A 57~66GHz CMOS Voltage-Controlled Oscillator using Tunable Differential Inductor

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Abstract— Short-range wireless data transmission around the 60GHz band has been flourishing for various biomedical applications due to its features of high speed, high security and small device size. Wireless monitoring of human body with such transceivers has enabled numerous research areas in healthcare and biomedical engineering, such as long-term real-time recording of the Electroencephalography signal while the subject is in real-life scenario. Among the design challenges of such transceiver, the voltage-controlled oscillator (VCO) design plays a key role. Large tuning range of the VCO enables the effective utilization of the spectrum while small area is desired for biomedical application with implantation. This paper proposes a novel circuit topology for 60GHz VCO. It covers the full unlicensed 57~66GHz frequency band and supports multi-band operation. Simulated in UMC 1P9M 65nm CMOS technology, a tuning range of 14% has been achieved with low power consumption. The VCO core only occupies an area of $60 \times 80 \mu\text{m}^2$, which is the smallest for 60-GHz applications published ever.

Keywords—60GHz; VCO; Tuning Range; 65nm CMOS.

I. INTRODUCTION

Though the bandwidth around the 60GHz spectrum is considered incapable of long distance wireless transmission applications due to the high absorption rate of oxygen molecules at this frequency, this unlicensed band has shown unique potential and numerous advantages in short-range-high-speed data transmission for biomedical applications. One of them is body-centric applications aiming to characterize the interactions between the millimeter waves and the human body. The body area network (BANs) operating in the unlicensed 57~64 GHz band has been identified as a highly promising solution since they provide several advantages compared with microwave BANs. [1] First, very high data rates can be reached because of the large available spectrum [2]. Second, high absorption around 60 GHz result in a high level of security and low interference with adjacent networks [3]. Finally, the size of on-body devices is greatly reduced compared with similar systems operating at microwaves. The application of wireless sensor network (WSN) system for healthcare monitoring is demonstrated in [4], which uses the 60GHz band for data transmission between sensor groups. Other research work investigating the in-depth detection

capability of the near-field microscopy at 60GHz band has been flourishing for diagnosis of bio-structures. [5]

As the key component of a frequency synthesizer, the voltage-controlled oscillator performance has a large influence on the system architecture. The challenge in the design of a fully integrated 60GHz VCO is to achieve a large tuning range while maintaining low-power consumption and low phase noise. The special requirements of biomedical applications desire the circuit area as small as possible. In this paper, we propose a novel topology which is capable of achieving large tuning range with low phase noise and small area for 60GHz VCO.

II. TUNABLE DIFFERENTIAL INDUCTOR (TDI)

The proposed TDI is constructed with a six-port differential transformer and two varactors. The transformer used in this paper has been well designed and modeled in [6], which is a 1:1 stack transformer with centre taps on both primary and secondary coils. This transformer has been chosen for the following two reasons. Firstly, the centre taps effectively facilitate DC biasing and AC grounding for differential circuits, reducing area consumption. Secondly, inherent in stack transformers, both edge and vertical coupling can be utilized, especially vertical coupling with the dielectric separation between layers generally in sub-1 μm regime, resulting in high magnetic coupling factor ($k \approx 0.9$), which can be shown desirable in later derivations.

III. VCO DESIGN AND ANALYSIS

The target is to cover the unlicensed 57~66GHz frequency band, which translates to a tuning range as large as 15% at a centre frequency of 61.5GHz. Two circuit techniques are employed together in this novel VCO design, which are TDI introduced in II and Switched Capacitor-Bank [7], as shown in Fig. 1, where the TDI consisting of a transformer and varactors is connected to the cross-coupled negative g_m NMOS pair. The bias current is injected using a PMOS current mirror into the centre tap of the primary coil of the transformer. The switched capacitor bank is connected to the resonator RLC tank, where L is realized by the TDI technique. The

output of the VCO core is connected to the common-source buffer stage to drive a 50-Ω resistive load.

The oscillation frequency can be expressed as

$$f_{VCO} = \frac{1}{2\pi\sqrt{C_p L_{eq}}} \quad (1)$$

where C_p represents the total loading capacitance at the input of TDI, including the parasitic capacitance contributed by the cross-coupled pair, the input capacitance of the succeeding buffer stage and the capacitance of the switched bank when the switch is ON.

