VCO has no immunity to common mode noise such as power supply and substrate noise. Thus, a balanced VCO which has common mode noise rejection is used widely in integrated circuits. On the other hand, this topology increases power consumption by a factor of two, if the same start-up condition is to be met. To decrease current consumption, the current sources are switched [4]. This approach can achieve low noise oscillator under low power consumption.

The accurate quadrature signal source is a prerequisite part in image-rejection transceivers. Recently, Many quadrature VCOs have been implemented by using many topologies of cross-coupled VCO [5][6]. But, It has not been reported that a balanced topology is used to generate quadrature signal despite low noise property in high frequency.

In this paper, balanced VCOs which switch current source are used for differential and quadrature signal

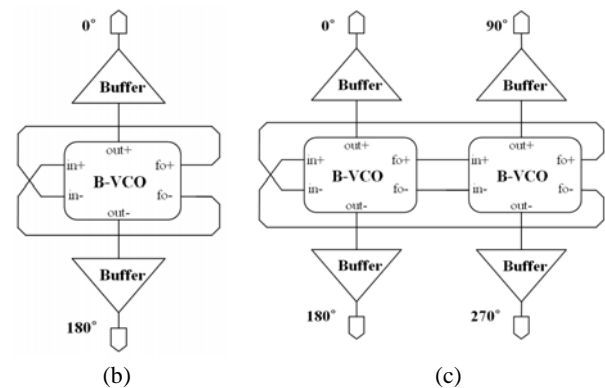
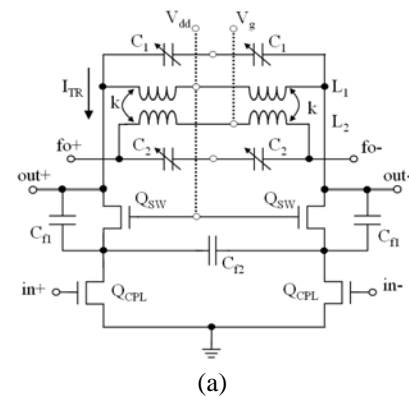


Fig. 1. (a) Schematic of the new balanced VCO (b) A Single balanced VCO (c) A quadrature balanced VCO

generation. And these VCOs are compared about phase noise and current/voltage vector.

## II. CIRCUIT DESIGN

The proposed balanced VCO block which switches current source consists of n-MOS transistors and a transformer as shown in Fig. 1. Two inductors,  $L_1$  and  $L_2$ , in the transformer are coupled by factor of  $k$ .  $L_1$ ,  $C_1$ ,  $L_2$ , and  $C_2$  are the LC resonators. The quality factor of the resonator is improved due to coupling effect of the transformer [5]. In addition, the transformer can make two differential RF output ports with separated DC biases. One is out+/- port with power supply of  $V_{dd}$ . And the other is fo+/- to switch a current source with external bias of  $V_g$ .

