A Cross-Coupled Ka-Band GaAs-pHEMT Based VCO

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Abstract. A cross-coupled GaAs pseudomorphic high electron mobility transistor (pHEMT) based Ka-band voltage-controlled oscillator (VCO) is reported in this work, by using commercial OMMIC 0.13 μm depletion-mode power pHEMT (D01PH) process. The simulation of the proposed VCO demonstrates an operating frequency range from 28.54 GHz to 32.44 GHz with the tuning range of 12.8%, an output power from 15.2 dBm to 15.9 dBm, total dc power consumption of 124 mW and power efficiency from 27.2% to 31.9%. The simulated phase noise is from -105.7 dBc/Hz to -100.4 dBc/Hz at 1 MHz offset frequency and the figure-of-merit (FoM) is -207.4 dBc/Hz at the center frequency of 30.3 GHz.

Introduction

In the modern communication transceiver system, a voltage-controlled oscillator (VCO) used as local oscillator (LO) plays a significant role in signal frequency conversion between the radio frequency (RF) band and the baseband. At high operating frequencies in millimeter-wave range, the VCOs with low power consumption, wide frequency tuning range, low phase noise and large output power still remain as a challenging design task.

Although the MOSFET scaling technique has brought the transient frequency of the silicon-based transistor up to millimeter-wave region, the high electron mobility as well as the high power characteristics of pseudomorphic high electron mobility transistor (pHEMT) technologies still allows them to compete with silicon-based applications in the area of low noise amplifier (LNA), mixer and power amplifier (PA). In general, pHEMT is not suitable for VCO design due to its relatively high flicker noise [1]. However, extensive research on pHEMT based VCOs are still carried out during the last decades in the view of system integration [1-7]. In [1], a GaAs based differential Colpitts VCO operating at 7.5 GHz and used in a 60 GHz transceiver system is presented. The design in [2] exhibits a single-ended Ka-band VCO by using a common-source series feedback to generate the negative resistance. In addition, by adopting the enhancement/depletion mode pHEMT process, a differential VCO with wide tuning range as well as low phase noise can be implemented with two common-gate transistors [3]. Moreover, the cross-couple based sub-harmonic oscillator reported in [4] can achieve operating frequencies at V-band.

In this work, a cross-coupled VCO operating at Ka-band is proposed based on 0.13μm GaAs pHEMT by using OMMIC D01PH process. Sections II presents the pHEMT technology related to the VCO design. Section III describes the proposed VCO circuit and also analyzes the negative conductance issue. In section IV, the simulation results are shown and the comparison work is made. Section V summaries the conclusion of this paper.

pHEMT Technology

The design kit used in this work is commercial D01PH process from OMMIC which has a 0.13µm GaAs depletion mode pHEMT. The pHEMT threshold voltage as well as the allowed voltage range at the gate-source terminals serves as the fundamental parameters which are highly related to the VCO design. In this process, the transistor threshold voltage Vth is -0.85 V and the allowed gate-source voltage can be operated from -4 V to 0.9 V.

VCO Circuit Design

Fig. 1 illustrates the schematic of the proposed VCO design without the buffer. The transistors M1 and M2 together with the capacitors C1 form the cross-coupled pairs to compensate the tank loss. Compared to the conventional cross-coupled topology, the fixed capacitor C1 is added to provide the ac-coupling between the two transistors. The pHEMT normally conducts a large drain current even with a small gate voltage, resulting in an output voltage swing that usually exceeds the maximum allowed value of gate-source voltage. Therefore, by properly choosing the value of C1 for ac-coupling as well as the dc biasing inductor L1, the gate-source voltage of the pHEMTs can be kept within the safe operating region between -4 V to 0.9 V.

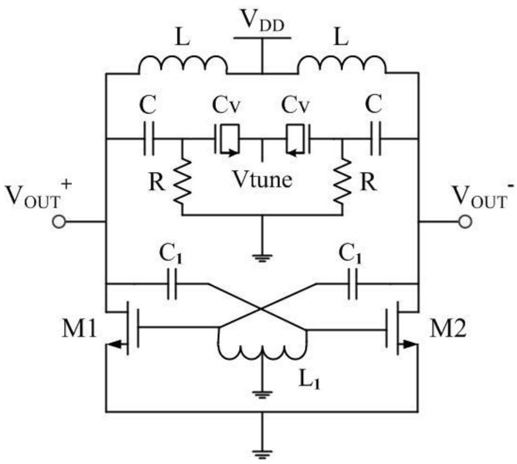

Figure 1. Schematic of proposed VCO design

The negative resistance (NR) provided by this cross-coupled pair can be calculated as,

$$NR = -\frac{2g_m}{(2\pi f)^2 C_1^{\,2} + g_m^{\,2}} \tag{1}$$

where, g_m is the transconductance of the pHEMT, f is the VCO operating frequency. After tuning the VCO operating frequency to 30 GHz, the relationship between NR and g_m is plotted in Fig. 2 (a). While Fig. 2 (b) shows the pHEMT transconductance value under different bias conditions with the minimum transistor width.

