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Study and Design of a MMIC Voltage Controlled Oscillator for 5G mm-wave band Applications

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ABSTRACT

A design of voltage controlled oscillator (VCO) in the 5G mm-wave band is presented in this paper. The circuit is designed in Monolithic Microwave Integrated Circuit (MMIC) technology in PH15 process from UMS foundry using ADS software from Agilent. This oscillator will be suitable for wireless communication systems of the next generation 5G mm-wave band. The simulation results show that the designed circuit can deliver a quasi-sinusoidal signal with an output power up to 5 dBm for an oscillation frequency of 28.02 GHz with a rejection rate of 25 dB for the second harmonic. This VCO consumes 76 mW and exhibits a tuning range of 1.77 GHz with a good linearity over the entire range. The phase noise achieved is about -100.9 dBc / Hz at a 1 MHz offset and a good figure of merit (FOM) of -180.37 dBc / Hz. The total area occupied by this VCO is 0.25 mm^2.

Key words: 5G mm-wave band, Colpitts VCO, pHEMT VCO, MMIC VCO.

1. INTRODUCTION

The 5G is expected to support theoretical download speeds about of 10 Gbps versus 1 Gbps for 4G, with a latency less than 1ms versus 60-98 ms and 212 ms for 4G and 3G respectively [1]. In order to reach the highest speed broadband for 5G [2]-[4], the integration of millimeter frequencies promises a hyper-connected world in terms of speed, latency, reliability and capacity. The 26 GHz and / or 28 GHz bands are the most recommended by 5G actors for their large potential harmonization and low complexity equipment [5], [6].

Any radio transmission / reception system has one or more local oscillator whose role is to transpose the signal to be transmitted in the useful frequency band. The local oscillator performance in terms of phase noise and frequency tuning range determines the transmission / reception chain quality and becomes a major challenge for MMIC designers. An oscillator (Figure 1) is an electronic system that generates a RF signal by transforming the DC bias energy. It generally consists of two blocks; an amplifier includes an active device and bias network and resonator (tank circuit) comprising passive elements [4], [5].

In the literature [7]-[11], most of the VCOs are based on very complex structures with large dimensions. In this paper, we propose the study of a voltage controlled oscillator (VCO), of a simple structure, with a bandwidth that exceeds 6% of central frequency, based on the pHEMT transistor of PH15 process from UMS foundry, dedicated to RF applications, with a transition frequency of f_T = 110 GHz [12]. This oscillator can be used to deliver, directly, a signal around 28 GHz or be combined with a frequency quadrupler to generate an extremely high frequency signal.

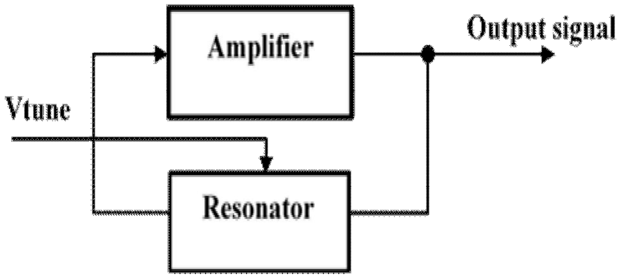

Figure 1: Synoptic diagram of a voltage controlled oscillator.

2 5G MM-WAVE COLPITTS VCO DESIGN

2.1 Amplifier Circuit

The amplifying circuit (Figure 2) is designed based on pHEMT transistor biased with two voltages Vgs and Vds, the two connecting capacitors C1 and C2 are short circuits at the oscillation frequency. The role of this part of the oscillator is to compensate the losses generated by the tank circuit, hence the need to carefully choose the circuit parameters to have a positive transmission coefficient S21 around the oscillation frequency and to satisfy the oscillation conditions. For Vgs

= - 0.5 V and Vds = 3 V, Figure 3 shows that the transmission coefficient S21 of the amplifying circuit is maximal at 28 GHz oscillation frequency, it is about 11.4 dB.

