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An overview of new design techniques for high performance CMOS millimeter-wave circuits

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***Abstract*—The nanoscale CMOS technology becomes popular in mm-wave integrated circuit design due to its higher integration potential and lower price compared to SiGe and GaAs process. Meanwhile, its cut-off (f_t) frequency is continuous increasing and comparable to these special process due to the size shrinking according to the Moore's law. However, the CMOS process suffers from high substrate loss and low quality (Q) of passives. As a result, the performances of some key blocks are degraded such as VCO, divider and LNA. In this paper, tunable inductors, meta-material oscillator and coupled oscillator are proposed to overcome the problems.**

***Index Terms*—mm-wave integrated circuit (MMIC), tuning inductor, meta-material, VCO, coupled oscillator**

I. Introduction

Mm-wave frequency can provide wide unlicensed frequency spectrum to realize Gb/s communication system such as IEEE820.15.1c [1]. Meanwhile, due to the wideband benefit, the resolution of the mm-wave passive imaging system can be greatly improved because its resolution is proportional to the bandwidth [2-3]. However, designing these high-performance MMICs meets many challenges which mainly comes technology process and working frequency.

Conventional MMICs are widely implemented in SiGe or GaAs technology process due to its high f_t and low loss substrate. However, these processes have limited integration capability. As a result, CMOS process becomes increasingly popular due to its high integration capability while its low resistivity substrates with 10 ohm-cm will induce significant the eddy currents. Thus the quality (Q) of the passive devices are degrades such as inductor, capacitor and transformer [4-5]. As a result, the phase noise of the VCO is poor because it is inversely proportional to Q as shown in Fig.1. Through using special process, such as the un-doped silicon or insulators in Silicon-on-Insulator (SOI) technologies can achieve high-Q passives due to the high resistivity, this requires extra processing steps during lithography, much increasing the implementation costs. This paper introduces some novel techniques to enhance the Q and realize the circuits in traditional CMOS achieving high performance which are comparable to these circuits in special process.

The other challenge is that mm-wave circuits are very sensitive to the parasitic and process variation. For example, in mm-wave VCO design, the parasitic capacitance of inductors, MIM capacitors, varactors, and interconnect, and the series resistance of gate fingers and interconnect vias can reduce the

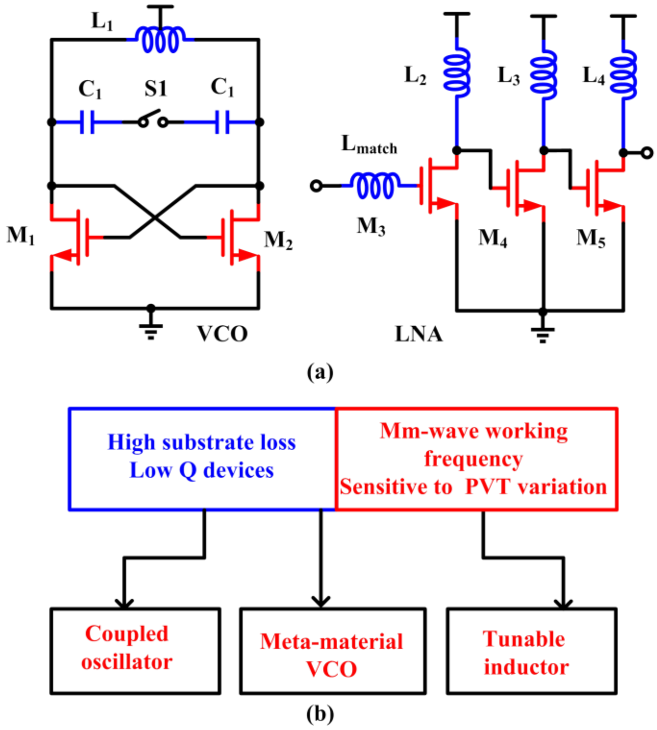


Fig. 1. (a) Some MMIC key blocks such as VCO and LNA (b) two challenges: one is the high substrate loss causing low Q passives device; the other is the high working frequency.

oscillation frequency by more than 30% and significantly degrade the phase noise [1,4,5]. Meanwhile, the process, temperature, and voltage (PVT) variation will drive the performances from the targeted design such as the center oscillation frequency of the VCO as shown in Fig.1. Then, the drift will introduces the uncertainly of the loop stability and makes the chip fail to work such as causing the phase-lock-loop (PLL) unlock. As a result, it is better to design wideband circuits to overcome the parasitic effect and PTV variation.