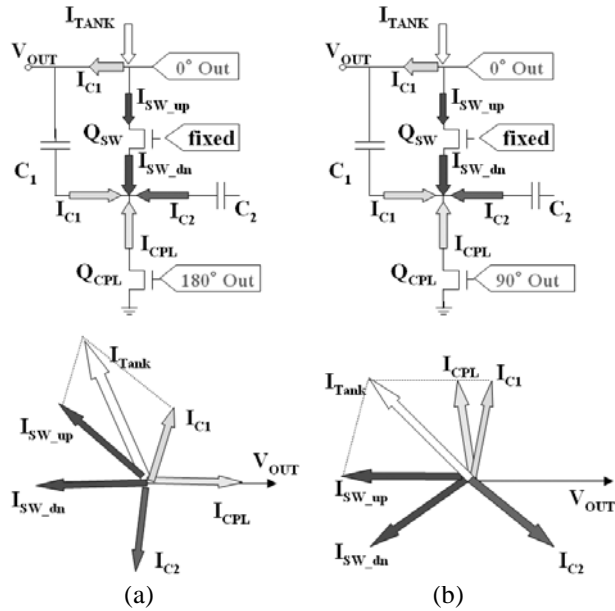


Fig. 2. Current and voltage vector (a) in single (b) in quadrature balanced VCO

The capacitive voltage divider to provide a positive feedback path is formed by  $C_{F1}$  and  $C_{F2}$ .  $Q_{SW}$  and  $Q_{CPL}$  are transistors for negative resistance and current source respectively. The VCO blocks to generate differential and quadrature signal are identical. The two VCOs are different only in connections of feedback signal as shown in Fig. 1 (b) and (c). Thus, the gate bias of  $Q_{CPL}$  is controlled by external one of  $V_g$ . It is useful to observe the effect of bias current.

Fig. 2 shows current and voltage vector. It is not accurate that current and voltage waveforms of a balanced VCO are described as vector since their waveforms are nonlinear. But, this approach gives good insight into the effect of current switching. The vectors are placed as the harmonic balance simulation results of Agilent ADS with BSIM CMOS model version 3.2.

In a balanced VCO, drain current of  $Q_{SW}$  is maximized at the minimum point of output voltage. The phase of drain current is hardly changed by switching the current source in single B-VCO. This phase difference makes the rms values of effective impulse sensitivity function (ISF) small [1]. In high frequency, there is time delay between the drain and the source current due to non-quasi static effect of the transistor. The channel noise and flicker noise in CMOS are dominant noise sources. Since these noises are correlated to channel current, it is estimated that the maximum point of the noise is about between  $I_{SW\_up}$  and  $I_{SW\_dn}$ .

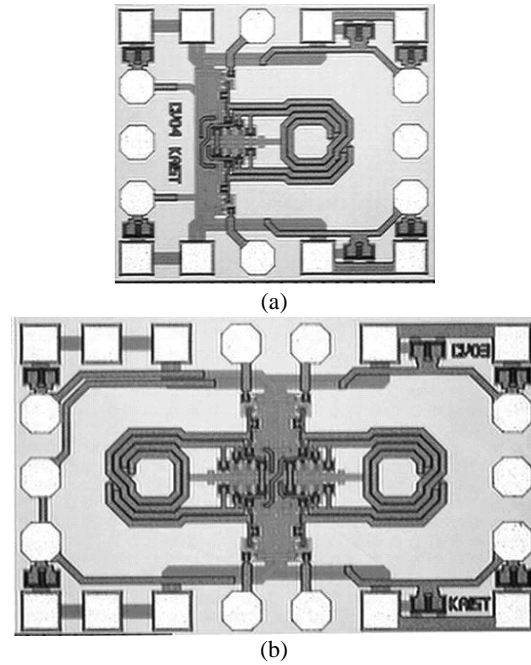


Fig. 3. Photographs of the fabricated (a) single ( $670 \times 770 \mu\text{m}^2$ ) and (b) Quadrature balanced VCO ( $680 \times 1100 \mu\text{m}^2$ )

In the quadrature VCO, The phase of switching signal is  $90^\circ$  not  $180^\circ$  as shown in Fig. 2 (b). Although the phase of  $I_{CPL}$  is changed as about  $90^\circ$ , the phase of  $I_{SW}$  is changed as only about  $45^\circ$ . To maintain the conservation of current, the phase of  $I_{C2}$  is changed as about  $45^\circ$ . Since the absolute values of phase different between  $V_{OUT}$  and  $I_{SW}$  are similar in single and quadrature B-VCO, it is expected that the rms values of effective ISF are also similar. But the phase noise of the quadrature VCO is 3 dB in simulation because coupling of two LC oscillators can reduce phase noise [7] as

$$Q_N \approx \sqrt{2} \cdot Q_P \quad (1)$$

where  $Q_N$  and  $Q_P$  are quality factors of quadrature and single VCO.