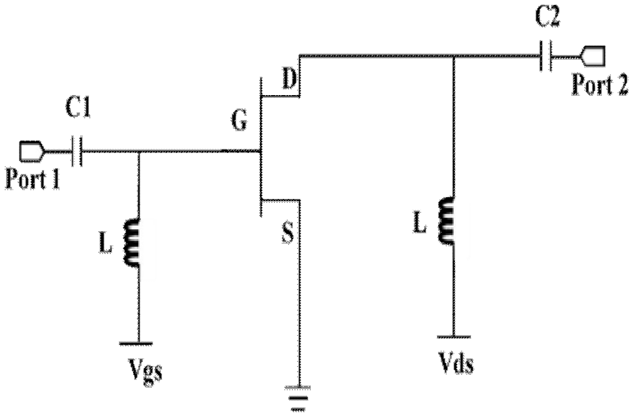

Figure 2: Amplifier circuit

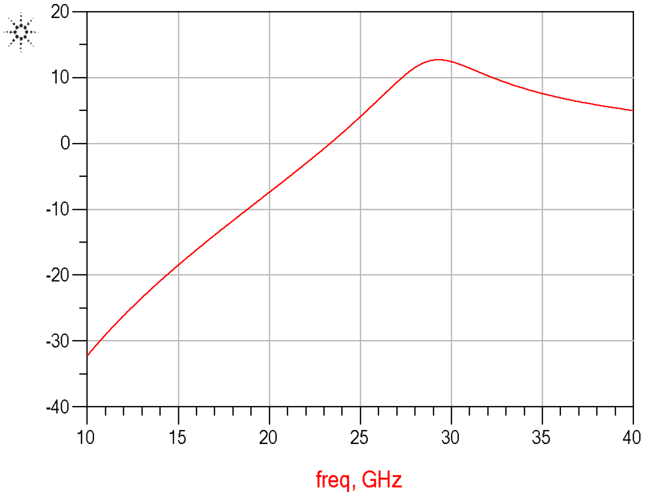

Figure 3: Transmission coefficient of the amplifier circuit

2.2 Tank circuit

The tank circuit of Colpitts oscillator is shown in Figure 4-(a); it consists of two capacitors C3 and C4 and an inductor L1. The transmission coefficient S21 and reflection coefficient S11 of this circuit are shown in Figure 5 and Figure 6. The Transmission coefficient S21 is maximal at 28 GHz, whereas the reflection coefficient is minimal at this frequency. These results correspond to the values 0.13 pF, 0.2 pF and 0.13 nH, respectively for C3, C4 and L1.

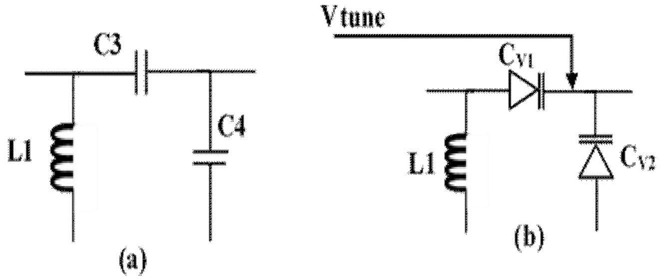

Figure 4: Tank circuit with capacitors (a), with varactors (b)

In order to design a VCO, the tank circuit must have a variable resonant frequency, therefore the capacitors C3 and C4 are changed by two varactors CV1 and CV2 respectively (Figure 4-(b)). These two varactors allow to obtain a variable capacitance value, according to their reverse bias voltage Vtune. In this paper, we opted for the choice of single-ended configuration since it is simple to implement and less cumbersome. The S-parameters of this circuit are represented for each value of Vtune (Figure 7 and figure 8).

The resonance frequency changes by varying the tuning voltage Vtune; i.e., we get the resonance frequencies 27.57, 28.87 and 29.75 GHz for the tuning voltage (Vtune) 0.00, 0.5 and 3 V respectively. while the maximum value of the transmission coefficient S21 remains almost stable; -2.695 dB for Vtune = 0.0 V, -2.633 dB for Vtune = 0.5 V and -2.774 dB for Vtune = 2 V. On the other hand, the reflection coefficient S11 takes a minimum value around the resonance frequency.