Fig 1 Schematic of the proposed VCO with buffer

To determine the oscillating frequency as a function of the variable capacitance C_v , noting that (1) must be satisfied at resonance, we obtain

$$\omega_0 = \frac{1}{\sqrt{C_p L_a [k_{ac}^2 (\frac{1}{1 - C_v L_c \omega_0^2} - 1)]}} \quad (2)$$

Solving for ω_0 , we find it has two possible oscillating frequencies $\omega_{1,2}$ ($\omega_1 < \omega_2$) given by

$$\omega_{1,2} = \frac{\sqrt{1 \pm \sqrt{1 - \frac{4}{C_p L_a} (1 - k_{ac}^2) C_v L_c}}}{2 C_v L_c (1 - k_{ac}^2)} \quad (3)$$

Simulations find that the oscillator will only work at the lower frequency, as the transistors cannot provide enough power gain to make the oscillator start-up at the higher frequency.

The band switching technique has been developed to resolve the problem of insufficient tuning range of single varactor to cover ultra-wide band while at the same time providing multi-band operation capability, which uses a fixed capacitor in series with a MOS switch connected to the cross-coupled core, as in Fig. 1. Generally if a single varactor cannot achieve the tuning range required, band switching can be used so that many of the tuning range of single varactor can be connected to cover the whole range. In some cases, multi-band operation is also desirable in application to perform multi-channel separation, etc. The fixed capacitors can be controlled digitally by way of MOS switches. In this project, the total frequency range is divided into two bands for demonstration. The fixed capacitor is realized using Metal-Insulator-Metal (MIM) capacitor of metal 3 to metal 6 layer with a

dimension of $8 \times 7.5 \mu\text{m}$ which provides a capacitance value that make full use of the single varactor tuning while ensuring multi-band connection is enforced under process and temperature variation.

The buffer is designed as common-source stage with inductive load to provide the required output magnitude (differential 1V peak-to-peak) to 50-Ω load. The inductive load is realized by the differential inductor with center tap as shown in Fig. 2 to save silicon area.

Fig 2 Differential Inductor used in the Buffer

The up-conversion of Flicker Noise in tail current happens due to the AM-FM conversion mechanism of a high gain varactor. In general, the wider the frequency tuning range, the stronger the varactor's proclivity to convert AM into FM. This suggests that wide tuning range is at odds with low phase noise. However, it is possible to decouple tuning range from phase noise by using the differential transformer. Since the varactor bias voltage is isolated from the tail current with one-end grounded, only the control line and supply noise modulate it, which can be eliminated by using a low-dropout low-noise voltage regulator. So the common-mode AM noise does not induce phase noise.

IV. IMPLEMENTATION AND RESULTS

A. Layout

The UMC 65nm CMOS technology offers 9 layers of metal. Both the inductor and the transformer are implemented by the topmost layer which is thicker and farther from the silicon substrate resulting in higher Q value, lower parasitic capacitance and reduced substrate coupling current loss. Interconnects are made as short as possible to avoid the influence of transmission line effect on the circuit impedance since at 60GHz the wavelength is comparable to the interconnects and a long wire behaves like a transmission line contributing to unknown impedance. The output signal has to travel approximately $80 \mu\text{m}$ to the output pad through Metal 9 transmission line, which is modeled through EM simulation as

an inductor of 77pH with a series resistance of 5Ω. This has been added into the circuit when running the post-layout simulation to guarantee an accurate simulation result. The layout of the circuit is shown in Fig. 3. The VCO core occupies an area of 60×80μm².

Fig 3 Layout of the VCO with buffer and output pads

B. Post-layout Simulation Results

The circuit is simulated using the *SpectreRF* simulator with typical process corner under 27°C temperature. The dimensions of the components in Fig. 1 are listed in Table I.

The lower-band frequency is tunable 58.81~62.77GHz as V_{tune} changes from 0 to 1V, while the upper-band frequency is tunable from 62.55~67.59GHz, as shown in Fig. 4. The two frequency bands connect well with a total tuning range of 9GHz. The overall frequency is designed around 1.6GHz higher than the 57~66GHz band to account for various parasitic capacitance associated with testing pads. The differential output voltage to a 50-Ω resistive load is depicted in Fig. 5, together with the power consumption of the VCO core. The simulated phase noise of output signal is -107dBc/Hz at 10MHz offset from 62.77GHz.

