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28 GHz balanced pHEMT VCO with low phase noise and high output power performance for 5G mm-wave systems

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Article Info	ABSTRACT
	This paper presents the study and design of a balanced voltage controlled oscillator VCO for 5G wireless communication systems. This circuit is designed in monolithic microwave integrated circuit (MMIC) technology using PH15 process from UMS foundry. The VCO ensures an adequate tuning range by a single-ended pHEMT varactors configuration. The simulation results show that this circuit delivers a sinusoidal signal of output power around 9 dBm with a second harmonic rejection between 25.87 and 33.83 dB, the oscillation frequency varies between 26.46 and 28.90 GHz, the phase noise is -113.155 and -133.167 dBc/Hz respectively at 1 MHz and 10 MHz offset and the Figure of Merit is -181.06 dBc/Hz. The power consumed by the VCO is 122 mW. The oscillator layout with bias and RF output pads occupies an area of 0.515 mm^2.

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1. INTRODUCTION

Reflected by the fast pace of technology innovation, wireless communication is the fastest growing technology in the world. Currently, necessitates more than ten billion of machine-to-machine communications and Internet of Things to fulfil the requirements for autonomous vehicles, intelligent home, smart grid, smart city [1] and E-health services [2, 3]. Therefore, the enormous need for the new broadband frequencies [4]. Fortunately, large quantities of relatively inactive spectrum exist in the millimeter wave band [5]. The most recent researches focused on the 28 GHz band, the 38 GHz band, the 60 GHz band and the E-band [6].

The object of a communication system is to establish seamless communications with reasonable cost and reduced power consumption, the upcoming mobile communication system generation 5G is aiming to fulfil these important requirements [4]. Any RF transmission / reception shown in Figure 1 system has one or more local oscillators. An oscillator is an autonomous system generating a fixed or variable frequency signal [7]. In RF transceivers, oscillator signals are used as a frequency reference to convert the RF signal to an intermediate frequency. In all RF applications, it is necessary to have sinusoidal references of a high spectral purity, this is, moreover, one of the most important characteristics of an oscillator.

In the literature, many VCOs have a relatively good FoM, however, observing the covered frequency range, we notice that it is very low: 5.45% and 6.91% of the central frequency for the two VCOs proposed in [8], 5.44% and 3.3% respectively for the VCOs proposed in [9, 10]. On the other side, structures with wide frequency ranges but low phase noise levels, less than -102 dBc/Hz, which do not fulfill the 5G

requirements [11-13]. In addition to all these considerations, there is also the problem of the large space occupied by these circuits, of which it is in the order of 1.5 mm^2 [9] or much more [12-14].

In this paper, a large tuning range MMIC VCO with good phase noise level is proved. The circuit is designed based on a balanced Colpitts architecture. It has a tuning range that exceeds 8.8 % of central frequency and a phase noise around -113 dBc/Hz at 1 MHz offset. This circuit is designed based on the pseudo-morphic High Electron Mobility Transistor pHEMT of PH15 process from UMS foundry, dedicated to RF applications, with a cut off frequency of $f_T = 110GHz$ and a 0.15 µm gate length [15]. The remainder of this paper is structured as follows: Section 2 presents the 5G mm-Wave VCO circuit design, Section 3 reports VCO layout and discusses the simulation results. A conclusion is given in section 4.
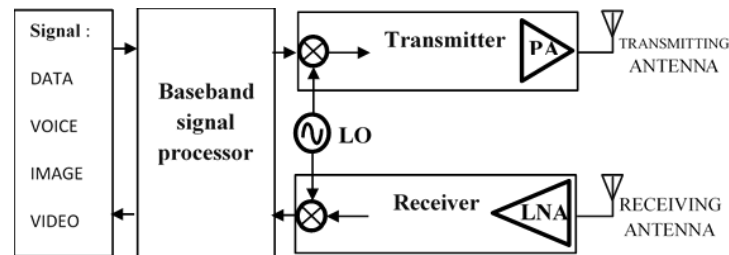