### III. EXPERIMENT RESULTS

The Presented quadrature VCO is implemented using a standard  $0.18 \mu\text{m}$  CMOS process, which provides 5 layers of Al metal and  $2 \mu\text{m}$  thick top AlCu metal. Octagonal-shaped transformers are implemented with the top metal layer and 4<sup>th</sup> and 5<sup>th</sup> layers for interconnections. The Optimum number of gate fingers is obtained using harmonic balanced simulation in Agilent ADS. The Chip

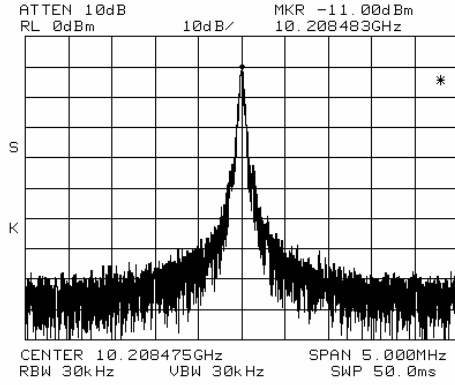


Fig. 4. The single balanced VCO output spectrum over 5 MHz span at 10.21 GHz. The measurement loss is not included.

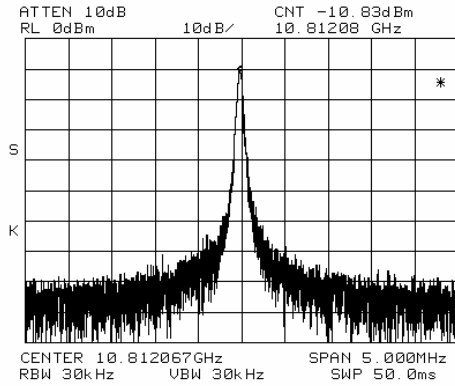


Fig. 5. The quadrature balanced VCO output spectrum over 5 MHz span at 10.81 GHz. The measurement loss is not included.

sizes of the single and quadrature VCO are  $670 \times 770 \mu\text{m}^2$  and  $680 \times 1100 \mu\text{m}^2$  as shown in Fig. 3. All components in both VCOs are identical to compare phase noises.

The test of VCOs was carried out on-wafer. The output spectrums and the phase noise performances were obtained from HP9764E spectrum analyzer and its phase noise measurement kit. The VCOs were measured using the GSSG probes from 1.8 V power supply. The cable loss in the measurement setup is about 2 dB at 10 GHz.

Fig 4 and 5 show output spectrums of the single and quadrature B-VCO respectively. The oscillation frequency of the quadrature B-VCO is slightly higher than that of the single B-VCO although all the components and bias current in both VCOs are identical. The  $C_{DG}$  is proportional to  $V_{DG}$ . The parasitic capacitance in the single VCO is larger than that in the quadrature, since the phase difference of gate and drain voltage in  $Q_{CPL}$  is 180 and 90 in single and quadrature VCO respectively.

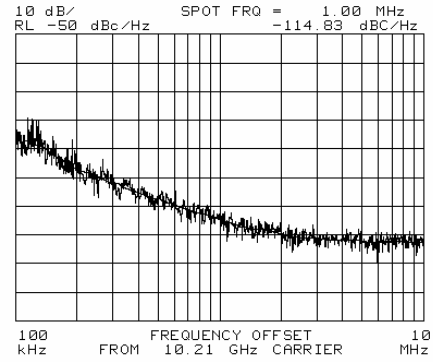


Fig. 6. Phase noise measurements of the single balanced VCO between 100 kHz and 10 MHz offset. The VCO shows phase noise of -114.83 dBc/Hz @ 1 MHz offset.

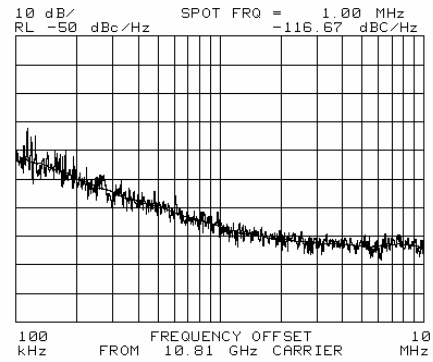


Fig. 7. Phase noise measurements of the quadrature balanced VCO between 100 kHz and 10 MHz offset. The VCO shows phase noise of -116.67 dBc/Hz @ 1 MHz offset.

