Dual-band voltage controlled oscillator with optimized Gm

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Abstract: A differential VCO with differential push-push frequency doubler for dual-band application is proposed. The dual-band VCO (DB-VCO) adopts the tunable $-G_m$ to optimize the wide tuning start-up condition. The proposed DB-VCO was implemented in 180-nm CMOS process. The DB-VCO provides a fundamental center frequency at 4.476 GHz and a double frequency at 8.985 GHz. A tuning range of fundamental frequency is 1.125 GHz ($3.928$ GHz–$5.053$ GHz), and a tuning range of the double frequency is 2.257 GHz ($7.856$ GHz–$10.113$ GHz) with maximum control voltage of 1.0 V can be achieved. The phase noise is $-96.0$ dBc/Hz at 1 MHz offset from center of the DB-VCO fundamental frequency. And the phase noise is $-86.4$ dBc/Hz at 1 MHz offset from center of the DB-VCO double frequency. The power dissipation of the DB-VCO core is 6.6 mW through 1.0 V supply voltage. The active area is 0.09 mm².

Keywords: UWB, VCO, dual-band, push-push, frequency doubler

Classification: Integrated circuits

References

[1] A. Valdes-Garcia, C. Mishra, F. Bahmani, J. Silva-Martinez and E. Sanchez-Sinencio: IEEE J. Solid-State Circuits 42 (2007) 935. DOI:10.1109/JSSC.2007.892160
[2] C. Sandner, S. Derksen, D. Draxelmayr, S. Ek, V. Filimon, G. Leach, S. Marsili, D. Matveev, K. L. R. Mertens, F. Michl, H. Paule, M. Punzenberger, C. Reindl, R. Salerno, M. Tiebout, A. Wiesbauer, I. Winter and Z. Zhang: IEEE J. Solid-State Circuits 41 (2006) 2787. DOI:10.1109/JSSC.2006.884804
[3] O. Werther, M. Cavin, A. Schneider, R. Renninger, B. Liang, B. Long, Y. Jin, J. Rogers and J. Marcincavage: IEEE J. Solid-State Circuits 43 (2008) 2829. DOI:10.1109/JSSC.2008.2005744
[4] H. Zheng, S. Lou, D. Lu, C. Shen, T. Chan and H. C. Luong: IEEE J. Solid-State Circuits 44 (2009) 414. DOI:10.1109/JSSC.2008.2010758
[5] G. Zhang, A. Kochhar, K. Yoshida, S. Tanaka, K. Hashimoto, M. Esashi, H. Kanaya and R. K. Pokharel: IEICE Electron. Express 10 (2013) 20130425. DOI:10.1587/elex.10.20130425
[6] A. Scuderi and G. Palmisano: IEEE Microw. Wireless Compon. Lett. 16 (2006) 191. DOI:10.1109/LMWC.2006.872127
[7] E. Monaco, M. Pozzoni, F. Svelto and A. Mazzanti: IEEE J. Solid-State Circuits 45 (2010) 1565. DOI:10.1109/JSSC.2010.2049780
1 Introduction

In the specification of the WiMedia, there are 14-bands were defined. And the bandwidth of the each band is 528 MHz. The transceiver architecture was proposed as low-IF architecture or zero-IF architecture [1, 2, 3, 4]. The center frequency of the 14-bands is from 3432 MHz to 10296 MHz, and the bandwidth of the band center frequency is 6864 MHz. The bandwidth of the conventional voltage-controlled oscillator (VCO) is not able to reach. Therefore, the frequency synthesizer is a great challenge in the transceiver design. In paper [1], the frequency synthesizer adopts one VCO, four single-sideband (SSB) mixers, five frequency dividers, and two mux. In paper [2], the frequency synthesizer adopts two VCOs and four SSB mixers and two mux. In the paper [3], the frequency synthesizer adopts one VCO, five SSB mixers, five frequency dividers, and three mux. In the paper [4], the frequency synthesizer adopts one VCO, three SSB mixers, six frequency dividers, and one mux. The frequency synthesizers are very complicated, are consumed additional power, and are occupied large chip area. There are two band-groups were defined for world-wide regulatory. The former, band-group #1 is defined from 3168 MHz to 4752 MHz, and the other, band-group #6 is defined from 7392 MHz to 8976 MHz. And both bandwidths of the band center frequencies are 1056 MHz. The proposed transceiver architecture for world-wide regulatory is shown in Fig. 1(a). There are two individual antennas and receivers, and one dual-band frequency synthesizer. The frequency synthesizer is simple, only one dual-band VCO (DB-VCO) and one conventional frequency synthesizer are necessary.