Figure 1. Simplified diagram of transmission/reception system

2.   5G MM-WAVE VCO DESIGN

After choosing the semiconductor technology and transistor type, it is time to choose the most suitable VCO topology for the 5G mm-wave band application. The simplified schematic (i.e., without transmission lines) of the studied VCO is shown in Figure 2, it is a modified version of the Colpitts structure, which combines a good phase-noise level with improved starting conditions. The active part of the VCO is composed of the two GaAs pHEMT transistors, T1 and T2, of gate length of 4*0.15 µm and width of 20 µm, and their bias elements, we have chosen transistors with a high number of fingers to increase the output power [9]. The performance of the active device, at the millimeter frequency, depends strongly on biasing conditions [16], the biasing of these transistors is provided by the two voltage sources Vds and Vgs of 2 V and 0.2 V respectively. While the inductance Lr as well as the two varactors T3 and T4 constitute the resonator. These varactors are based on the pHEMT transistor whose source is connected to the drain, the capacitance value of these varactors is controlled by the voltage applied to the gate Vtune. Finally, a capacitor C has been added at the output of the oscillator whose role is to filter the DC component which comes from the bias sources. We announce that this circuit is based on the PH15 process elements of the UMS foundry, whose behavior is very close to reality, thus they present parasites and imperfections.
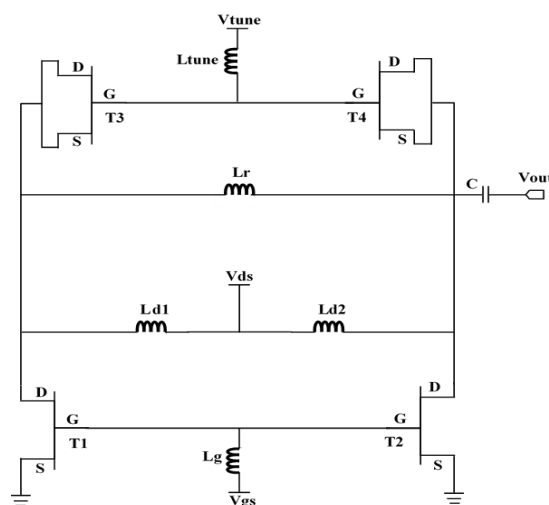

Figure 2. pHEMT balanced VCO circuit

3. SIMULATIONS AND DISCUSSIONS

At millimeter frequencies, parasitic capacitances, transmission line inductances and other connections can catastrophically change reactances and can have a significant impact on the performance of the final circuit, which is why several optimization and retro-simulation steps are performed before the final layout as shown in Figure 3. Particular attention is paid to the Layout symmetry, to avoid the introduction of asymmetry in the oscillation waveforms and thus introduce additional phase noise [17]. According to the circuit layout as shown in Figure 3, we observe three bias pads, one pad for the tuning voltage Vtune and one RF pad for the output signal. The circuit is implanted on the GaAs substrate, it is a multilayer technology. The total number of layers used in the PH15 process is 16 layers [18]. The length of this Layout is 0.761 mm while the width is 0.677 mm, thus a total surface area of 0.515 mm^2, since this surface includes the VCO with RF pad, the tuning voltage pad and the three bias pads as well as the capacity that acts as a low pass filter. We can note that it is a very compact Layout and takes up a small area compared with the architecture published in the literature.
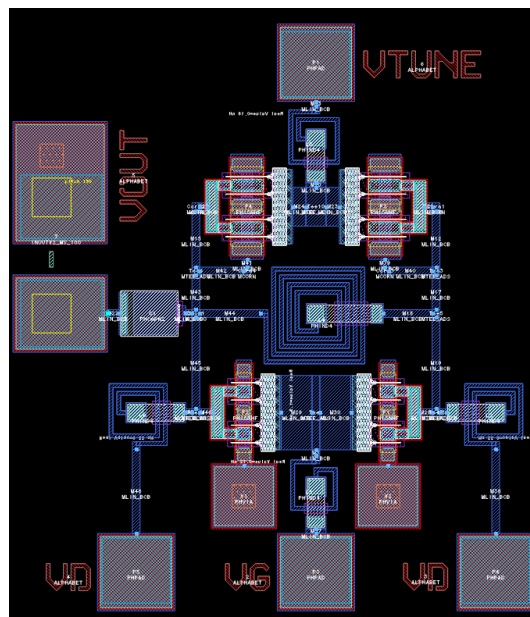

