Dual-band ultra-wide tuning range CMOS voltage-controlled oscillator

B. Çatlı and M. Hella

A dual-band wide-tuning range LC CMOS voltage controlled oscillator (VCO) topology is proposed. Dual-band operation is realised by employing a double-tuned double-driven transformer as a resonator. The proposed approach eliminates MOS switches, which are typically used in multi-standard oscillators, and thus improves phase noise and tuning range characteristics. The concept is demonstrated through the design of an LC VCO in a standard 0.18 µm CMOS process. Two frequency bands are realised (2.4 and 6 GHz) with 740 MHz tuning range in the first band and 1.56 GHz tuning range in the second band. Operating from a 1.8 V supply, the VCO has a simulated phase noise of −119 dBc/Hz in the 2.4 GHz band and −110 dBc/Hz in the 6 GHz band at 600 KHz offset from the carrier.

Introduction: Multi-band system-on-chip (SoC) transceiver design has attracted considerable interest recently. The increased demand for adaptive, spectrum-agile SoC such as cognitive radios requires reconfigurable multi-band/multi-mode RF front-end components that can operate over a wider frequency range with sustained performance. From a circuit design perspective, the challenge is to realise high frequency reconfigurable front-end blocks with minimum power and area consumptions.

Among the RF front-end blocks, the VCO remains one of the most challenging circuits despite being the subject of intense research. For multi-band operation, the VCO should satisfy the phase noise requirements of different standards with reasonable switching time from one band to the other. Existing solutions require switched L and/or C resonators [1, 2], which suffer from the channel resistance and parasitic capacitance of the MOS switch degrading both the phase noise and the tuning range. Another approach utilises frequency dividers or up-/downconversion mixers with bandpass filters that shifts the frequency generated by the oscillator depending on the required operating band [3]. This degrades both the phase noise performance and the overall power dissipation. Using non-standard CMOS processes for the realisation of an MEMS-enabled LC tank has also been reported [4] at the expense of extra processing cost and reduced reliability owing to the mechanical nature of the switch.

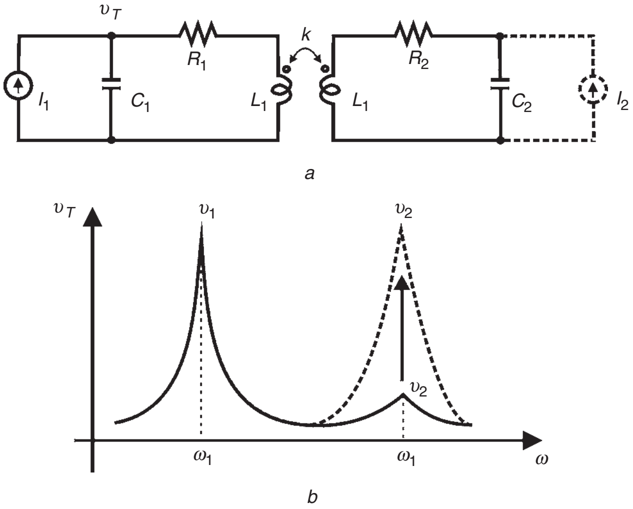

Fig. 1 *Double-tuned–single/double-driven transformer and related resonance characteristics*

a Transformer
b Related resonance characteristics

In this Letter, we present a dual-band, switch-less, transformer-based CMOS VCO. The VCO employs a transformer the secondary port of which is ON/OFF driven by a buffer stage to create multi-resonant points in the frequency scale. The main advantage of this topology is that it does not require any switching element connected directly to the LC tank. Thus, the multi-band operation requirement does not result in reduced phase noise behaviour. The switching between the two bands is performed by enabling/disabling the current through the buffer.