2 Circuit design

In the dual-band receiver, the dual-band VCO generates two differential sinusoid signals for 3–5 GHz band group #1 and 7–9 GHz band-group #6 which is shown in Fig. 1(b). In paper [5], the dual-band VCO is including one differential VCO and one CML frequency multiplier. But, the output signal of the frequency multiplier is one phase. In paper [6], the double frequency VCO is including one differential VCO and one frequency doubler. But, the output signal of the frequency doubler is one phase. In paper [7], the double frequency VCO is including one differential VCO and one push-push frequency doubler. But, the output signal of the push-push frequency doubler is one phase. In paper [8], the double frequency VCO is including one differential VCO with the push-push frequency doubler. But, the output signal of the pus-push frequency doubler is one phase. In paper [9], the
double frequency VCO is including one differential VCO and one transformer based push-push frequency doubler. But, the output signal of the transformer based push-push frequency doubler is one phase. In paper [10], the double frequency VCO is including one QVCO with two push-push frequency doubler. And the output signal of the push-push frequency doubler is differential. In paper [5, 6, 7, 9], the VCO and the frequency doubler are independent, the doubler circuit consumes additional power. And an additional phase shift or phase splitter is necessary for the wireless transceiver. In paper [8], the VCO with push-push frequency doubler is one phase. And an additional phase shift or phase splitter is necessary for the wireless transceiver. In paper [10], QVCO with differential push-push frequency doubler generates double frequency differential signals. But, the QVCO consumes twice power from the differential VCO.

In this paper, a differential dual-band VCO with differential push-push frequency doubler is proposed in Fig. 2. The DB-VCO core is composed of the PMOS tunable $-G_{mP}$ cells, the NMOS tunable $-G_{mN}$ cells, and a differential push-push doubler cell. For measurement purpose, two source followers are designed for the differential fundamental output signals. And two three-stage amplifiers are designed to enlarge the differential second-harmonic output signals. The differential output signals of the fundamental frequencies are $F_C+$ and $F_C−$. And the differential output signals of second-harmonic frequencies are $2F_C+$ and $2F_C−$. $L_C$ is the inductor which determines the resonated center frequency of the LC-VCO. In paper [11], the VCO adopts a MOS cross-coupled pair as a variable capacitor, and the linearity is improved. In the proposed DB-VCO, $M_{V1}$ and $M_{V2}$ are the N-type variable moscap to contribute the wide tuning range and high linearity. The NMOS tunable $-G_{mN}$ cells are the transistors $M_1$ and $M_2$; and the PMOS tunable $-G_{mP}$ cells are the transistors $M_3$ and $M_4$. The complementary $-G_{mP}$ and $-G_{mN}$ cells are designed to optimize the total equivalent $-G_m$ of the DB-VCO. The bandwidth of the WiMedia channel is very wide, so the start-up conditions of the DB-VCO are different. The three complementary pairs control the different section of the oscillation frequency. When the oscillation frequency is in the low boundary, the three complementary pairs $-G_{mA}$, $-G_{mA}$ and $-G_{mC}$ are all turned on. When the oscillation frequency is in the middle boundary, the two complementary pairs

![Fig. 1. Proposed UWB receiver for world-wide regulatory (a) differential DB-VCO for 3–5 GHz and 7–9 GHz (b)](image)
Fig. 2. Gm optimization DB-VCO with complementary push-push frequency doubler

Fig. 3. Fundamental output waveform (a) push-push output waveform (b)
When the oscillation frequency is in the high boundary, only one complementary pair \(-G_{mA}\) is turned on. So the DB-VCO operates in the optimized start-up condition. The M5 and M6 are the source followers. The complementary push-push cells M_{CF1}, M_{CF2}, M_{CF3}, and M_{CF4} are designed for differential second-harmonic frequency without consuming additional power. The N-type push-push doubler cell generates one single-end second-harmonic frequency 2F_{C+}. And the P-type push-push doubler cell generates the other single-end second-harmonic frequency 2F_{C−}. In Fig. 3(a), the simulation result shows the differential output waveform of the fundamental frequency. In Fig. 3(b), the simulation result shows the differential output waveform of the push-push second-harmonic frequency. The three-stage cascade common-source amplifiers M7, M8, M9, M10, M11, and M12 are designed for high power gain to enlarge the push-push signals. Inductor L1 and L2 are designed to determine the specific frequency at 2F_{C}. R_{L1}, R_{L2}, R_{L3}, and R_{L4} are the loads of the common-source amplifiers. C_{DC} is the DC block capacitor, and R_B is the high impedance bias resistor.