TABLE I DIMENSION OF THE COMPONENTS IN FIG 1

Component	Dimension
M1,M2	40μm/60nm
M3,M4	20μm/60nm
M5,M6	16μm/60nm
M7	1μm/60nm
M8	64μm/60nm
C	9μm×7.5μm
N-Var	24μm/2μm
1:1 Transformer	49μm(Diameter)
Differential Inductor	85μm(Diameter)

Fig 4 VCO Tuning Characteristic

Fig 5 Output Voltage and Power Consumption

C. Performance Comparison

The performance and calculated Figure-Of-Merit (FOM) of the proposed VCO are summarized and compared with previous 60GHz VCO works in Table II. The FOM of VCO is defined as follows

$$FOM = PN - 20 \log \left(\frac{f_0}{\Delta f} \frac{TP}{10\%} \frac{1V}{\Delta V_{tune}} \right) + 10 \log \left(\frac{P_{cons}}{1mW} \right) \quad (4)$$

where PN is the phase noise at the offset frequency Δf , f_0 is the centre frequency, P_{cons} is the power consumption, TP is the frequency tuning percentage, and ΔV_{tune} is tuning voltage range. The proposed VCO exhibits performance which is comparable to state-of-the-art.

TABLE II VCO PERFORMANCE SUMMARY AND COMPARISON

Ref	[8]	[9]	[10]	[11]	[12]	This Work
Year	2008	2008	2009	2009	2009	2011
Technology	90nm CMOS	0.13 μ m CMOS	65nm CMOS	90nm CMOS	65nm CMOS	65nm CMOS
f_0 (GHz)	57.2	69.7	60.3	55.8	56.05	63.2
f_{min} (GHz)	53.1	65.8	57.5	53.2	51.4	58.8
f_{max} (GHz)	61.3	73.6	63.1	58.4	60.7	67.6
Tuning Range(GHz)	8.2	7.8	5.6	5.2	9.3	8.8
Tuning %	14.34	11.19	9.29	9.32	16.59	13.92
PN(dBc/Hz)	-118.75@10MHz	-107@10MHz	-95.3@1MHz	-91@1MHz	-99@1MHz	-107@10MHz
PN ref freq(GHz)	61.3	66	57.5	58.4	57.6	62.8
P_{diss} (mW)	8.7	32	36	8.1	15	15.5
ΔV_{tune}	1.2	2	1.8	1.2	1.8	1
FOM	-186.05	-163.77	-169.3	-174.65	-182	-174
Area	92 $\times$ 92 μ m ²	0.5 $\times$ 1.045mm ² *	340 $\times$ 340 μ m ² **	96 $\times$ 80 μ m ²	152 $\times$ 350 μ m ²	70 $\times$ 80 μ m ²

* Including Pads

**Including Buffer

V. CONCLUSION

The 60GHz frequency band has shown unique potential and numerous advantages in short-range-high-speed data transmission for biomedical applications such as wireless sensor network (WSN) system for healthcare monitoring and near-field microscopy for diagnosis of bio-structures. A novel multi-band VCO for 60GHz applications is designed to cover the unlicensed 57~66GHz frequency band. The circuit employs two techniques to achieve the targeted tuning range, which are Tunable Differential Inductor (TDI) and Switched-Capacitor Bank. The TDI helps to increase the tuning range by isolating the varactor from the parasitic capacitances of the transistors and interconnects. It also reduces phase noise due to varactor AM-FM conversion by isolating varactor bias voltage from low-frequency noise related to the bias current. Simulated in UMC 65nm CMOS Process, the VCO is tunable from 58.8GHz to 67.6GHz when tuning voltage changes from 1V to 0V. The tuning percent is 14% with upper band covering 62.6~67.6GHz and lower band 58.8~62.8GHz. The VCO core consumes 15.5mW, with buffer consuming 8mW. Differential output magnitude is 1V Peak-to-Peak to a 50- Ω load, with a phase noise of -107dBc/Hz at 10MHz offset from 62.77GHz. The VCO core takes an area of 60 $\times$ 80 μ m². To the best of the author's knowledge, this is the smallest VCO for 60-GHz applications published ever. The small size of the design makes it compatible for on-body applications.

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