Figure 3. Layout of 5G mm-wave voltage controlled oscillator

After checking the start-up conditions of our oscillator using the "OscTest" tool provided by Agilent's ADS software. A transient simulation is executed to verify the stability of the output signal. Figure 4 shows that the start-up conditions of the oscillations are very good, the oscillations start effectively, and they are perfectly stable.
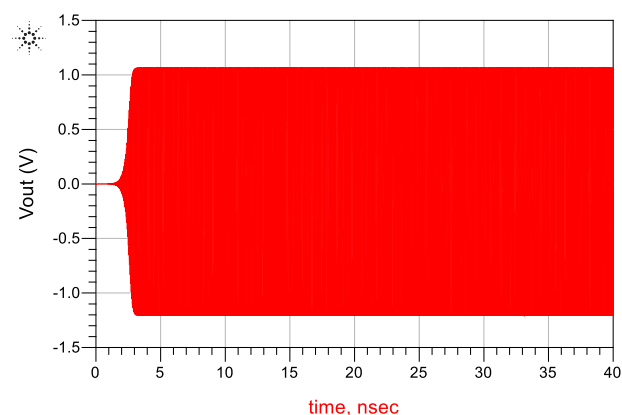

Figure 4. Temporal variation of the output signal Vout for Vtune= 2 V

The harmonic simulation shows that the minimum value of the output power is 5.02 dBm, while the maximum value is 9.75 dBm. The second harmonic rejection varies between 25.87 and 33.83 dB for the oscillation frequencies 28.12 and 26.48 GHz respectively, while the third harmonic rejection varies between 44.75 and 55.93 dB for the oscillation frequencies 28.41 and 26.48 GHz respectively shown in Figure 5. Therefore, we notice that our circuit has a good level of rejection of unwanted harmonics.

In Figure 6 we have plotted the variation of the oscillation frequency as a function of the tuning voltage Vtune. For a variation of the tuning voltage Vtune from -2 to 2.5 V, the oscillation frequency varies from 28.90 to 26.46 GHz. Therefore, a tuning range of 2.44 GHz and a gain of K_{VCO}=542 MHz/V are achieved. Figure 7 shows the temporel variation of the output signal Vout for Vtune=2.5 V, therefore it is a perfectly sinusoidal signal.
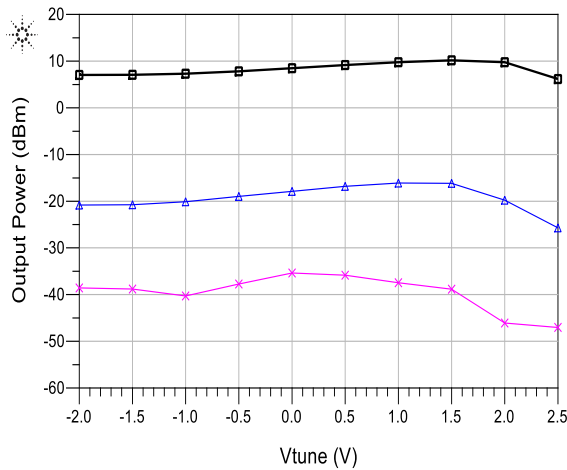
Figure 5. Output power of the first harmonic (-☐-), second harmonic (-Δ-) and third harmonic (-x-) versus tuning voltage Vtune
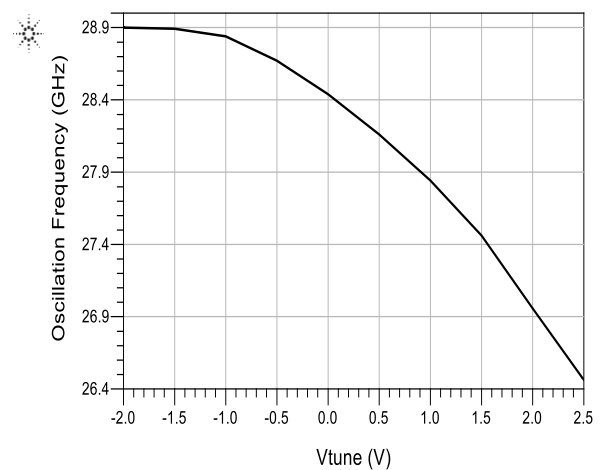
Figure 6. Variation of the oscillation frequency versus tuning voltage Vtune
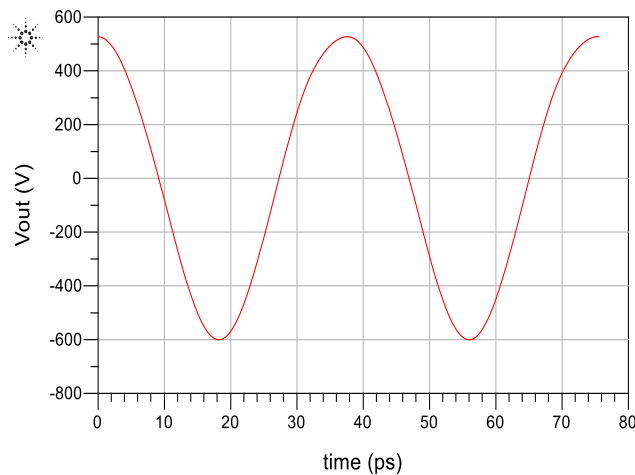
Figure 7. Temporal variation of the output signal for Vtune=2.5 V