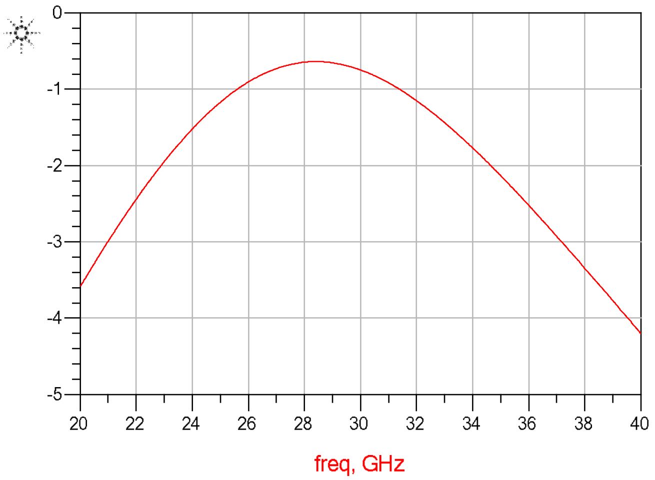

Figure 5: Transmission coefficient S21 of tank circuit with capacitors.

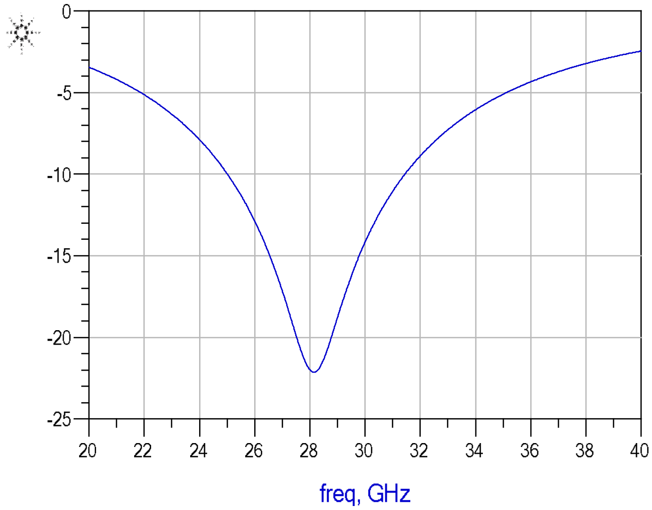

Figure 6: Reflection coefficient S11 of tank circuit with capacitors.

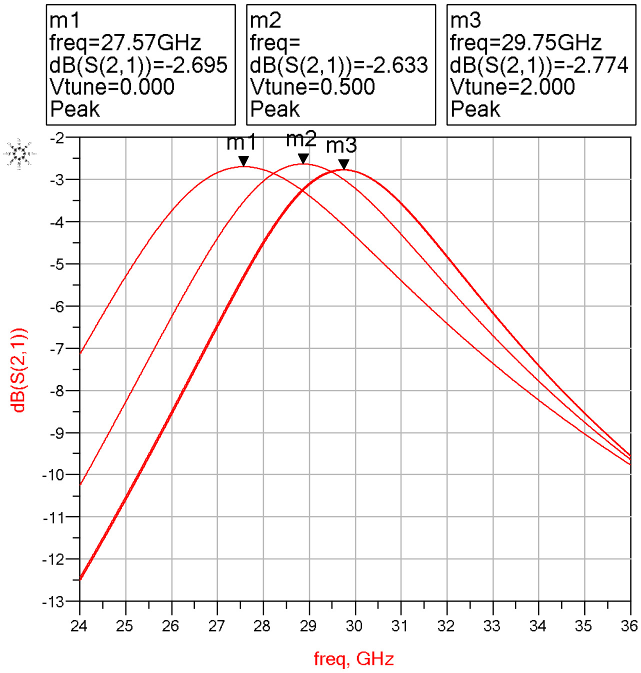

Figure 7: Transmission coefficient S21 of the tank circuit using single-ended varactors configuration