In Fig. 6, the phase noise performance (Single Side Carrier to noise Ratio: SSCR) is -114.83 dBc/Hz at 1 MHz offset in the single B-VCO. Fig. 7 presents that the phase noise in the quadrature is improved by 1.84 dB. The value is lower than 3dB improvement in simulation. But, it is proved for the first time that quadrature signal can be generated by balanced structure without any degradation.

The core and buffer current are about 8.8 mA and 3.6 mA in both VCOs. Output powers are low due to small output buffer. Generally, a balanced VCO consumes power two times to maintain the same start-up condition of a Colpitts VCO. However, the single B-VCO in this paper decrease the power consumption by switching current source, since the current switching is similar to a cross-coupled VCO at start-up. But, it is different in the quadrature VCO. As shown in Fig. 2(b), a part of  $I_{SW}$  should be stored in  $C_2$  due to the phase of  $I_{CPL}$ . It demands larger bias current level for start-up. Oscillation condition for bias current is measured by adjusting  $V_g$  port. The single VCO can oscillate until  $I_{bias} = 6.5 \text{ mA}$  while the

quadrature VCO can oscillate until  $I_{bias} = 7.5$  mA. Thus, the single VCO is superior in start-up condition, although the minimum points of the phase noise are about  $I_{bias} = 8.8$  mA in both VCOs.

The measurement results are summarized in Table I. The quadrature VCO is superior to the single one in phase noise, Oscillation frequency, tuning range, and figure of merit (FOM). Both VCOs show very high F.O.M. of 183 and 185 dB. These are better or comparable to ever reported CMOS VCOs in X-band as shown in Fig. 8.

TABLE I  
COMPARISON OF SB-VCO AND QB-VCO

	Single B-VCO	Quadrature B-VCO
Phase noise (SSCR @ 1 MHz)	-114.83 dBc/Hz	-116.67 dBc/Hz
Oscillation freq.	10.21 GHz	10.81 GHz
Tuning range	415 MHz (4.06 %)	457 MHz (4.23 %)
Output Power	-9.00 dBm	-8.83 dBm
Core current	8.74 mA	8.94 mA
Buffer Current	3.6 mA	3.6 mA
F.O.M.	183.04 dB	185.28 dB

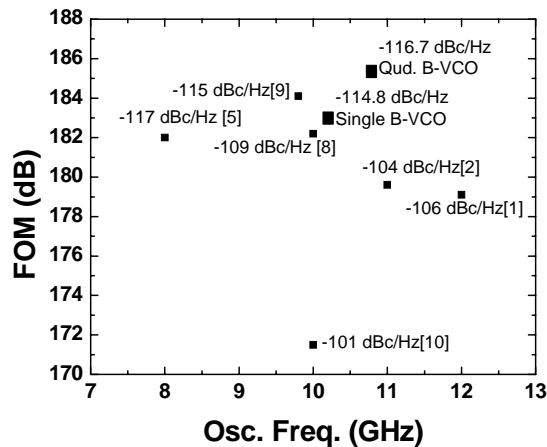


Fig. 8. figure of merit of X-band CMOS VCOs, (phase noise at 1 MHz offset [reference])

#### IV. CONCLUSION

An X-band CMOS quadrature balanced VCO is implemented for the first time. The single and quadrature balanced VCO use the current switching to reduce bias current. The measured phase noise values of the single and quadrature VCO are -114.83 and -116.67 dBc/Hz at the offset frequencies of 1 MHz at 10.21 and 10.81 GHz

respectively. The VCO cores consume about 8.8 mA from a 1.8 V supply. The FOM of 183 and 185 dB are achieved in the quadrature and single VCOs respectively. The phase noise performance and FOM of both VCOs are comparable to ever reported VCOs. The quadrature VCO is superior to the single one in phase noise, Oscillation frequency, tuning range, and figure of merit (FOM) except start-up condition.

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