Basic concept (double-tuned–single-driven transformer): Fig. 1*a* shows a double-tuned-single-driven transformer, where L_1 and L_2 are the inductance of primary and secondary ports, (R_1, R_2) and (C_1, C_2) are the total loss and tuning capacitances of each tank, respectively, and k is the coupling coefficient between the transfomer windings. If the transformer is excited by driving only one port, we will have two resonance points [5]. For the sake of mathematical brevity, we assume that the transformer is fully balanced, which means $L_1 = L_2 = L$, $R_1 = R_2 = R$ and $C_1 = C_2 = C$. The resonance frequencies occur at

$$\omega_1 = \frac{1}{\sqrt{LC(1+k)}} \tag{1}$$

$$\omega_2 = \frac{1}{\sqrt{LC(1-k)}} \tag{2}$$

The quality factor at each resonance frequency is given by

$$Q_1 \simeq \frac{1}{R}\sqrt{\frac{L}{C}(1+k)} \tag{3}$$

$$Q_2 \simeq \frac{1}{R}\sqrt{\frac{L}{C}(1-k)} \tag{4}$$

From (3) and (4) it can be easily stated that Q_1 is higher than Q_2, as shown in the characteristics in Fig. 1*b*.

Double-tuned–double-driven transformer: In the double-driven case, the secondary port of the transformer is also driven by the current source I_2. The amplitude of the signal at each frequency can be given as

$$v_1 \simeq \frac{(I_1 + I_2)(1+k)L}{2RC} \tag{5}$$

$$v_2 \simeq \frac{(I_1 - I_2)(1-k)L}{2RC} \tag{6}$$

Although the peak of the second resonance point is lower than the first one for the single-driven case ($I_2 = 0$), it can be boosted by the proper selection of the direction and magnitude of the driving current as shown conceptually in Fig. 1*b*. Note that the magnitude of I_2 provides an additional degree of freedom to vary the signal amplitude at the two frequencies.

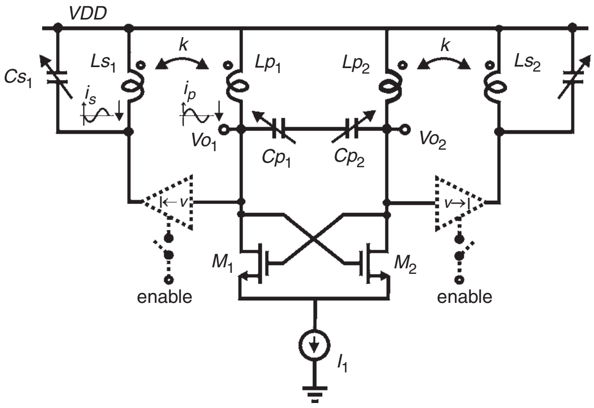

Fig. 2 *Schematic diagram of VCO*

Circuit design: The cross-coupled LC oscillator topology shown in Fig. 2 is used to prove the concept. The oscillator uses a double-tuned double-driven transformer as a resonator. The current source I_2 in Fig. 2 is realised by a simple buffer stage (transconductance amplifier). The multi-band operation is realised by turning on/off the tail current of the buffer stage. In the low frequency band operation, the buffer is disabled, thus $I_2 = 0$. The tank amplitude is only determined by I_1. For the high frequency band operation, the buffer is enabled. Note that the buffer applies an AC current to the secondary winding in the opposite direction to the AC current in the primary winding. Consider

(5) and (6). If the direction of I_2 is selected in the opposite direction of I_1, I_2 supresses the amplitude at ω_1 (v_1), while boosting the amplitude at ω_2 (v_2). Thus, switching between the bands is performed. In the high band, the $(1-k)$ factor in (2) reduces the effective inductance and enables a wider range of capacitance values for the varactor, and thus wider tuning range for the VCO.

The selection of k factor affects the overall performance of the oscillator in terms of tuning range, power consumption and phase noise. Consider (3) and (4). If k is maximised as in the case of the traditional transformer-based oscillators, although the quality factor is improved for the low band, the quality factor for the high band is severely degraded. Thus, to obtain a reasonable output swing at the high band, the power consumption has to increase. Intuitively, it can be stated that a k factor close to 0.5 is the best selection.

