LETTER

A quadrature voltage-controlled oscillator using phase-adjusting architecture for suppressing phase noise

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Abstract A low-phase-noise 25-GHz quadrature voltage-controlled oscillator (VCO) using 180-nm TSMC CMOS is presented. To equalize the oscillation frequency to the LC-resonant frequency, a phase shifter at a transistor gate adjusts a phase delay due to an RC delay in a transistor. This phase-adjusting architecture extends operation bias range and suppresses phase noise by 6 to 9 dB compared with a conventional differential VCO.

Keywords: phase noise, voltage-controlled oscillator, gate delay, phase-adjusting architecture

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

High-bit-rate wireless communications demand high carrier frequencies [1], such as 24-GHz WLAN [2], IEEE802.11ad [3], and 24-29 GHz 5G mobile phones [4]. One of essential circuit blocks in the high-frequency wireless systems is a voltage-controlled oscillator (VCO). Various quadrature (4-phase) VCOs are investigated [5, 6, 7, 8, 9] for quadrature signal processing [10, 11, 12, 13, 14, 15, 16, 17] in the high-performance wireless systems, however, a high-frequency VCO usually needs a very fine CMOS technology and/or a special high-Q inductor process [18, 19, 20, 21, 22, 23] for suppressing the phase noise. Thus, their process cost could be considerably high. In this letter, a quadrature VCO using a phase-adjusting architecture for suppressing phase noise is presented. This architecture can be implemented without process-cost increase.

2. Concept of phase adjusting and circuit design

Figure 1 shows the circuit structure and the ac-analysis results of a differential LC VCO. The open-loop gain and phase were calculated with a dummy LC amplifier for adding gate capacitances to an LC parallel resonant circuit. The gain peak locates at the LC resonant frequency of 29.4 GHz, however, the oscillation occurs at 28.7 GHz because of oscillation condition (180° phase delay). The difference between the LC resonant frequency and the oscillation frequency arises from an RC delay in a transistor. The RC delay causes

Fig. 1 (a) The circuit structure and (b) the gain and phase results of open-loop ac analysis for a differential LC VCO.

Fig. 2 (a) A differential VCO with two phase shifters and (b) a phase shifter circuit using a weight-average architecture with two capacitors and a source follower circuit. R is a resistor for DC bias.

Fig. 3 Circuit architecture of a quadrature VCO using four phase adjusters formed by 8 capacitors and 4 source followers.

phase delay ($-\Delta\phi \approx -24^\circ$) and lowers the oscillation frequency.

The loop gain of VCO should be maximum to suppress its phase noise [24], thus the oscillation frequency should be the LC resonant frequency. Therefore $\Delta\phi$ -phase shifters at two gate inputs of a differential VCO (depicted in Fig. 2(a)) are thought to be very helpful to adjust phase delay and suppress phase noise. The $\Delta\phi$ -phase shifter was designed

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using a weight-average architecture with two capacitors and a source follower circuit as shown in Fig. 2 (b).

Figure 3 shows the quadrature VCO circuit using the phase adjusting architecture. Four $\Delta\phi$ -phase shifters are added to two conventional differential VCOs.

3. Measurement results and discussion

Two conventional differential VCOs [25, 26, 27, 28, 29] and the phase-adjusting quadrature VCO were fabricated using TSMC 180-nm CMOS technology (as shown in Fig. 4). The conventional VCOs were realized by just removing the $\Delta\phi$ -phase shifters from the phase-adjusting quadrature VCO. The values of C_1 and C_2 of the $\Delta\phi$ -phase shifter were 600 fF and 60 fF, respectively.

Fig. 4 Chip microphotographs of (a) two conventional differential VCOs and (b) a phase-adjusting quadrature VCO.

The phase noises of the VCOs were measured with various bias voltages, $V_{DD} = 2.2\text{V}$ and $V_{ctrl} = 0\text{V}$. Figure 5 shows the relation between phase noise at 1-MHz offset frequency and current consumption. The current consumption shows the current of the one conventional differential VCO and that of the phase-adjusting quadrature VCO with four source followers. In terms of bias setting, the quadrature VCO has a larger operation range than that of a conventional VCO. Oscillation frequencies were 28.05 GHz for the conventional VCO and 25.17 GHz for the quadrature VCO. The $\Delta\phi$ -phase shifter worked not only as a phase shifter but also as an additional capacitor and thus both of the LC-resonant frequency and the oscillation frequency of the phase-adjusting quadrature VCO were lowered. The ranges of oscillation frequencies were 28.05 to 28.73 GHz for the conventional VCO and 25.17 to 25.73 GHz for the quadrature VCO when V_{ctrl} was changed from 0 to 2.2V. The additional capacitance of the $\Delta\phi$ -phase shifter reduced the frequency range by about 10%. The figure-of-merit (FOM) is defined as [30]:

$$FOM = L(\Delta f) - 20\log\left(\frac{f_0}{\Delta f}\right) + 10\log\left(\frac{P_{DC}}{1\text{mW}}\right). \quad (1)$$

The best FOMs of the VCOs in Fig. 5 are evaluated as -175.1dBc/Hz and -176.4dBc/Hz for the conventional VCO and the phase-adjusting quadrature VCO, respectively. A quadrature VCO usually consumes two times larger current than that of a differential VCO, thus the FOM improvement is effectively 4.3 dB. Figure 6 shows the offset-frequency dependence of phase noise at the conditions of minimum phase noise in Fig. 5. Thus in Fig. 6, the current consumptions of the conventional VCOs and the phase-adjusting quadrature VCO were 15.4 mA and 41.2 mA, respectively. The phase-adjusting architecture suppresses

phase noise about 9 dB and 6 dB at 100-kHz and 1-MHz offset frequencies, respectively. The 3-dB reduction of phase noise suppression at 1-MHz offset frequency was probably due to measurement errors as shown in Fig. 6.

Fig. 5 Relation between phase noise and current consumption. Phase noise was measured at 1-MHz offset frequency from the carrier frequency.

Fig. 6 Measured phase noise as a function of the offset frequency from the carrier frequency.

Performance comparison with recently published CMOS LC VCOs is illustrated in Table I [31, 32, 33, 34]. All VCOs are quadrature VCOs. The proposed VCO shows phase-noise performances comparable to the finer-process VCOs.

Table I Performance comparison

Ref	This work	[31]	[32]	[33]	[34]
process (nm)	180	180	130	65	65
f_{osc} (GHz)	25.17	19.85	20.17	20.88	26
T.R. (%)	2.2	10.4	-	17.9	14.4
V_{DD} (V)	2.2	1.8	1.2	1.2	-
P_{DC} (mW)	90.6	40.3	28.8	80.0	11.8
PN @1MHz (dBc/Hz)	-107.5	-111.5	-102.4	-100	-100
FOM (dBc/Hz)	-176.4	-181.4	-173.9	-173.4	-177.6

4. Conclusion

A low-phase-noise 25-GHz quadrature VCO using 180-nm TSMC CMOS is presented. A phase shifter equalizes the

oscillation frequency to the LC-resonant frequency, extends operation bias range and suppresses phase noise by 6 to 9 dB compared to a conventional differential VCO.

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