The VCO performance determines the characteristics of the entire transmission system, therefore, to have a signal of high spectral purity, the VCO phase noise must be as minimal as possible [19, 20]. Figure 8 shows the single sideband phase poise and the absolute noise voltage spectrum for Vtune=1.5 V, thus the phase noise is -93.04 and -113.155 dBc/Hz at the offset frequency of 100 KHz and 1 MHz respectively. On the other hand, the simulation shows that the power consumed by this VCO topology is122 mW.

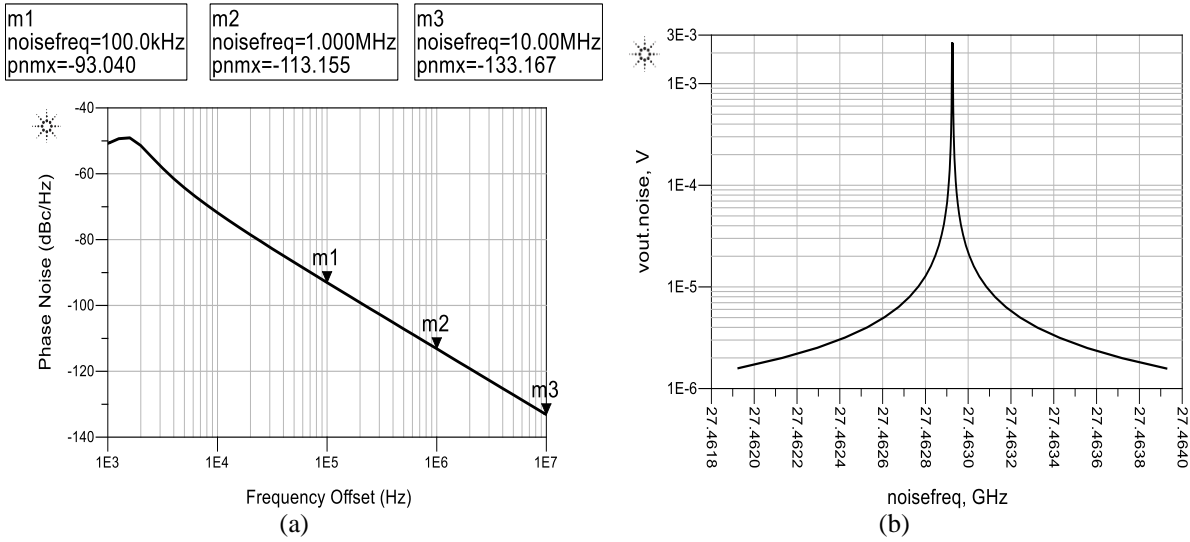| m1	m2	m3
noisefreq=100.0kHz	noisefreq=1.000MHz	noisefreq=10.00MHz
pnmx=-93.040	pnmx=-113.155	pnmx=-133.167

Figure 8. Single sideband phase noise, (a) absolute noise voltage spectrum, (b) for tuning voltage Vtune= 1.5 V

Depending on the desired application, a voltage-controlled oscillator could even have completely different specifications, making it difficult to compare VCOs with each other. A FoM merit factor is then defined to represent the overall performance of an oscillator [14, 21-23]:

$$\text{FoM} = L(f_0, \Delta f) + 10 \log(P_{DC}) - 20 \log(\frac{f_0}{\Delta f}) \tag{1}$$

where $L(f_0, \Delta f)$ is the phase noise at Δf frequency offset, f_0 is the oscillation frequency and P_{DC} is the power consumption of VCO in mW.