The transformer is designed using the top thick metal of the process. The transformer was designed using SONNET. The spacing between the transformer windings is selected as wide enough to reduce the coupling coefficient down to 0.65 and to reduce the sensitivity of the coupling coefficient to the spacing.

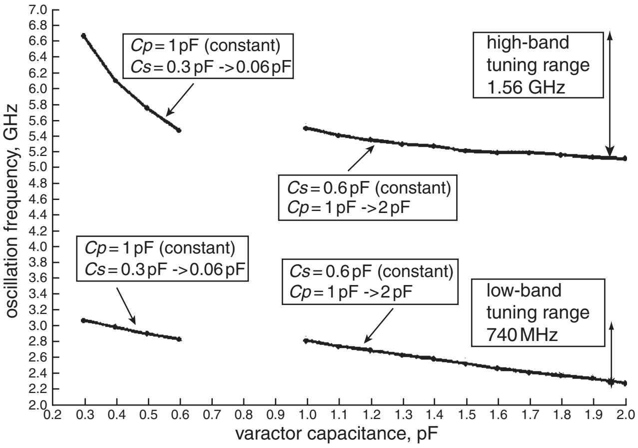

Fig. 3 *Simulated tuning characteristics of VCO*

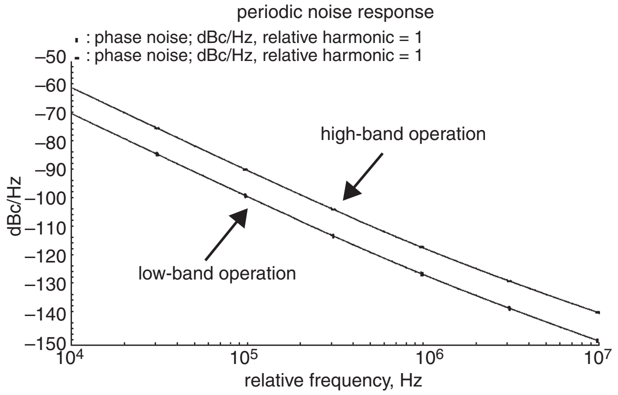

Fig. 4 *Simulated phase noise characteristics of VCO*

Simulation results: The oscillator is designed in a standard 0.18 μm CMOS process. Fig. 3 shows the simulated tuning characteristic. The frequency tuning range is 2.26 to 3.06 GHz for the low frequency band and 5.1 to 6.66 GHz for the high frequency band operation. Note that the transformer offers two degrees of freedom in the tuning mechanism (i.e. C_p and C_s) as shown in Fig. 3. This can ultimately be used to improve the performance of a frequency synthesiser by varying the gain of the VCO through selecting either C_p or C_s. Fig. 4 shows the simulated phase noise characteristic of the oscillator. For the low-band operation the simulated phase noise is −119 dBc/Hz at 600 kHz offset and −124 dBc/Hz at 1 MHz offset from a 2.4 GHz carrier. For the high-band operation the simulated phase noise is −110 dBc/Hz at 600 kHz offset and −115 dBc/Hz at 1 MHz offset from a 6 GHz carrier. The oscillator consumes 1.8 mW in the low-band operation and 9 mW in the high-band operation.

Conclusion: A switchless dual-band LC CMOS VCO topology is proposed. The oscillator topology eliminates the MOS switch employed in traditional multi-band oscillator topologies. Thus the overall performance of the oscillator is improved in terms of phase noise and tuning range, as verified by simulation results. The proposed dual-band VCO can be used in integrated multi-band transceivers for Bluetooth, WLAN and WiMAX applications.

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B. Çatlı and M. Hella (*Electrical, Computer, and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, 12180, USA*)

E-mail: catlib@rpi.edu

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