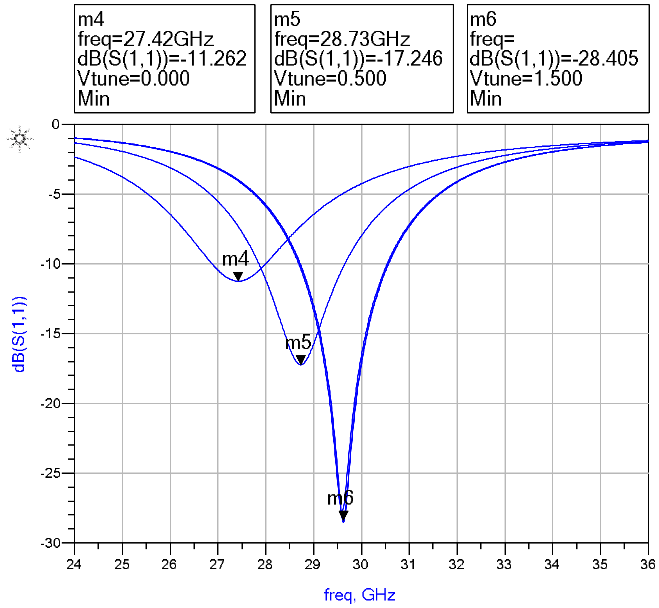

Figure 8: Reflection coefficient S11 of the tank circuit using single-ended varactors configuration

2.3 Band pass filter

To improve the rejection of unwanted harmonics as well as the DC component coming from the bias sources of our circuit, we have added a simple band pass filter (Figure 9) at the output of our VCO circuit. The filter is composed of a C3 capacitor and an L2 inductance, its bandwidth is around the oscillation frequency of our VCO, i.e. around 28 GHz (Figure 10).

Figure 9: Bandpass filter circuit configuration

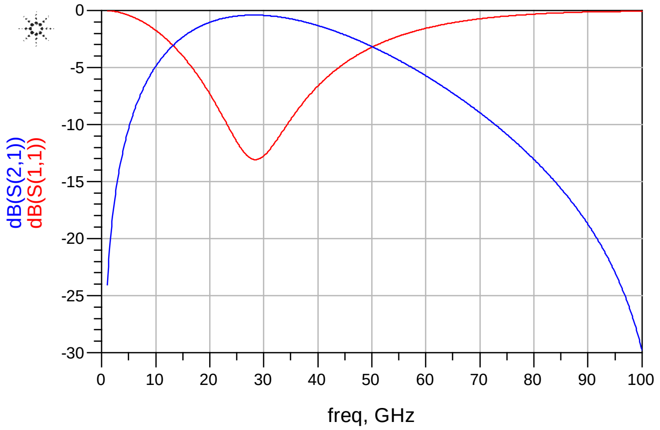

Figure 10: Transmission coefficient S21 and Reflection coefficient S11 of the bandpass filter

2.4 VCO Circuit

The VCO final circuit designed is shown in Figure 11. The final circuit consists of a GaAs pHEMT transistor with a gate length of 0.15 µm and a width of 40 µm and their bias elements, the tank circuit composed of three passive components, and the band-pass filter at the output of the VCO in order to reject the DC component as well as the unwanted harmonics.

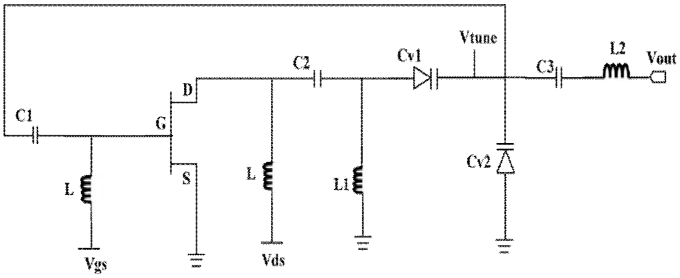

Figure 11: Colpitts VCO final circuit

The VCO circuit is basically designed using PH15 process elements (from UMS foundry) which contain parasites and imperfections. Hence, their behavior is very close to reality.

2.5 VCO Layout

The layout of the VCO circuit is shown in Figure 12. The total area occupied by this layout is 0.25 mm^2, with a length of 0.535 mm and a width of 0.475 mm. This surface includes the VCO with RF pad, the tuning voltage pad and the two bias pads as well as the bandpass filter.