### 3 Experimental results

The proposed DB-VCO was implemented in a TSMC 180-nm 1P6M RF-CMOS process. Fig. 4(a) shows the measured tuning characteristic of the DB-VCO, indicating a measured tuning frequency from 3.9280 GHz to 5.0525 GHz, and from 7.8560 GHz to 10.1125 GHz through 1.0 V control voltage. The tuning range covers the WiMedia band-group #1 and band-group #6. In Fig. 4(b), the output spectrum shows the output fundamental frequency of the DB-VCO is 5.0525 GHz, and the output power is \(-27.02\) dBm. In Fig. 4(d), the output spectrum shows the output push-push frequency of the DB-VCO is 10.1125 GHz, and the output power is \(-14.66\) dBm. The cable loss and probe loss are not compensated in the experimental results. The output buffer loss is more than expected, so the output power of the fundamental frequency is lower than the output power of the push-push frequency.

The proposed DB-VCO is a free running oscillator, thus the frequency is not stable enough for Series Spectrum Analyzer (SSA) to capture and analyze the phase noise. The 1-MHz offset from the output frequency is marked in the Fig. 4(c) and Fig. 4(e). In Fig. 4(c), the 1-MHz offset from the output frequency is \(-46.0\) dBC/Hz, and the calculated phase noise at 1-MHz offset is \(-96.0\) dBC/Hz. In Fig. 4(e), the 1-MHz offset from the output frequency is \(-46.4\) dBC/Hz, and the calculated phase noise at 1-MHz offset is \(-86.4\) dBC/Hz. The proposed DB-VCO consumes 6.6 mW excluding the buffers and the amplifiers from a 1.0 V power supply. Fig. 5 shows the micrograph of the chip, where the DB-VCO core area marked by black dash line is only 0.22 mm \(\times\) 0.43 mm (0.09 mm²). Most of the UWB VCOs are designed for the full-band regulatory or a part of the full-band. And the output frequencies of the double frequency VCOs are various. There is no similar design for UWB VCO with double frequency. Therefore, the comparisons are not available. The performance summary of the dual-band VCO is shown in Table I.
Fig. 4. Tuning range of DB-VCO (a) maximum fundamental frequency (b) phase noise of the fundamental frequency @ 1 MHz offset (c) maximum double frequency (d) phase noise of the double frequency @ 1 MHz offset (e)
4 Conclusions

A differential VCO with differential push-push frequency doubler for dual-band application is proposed. The dual-band VCO adopts the tunable $\frac{1}{C_0}$ to optimize the wide tuning start-up condition. The VCO provides a fundamental center frequency at 4.476 GHz and a center double frequency at 8.985 GHz. A tuning range of fundamental frequency is 1.125 GHz (3.928 GHz – 5.053 GHz), and a tuning range of the double frequency is 2.257 GHz (7.856 GHz – 10.113 GHz) with maximum control voltage of 1.0 V can be achieved. The phase noise is $-96.0 \, \text{dBc/Hz}$ at 1 MHz offset from center of the VCO fundamental frequency. And the phase noise is $-86.4 \, \text{dBc/Hz}$ at 1 MHz offset from center of the VCO double frequency.

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Table I. Summary of the dual-band VCO performances

|                      | 3–5 GHz          | 7–9 GHz          |
|----------------------|------------------|------------------|
| Technology           | 180 nm 1P6M CMOS |                  |
| Active Area          | 0.22 mm × 0.43 mm (0.09 mm$^2$) |                  |
| Supply               | 1.0 V            |                  |
| Power consumption    | 2.2 mW–6.6 mW    |                  |
| Control Voltage      | 0.0 V–1.0 V      |                  |
| Oscillation Frequency| 3.928–5.053 GHz  | 7.856–10.113 GHz |
| Phase Noise @ 1-MHz offset | −96.0 dBc/Hz     | −86.4 dBc/Hz     |

Fig. 5. Micro-photography of the DB-VCO