In order to solve above problems such as the low Q of the passives, the paper introduce meta-material T-line based high quality resonator. Furthermore, tuning inductor based transformer loaded can be used in wideband mm-wave VCO and LNAs [6-8]. Meanwhile, coupled oscillator based ZPS is also introduced to improve output power with power combing and low phase noise [9-10]. Each technique will be briefly introduced and explained by design cases.

The remaining part of the paper is organized as follow: Section II will present the brief theory explanation of the three new techniques. The design cases will be introduced in section III. The conclusions will be drawn in section IV. .

II. New Design techniqes

A Tuning Inductor with loaded transformer

In order to cover PTV variation, tuning mechanism is necessary to be introduced to realize wideband bandwidth performance. It is well known to us that the inductor is widely used in MMIC such as VCO and LNA. Thus, realizing wideband tunable inductor is meaningful. This paper will introduce tunable inductor with loaded transformers which can be explained by Fig. 2. Though various types of load have been explored on transformer for inductive tuning [5], such as resistor, capacitor, and inductor, they can all be equalized to a

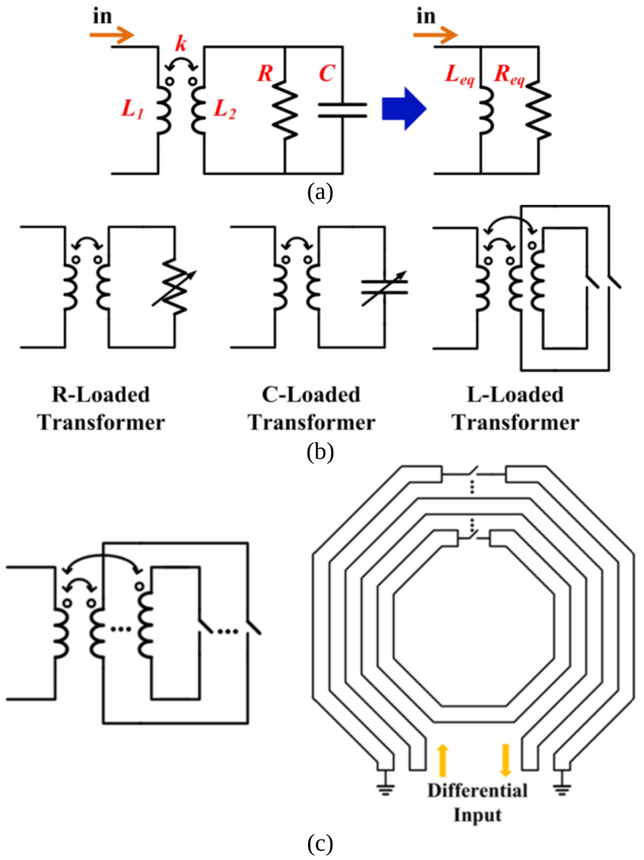


Fig. 2. Loaded-transformers for wide range tuning: (a) equivalent circuit, (b) various types of loaded transformer, and (c) implementation for L-loaded transformer.

RC tank, and thus can be analyzed as follows.

Assuming the transformer is ideal with coupling factor k, and with L_1 and L_2 as the primary inductance and secondary inductance, respectively. The equivalent circuit with L_{eq} and R_{eq} can then be calculated as:

$$\begin{cases} L_{eq} = \dfrac{R^2 L_1[1-\omega^2 C L_2(1-k^2)]^2+\omega^2 L_1 L_2^2(1-k^2)^2}{R^2(1-\omega^2 C L_2)[1-\omega^2 C L_2(1-k^2)]+\omega^2 L_2^2(1-k^2)} \\ R_{eq} = \dfrac{R^2 L_1[1-\omega^2 C L_2(1-k^2)]^2+\omega^2 L_1 L_2^2(1-k^2)^2}{R k^2 L_2} \end{cases} \quad (1)$$

For example, if the tunable inductor is utilized in VCO and the total capacitance in the oscillation LC-tank is C, the oscillation frequency becomes $\omega = \frac{1}{\sqrt{L_{eq}C}}$. As a result, the oscillation frequency can be tuned to overcome the PTV variation.