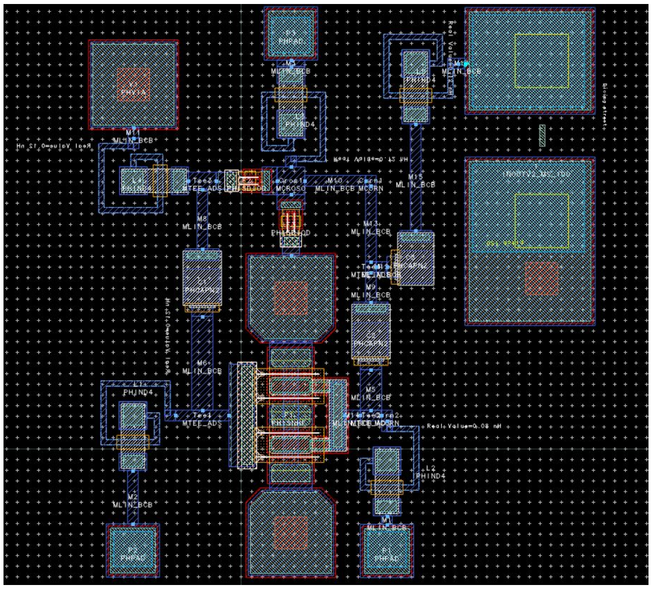

Figure 12: Layout VCO

2.6 VCO Simulation

In order to verify the VCO performance in terms of output power, oscillation frequency, tuning range and phase noise. A set of simulations are performed in HARMONIC BALANCE simulator using ADS software from Agilent.

The Figure 13 shows the output signal curve Vout for a value of Vtune = 2.9 V, it is a quasi-sinusoidal signal of oscillation frequency of 28.02 GHz.

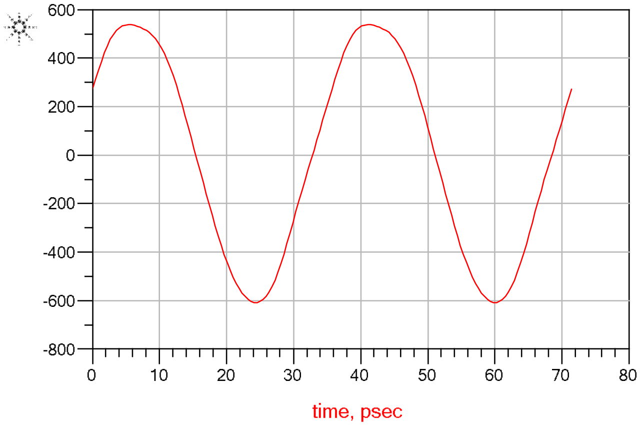

Figure 13: Temporal variation of the output signal for Vtune= 2.9 V

From Figure 14 we can deduce that at 28.02 GHz, the power of the fundamental harmonic is about 5.253 dBm, while the rejection of the second harmonic is about 25.682 dB. Therefore, the VCO has a good rejection level of unwanted harmonics.

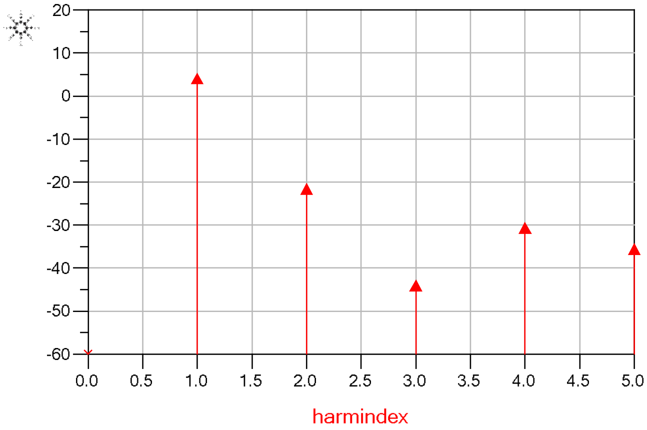

Figure 14: Output power level of the fundamental and harmonics 2, 3, 4 and 5 for Vtune= 2.9 V

On the other hand, the variation of the tuning voltage Vtune causes the variation of the oscillation frequency. Figure 15 shows the variation of the oscillation frequency as a function of the tuning voltage. The graph has a good linearity almost over the entire bandwidth of the VCO. The oscillation frequency varies between 27.08 GHz and 28.85 GHz for a variation of Vtune from 0 to 10.5 V, corresponds to a bandwidth of 1.77 GHz.