It can be seen from Fig. 2 (b) that the minimum g_m value of pHEMT is larger than 1 mS, therefore the negative resistance increases with g_m value within its allowed operating region. In order to ensure the robust start-up condition at the interested frequency , the g_m value is selected at around 10 mS in this work. In addtion, the gate-source voltage corresponding to a g_m of 10 mS is about 0V according to Fig. 2 (b). By biasing the gate and source terminals of pHEMT to ground, the external bias voltage supplies can be eliminated, which further simplifies the VCO design. Moreover, the removal of the biasing current source transistor could also help to reduce the phase noise contributed by the flicker noise of the tail current source transistor [8].

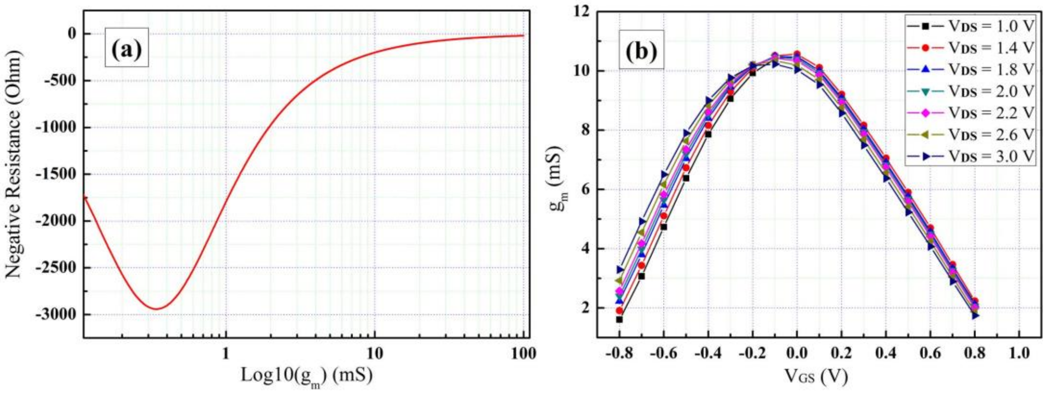

Figure 2. (a) Simulated relationship between NR and g_m (b) g_m value under different bias conditions.

To determine the supply voltage, the transistor I-V curve is depicted in Fig. 3. As the output voltage varies, the pHEMT should operate in the saturation region, where V_{DS} is larger than (V_{GS}-V_{th}). Moreover, the VCO phase noise would degrade if the transistors enter into the triode region, where V_{DS} is less than (V_{GS}-V_{th}). In this work, the supply voltage is selected as 2 V for an output swing of about 2.5 V.

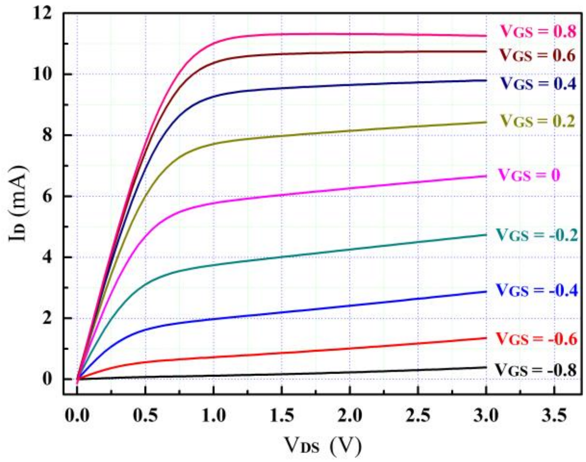

Figure 3. Simulated I-V curve of the pHEMT

Besides, fixed capacitors C are inserted in series with the varactors Cv to prevent the varactors from break-down. The resonant frequency of the tank is designed at 30 GHz and the varactors tuning voltage is from 0 V to 1.2 V.

Simulation Results

The proposed VCO is simulated by using OMMIC D01PH process. It can be observed from Fig. 4 that as the tuning voltage increases from 0 V to 1.2 V, the VCO oscillates from 28.54 GHz to 32.44 GHz with good linearity. The frequency tuning range (FTR) is 12.8%.