B Meta-material T-line Based Resonator

Due to the conductive substrates providing low impedance paths for RF signals to propagate through in traditional CMOS, especially in case of passive elements such as on-chip inductors and transformers with varying magnetic fields. Large eddy current will be introduced in the substrate. Once the passives used in VCO and LNA, the phase noise a VCO and the gain of the LNA are degraded.

To improve the Q of the resonator, meta-material T-line based resonators is a good method due to the coupling effect which can reduce the eddy current. Split ring resonator (SRR) structures have been explored on a printed circuit board (PCB) with operating frequencies below 10 GHz as shown in Fig.3(a) While the same theory has been explored recently for CMOS

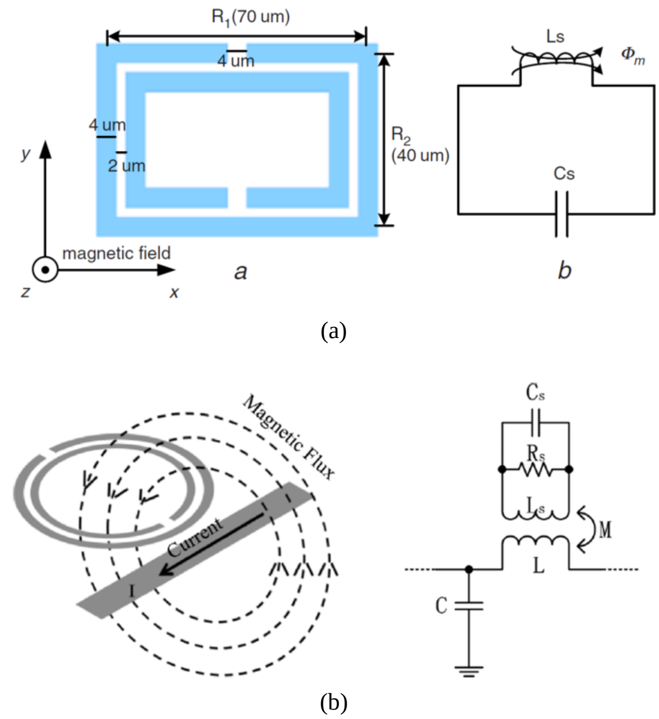


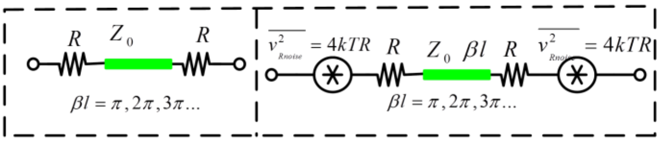
Fig. 3. :(a) Split ring resonator (SRR), (b) The model of the coupling effect of the meta-material T-line

MMIC applications.

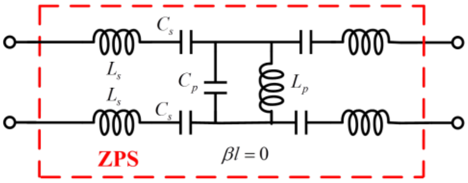
As shown in Fig.3 (b), the magnetic flux will penetrate the SRR. As a result, the electrical and magnetic files are constrained in SRR and the substrate current introduced are significantly reduced. Furthermore, in the SRR-loaded T-line, the resonant property is mainly determined by the SRR which behaves as a meta-material.

C Coupled Oscillators based ZPS

Besides improving the quality of passive device to get better phase noise, the in-phase coupled oscillator network is also a better solution for phase noise and power improvement [2]. As a result, in-phase coupled network can provide high quality signal source for millimeter-wave integrated circuit (MMIC) designs.



(a)



(b)

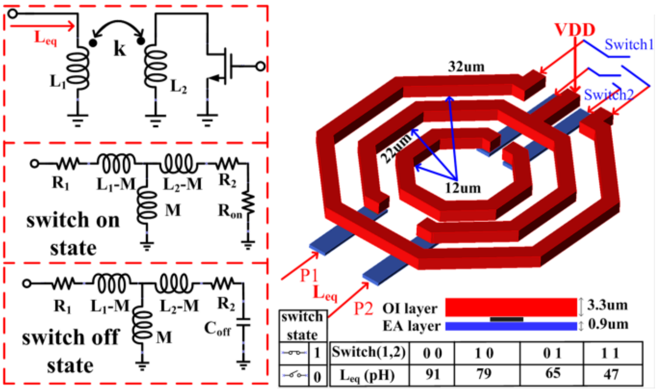
Fig.4. (a) Conventional coupling methods used in PCB around 10 GHz [9-10] by T-lines with resistors (b) ZPS structure