To compare the performance of our voltage controlled oscillator circuit with other structures published in the literature; Table 1 summarizes the performance of different oscillators, designed with different technologies, operating in the same frequency band and dedicated for the same applications. From Table 1 we can see that the architecture proposed in this paper has very good performance; the best level of phase noise, an excellent output power, a low power consumption and therefore a good figure of merit.

Table 1. Performance comparison of different VCOs

Ref.	Central frequency (GHz)	Tuning range (GHz)	Output power (dBm)	Phase noise (dBc/Hz) at 1MHz	FoM (dBc/Hz)	Chip area (mm²)	Structure	Technologie
[8]	25.6	1.77	3	-101.9	-176.7	0.034	On-chip inductor	0.13 μm CMOS
[8]	40.7	2.22	-6.6	-94.8	-172.1	0.018	On-chip inductor	0.13 μm CMOS
[12]	29.4	14.8	4.5	-100.7	-169.11	3.75	4 Colpitts VCO	0.13 Um SiGeBiCMOS
[13]	28.3	3.8	11.8	-102	-	0.5	Negativeres istance	0.15 μm pHEMT
This work	27.7	2.44	9.75	-113.155	-181.06	0.515	Colpitts	0.15 μm GaAs pHEMT

Finally, in order to characterize the performance of a millimeter frequency circuit, the effect of technological dispersion must be evaluated. The Monte Carlo analysis proposed by the ADS software, allows to cause small random variations in the values of the different circuit parameters, and to predict the impact of these variations on the performance of our circuit [24, 25]. We performed a Monte Carlo analysis at 50 iterations. Figure 9 shows the results of technological dispersion. We can deduce that for all iterations, the fundamental harmonic power and the second harmonic power are subject to limited and acceptable variations over the entire tuning range.
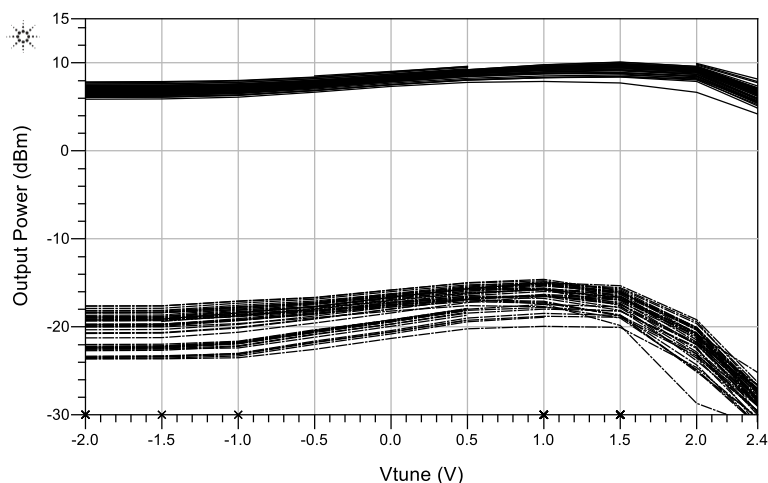
Figure 9. Monte Carlo analysis for the output power of the first harmonic (solid line)
and the second harmonic (dash-dotted line)

4.   CONCLUSION

In this paper we have presented and designed a pHEMT balanced VCO in MMIC technology for 5G mm-wave band systems. The simulations results showed a tuning range of 2.44 GHz (which represents 8.82% of the central frequency), an output power of 9 dBm, a phase noise of -113.155 dBc/Hz at 1 MHz offset frequency and a figure of merit of -181.06 dBc/Hz. The Layout area is 0.515 mm^2.

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