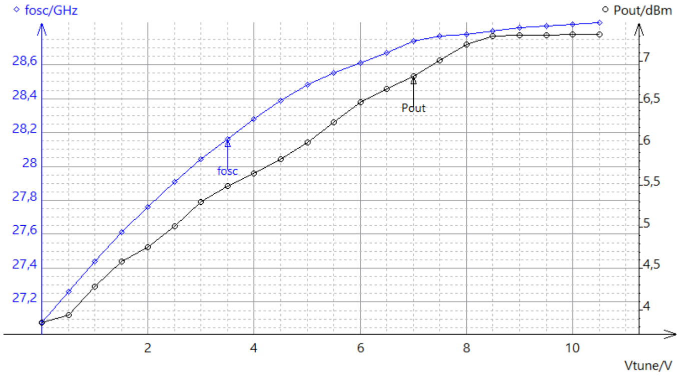

Figure 15: Variation of the oscillation frequency and the output signal power versus tuning voltage Vtune

The power consumption is very critical [13]. Therefore, the power consumption of our VCO Pdisp (Pdisp: Power dissipation) varies from 73 mW for Vtune = 0 V to 118 mW for Vtune = 10 V.

Phase noise is a critical feature for verifying the performance of a VCO [14]. The simulation shows that at the 28.02 GHz, the phase noise is about -40.24 dBc / Hz and -100.9 dBc / Hz @ 1 KHz and 1 MHz respectively of the carrier (Figure 16).

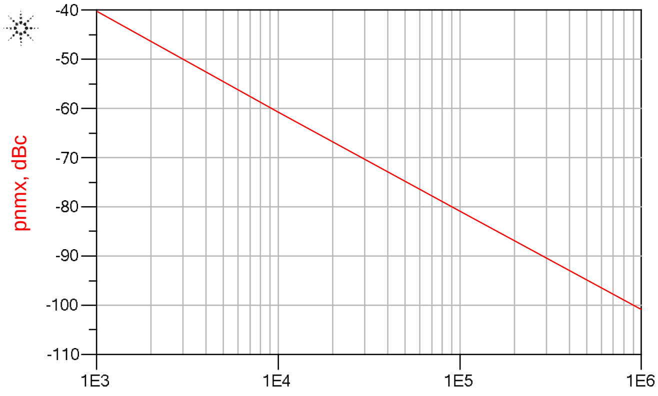

Figure 16: Single sideband phase noise for Vtune=2.9 V

Another parameter for evaluating the performance of a VCO is the FoM (Figure of Merit), it is determined by the following equation [7], [15]:

$$\mathrm{FoM} = L(f_0, \Delta f) + 10\log(P_{disp}) - 20\log\left(\frac{f_0}{\Delta f}\right) \quad (1)$$

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

Table 1 summaries the different oscillators performances produced in different technologies, with varied architectures and varying oscillation frequencies. It shown that our circuit performances are comparable to other structures; an acceptable phase noise level, relatively high output power and a good figure of merit (FoM). so, this simple structure has given promising results, but these results are only a first step to designing a high-performing VCO, and improving these results, by trying balanced structures, is the objective of our upcoming work.

Table 1: Performance comparison of different VCOs.

Ref.	**Oscillation frequency (GHz)**	**Output power (dBm)**	**Phase noise (dBc/Hz) at 1MHz**	**FoM (dBc/Hz)**	**Technologie**
[9]	27.55	1.87	-109	-	0.15 um GaAs pHEMT
[10]	28.3	11.8	-102	-	0.15 um GaAs pHEMT
[11]	25.6	3	-101.9	-176.7	0.13 um CMOS
[11]	39.6	-6.6	-94.8	-172.1	0.13 um CMOS
This work	28.02	5	-100.9	-180.37	0.15 um GaAs pHEMT

3 CONCLUSION

In this paper, we have presented and designed a Colpitts VCO for 5G mm-wave band applications. The designed VCO presents a wide tuning range that exceeds 6% of central frequency. The obtained results show that the Colpitts VCO achieves an output power up to 5 dBm and consumes 76 mW. A phase noise about -100.9 dBc/Hz @ 1MHz and a good figure of merit (FOM) of -180.37 dBc / Hz is achieved by this VCO. In order to improve the performance of this VCO, especially in term of phase noise, a balanced structure will be studied.

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