To realize of in-phase coupling, conventional coupling networks are implemented by T-line with resistors [9-10] which are too lossy and bulky. What is worse, the resistor introduces thermal noise which is converted into additional phase noise in oscillator. This paper introduces a novel coupling network realized by Composite Right/Left Handed (CRLH) T-line based Zero-Phase-Shifter (ZPS) as shown in Fig.4(a-b). Then, the ZPS can be used in-phase coupling VCOs. For in-phase VCO network, the phase noise is reduced and the output power can also be combined. As a result, the high quality mm-wave source can be realized.

III. Design Case

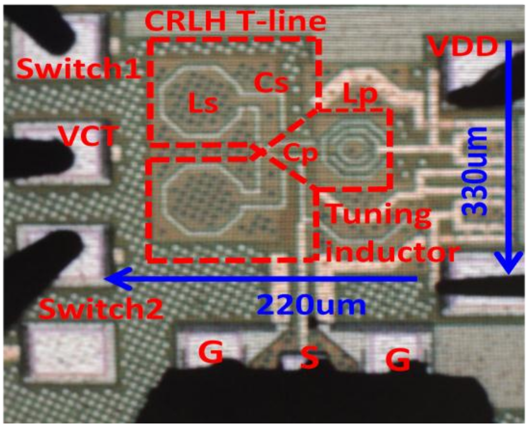
A. Tuning Inductor with Loaded Transformer

In order to verify the tuning inductor with loaded transformer, a RTW-VCO was implemented with tuning

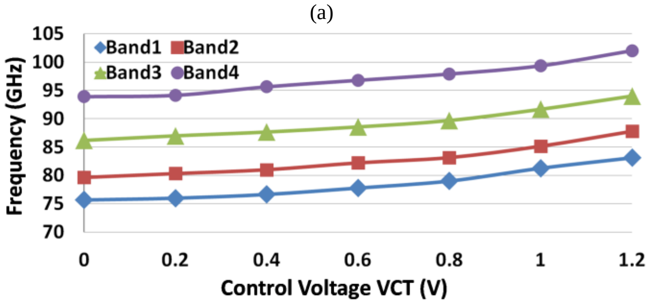


(a) (b)

Fig. 5. (a) Equivalent circuits of an inductor-loaded transformer with the loaded switches. (b) Layout implementation for inductor-loaded transformer where tuned inductance is determined by states of two switches



(a)



(b)

Fig. 6. (a) The chip photo of the proposed VCO based the tuning inductor (b) the tuning range

inductor as shown in Fig.5. By switching the state of the two switches [7], four bands were realized as shown in Fig.6(b). The oscillation frequency can be tuned from 75GHz to 101GHz which is enough to cover PTV variation.

B. Meta-material resonator

To further demonstrate the high-performance of the proposed meta-material resonator, especially in the phase noise improvement. Paper [8] designed a MMIC oscillator based on meta-material resonators in 65-nm CMOS.

The operating frequency is at 76 GHz using the DTL-SRR,

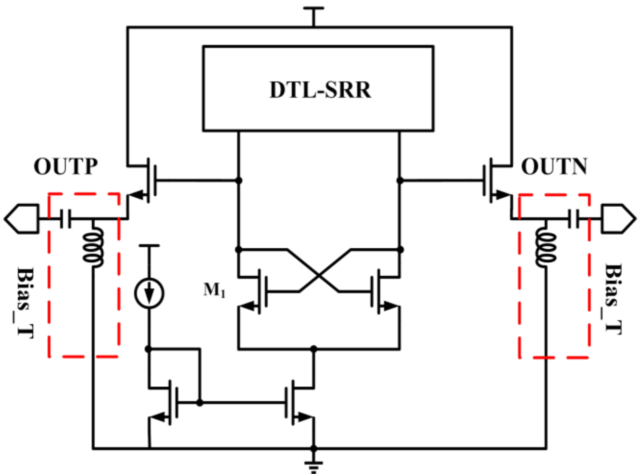
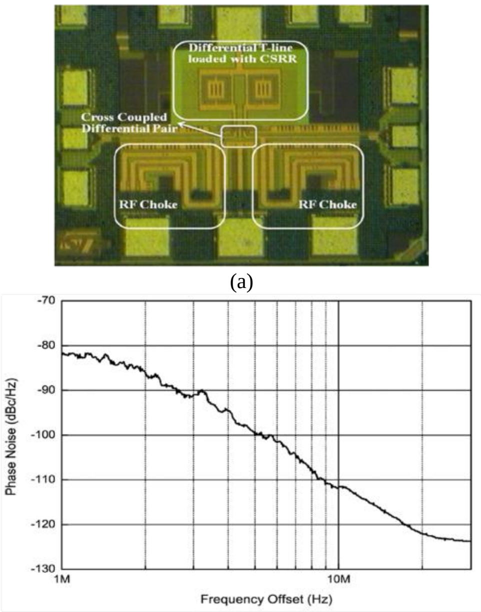


Fig. 7. Circuit diagram of the 76-GHz CMOS MMIC oscillator with DTL-SRR structure.



(a)

(b)

Fig.8(a) Layout of the MMIC oscillator based meta-material T-line loaded SRR (b) Measured phase noise

using the differential T-line loaded with the SRR.

The measured results show that the phase noise and figure of merit (FOM) of DTL-SRR-based oscillator achieves 108.8 and 182.1 dBc/Hz (@10-MHz offset, respectively. The power consumption is only 2.7 mW and the chip area is 0.15 mm as shown in Fig.8(a-b) .

C. Coupled Oscillator Network based ZPS

To verify the phase noise reduction and high output power, the circuits is designed as shown in Fig.9. Two individual oscillators are LC-tank based oscillator and coupling network is implemented by fully-differential ZPS. For LC-oscillator, W/L of transistors is 10um/65nm, L=80pH. For ZPS L_p=60pH, C_s=36fF, the in-phase coupling frequency is 125GHz.The output power is around -3dBm and phase noise is -95dBc/Hz

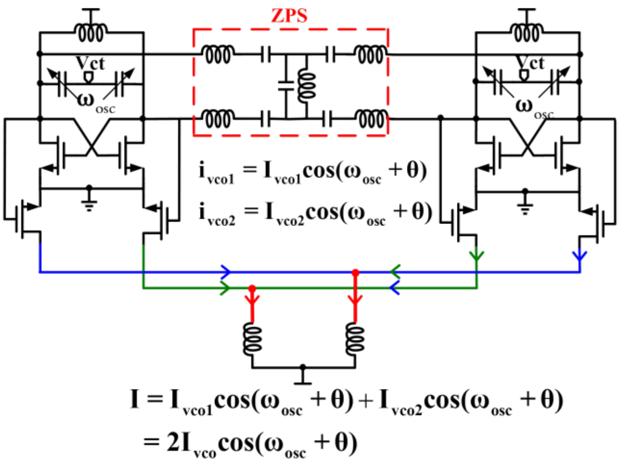


Fig.9 Circuit diagram of mm-wave signal generator with the proposed in-phase coupled VCO to realized high output power and lower phase noise generator

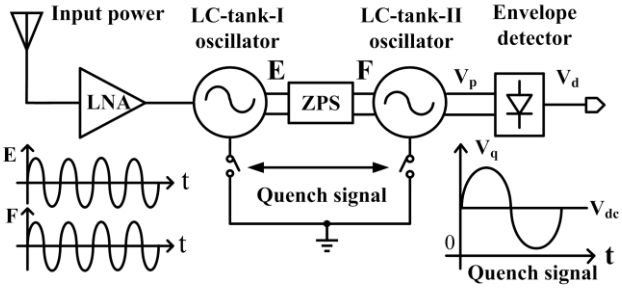


Fig.10 Circuit diagram of proposed SRR with ZPS-coupled oscillators

@ 10MHz offset frequency. Meanwhile, the structure can be used in super-generative receiver [11-12] as shown Fig.10. Due to the phase noise reduction, the sensitivity is -81dBm at 131.5GHz operating frequency.

IV. Conclusion

In this paper, in order to overcome the challenges coming from CMOS process and high working frequency, three novel techniques including tuning inductor, meta-material VCO and coupled VCO are introduced and verified . Tuning inductor is a better way to realized wideband circuits such as VCO and LNA. Meta-material resonator can achieve high quality and low phase noise. In-phase coupling VCO is a better solution to implement high quality mm-wave signal source with high output power and low phase noise.

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