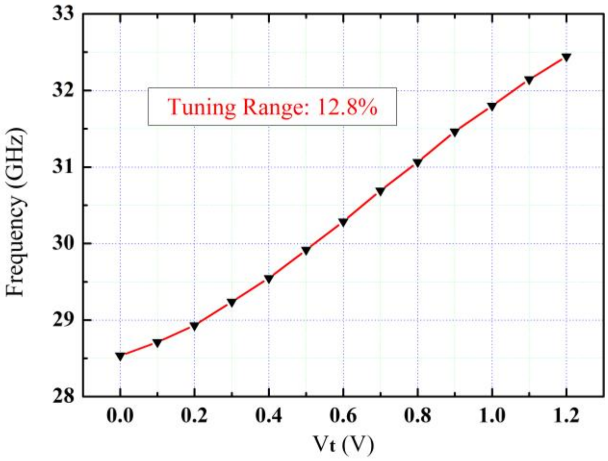

Figure 4. Simulated results of frequency tuning range

Fig. 5 summaries the proposed VCO's simulated results of phase noise, output power (P_{out}), power consumption (P_{dc}) and power efficiency. The power efficiency is defined as P_{out}/P_{dc}. It is found from the Fig. 5 (a) that the VCO demonstrates a phase noise from -105.7 dBc/Hz to -100.4 dBc/Hz at 1 MHz offset frequency. According to [9], the noise figure of pHEMT increases as the transconductance value decreases. Since in this design, the g_m value is selected small enough to ensure the start-up condition, the noise of pHEMT can be regarded as a significant contribution to the overall phase noise. Therefore, there exists a trade-off between the VCO's oscillation stability and the phase noise performance.

The output power achieved due to the large drain current is from 15.2 dBm to 15.9 dBm. Moreover, according to the Leeson's phase noise model [10], large output power can help to reduce the VCO phase noise. Moreover, in Fig. 5 (b), with the supply voltage of 2 V, the proposed VCO has a dc power consumption of 124 mW and the power efficiency variation is between 27.2% and 31.9%. From the pHEMT I-V curve shown in Fig. 3, it can be found that the reason behind such relatively high efficiency is the high output power which is caused by the large drain current.

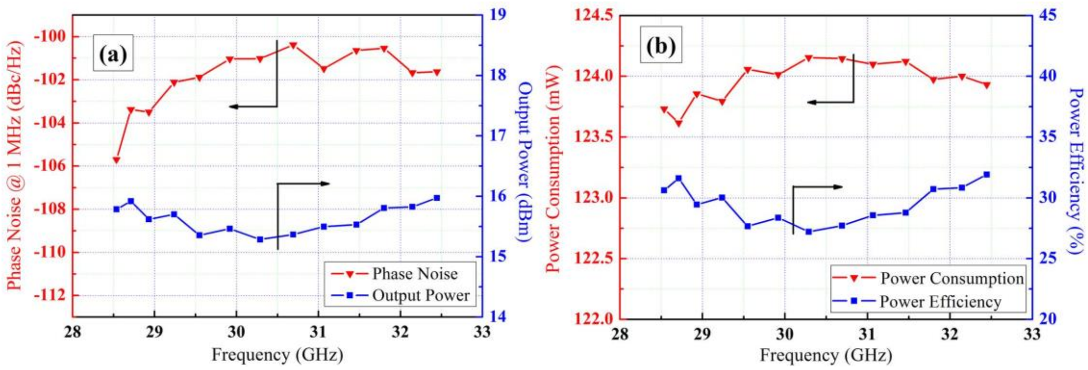

Figure 5. Simulated results of (a) phase noise and output power (b) power consumption and power efficiency

The figure-of-merit (FoM) of the proposed design is -207.4 dBc/Hz at center frequency of 30.3 GHz and the performance comparison with the previous work is summarized in Table 1. The FoM is defined as in [11]:

$$FoM = PN - 20\log(\frac{f_c}{\Delta f} \times \frac{FTR}{10}) + 10\log(\frac{P_{dc}}{P_{out}}) \qquad (2)$$

where PN is the phase noise in dBc/Hz, Δf is the offset frequency and f_c is the VCO center frequency, FTR is the frequency tuning range, P_{dc} is the dc power consumption in mW and P_{out} is the output power in mW.

Table 1. Comparison of performance with previous work

	Technology	f_c (GHz)	FTR (%)	Pout (dBm)	Pdc (mW)	Power Efficiency (%)	PN@1MHz (dBc/Hz)	FoM (dBc/Hz)
[2]*	0.15μm Enhancement pHEMT***	28.3	13.4	11.8	80	18.9	-102	-204.1
[3]	0.5μm E/D pHEMT	23.2	38	5	37	8.5	-109	-220.0
[6]*	0.2μm Enhancement pHEMT	29.1	0	0.2	15	7.0	-94	-
[7]*	0.15μm Enhancement pHEMT	37.8	1.2	6.3	129.9	3.3	-112.3	-154.4
This Work**	**0.13μm Depletion pHEMT**	**30.3**	**12.8**	**15.3**	**124.2**	**27.2**	**-101**	**-207.4**

*-The design is a single-ended topology.
**- The data are simulation results.
***- It is a laboratory process.

Conclusion

In this work, a Ka-band GaAs pHEMT based VCO is presented. The proposed VCO exhibits an operating frequency range from 28.54 GHz to 32.44 GHz with the tuning range of 12.8%, an output power from 15.2 dBm to 15.9 dBm, total dc power consumption of 124 mW and high efficiency from 27.2% to 31.9%. Besides, the simulated phase noise is from -105.7 dBc/Hz to -100.4 dBc/Hz at 1 MHz offset frequency and the figure-of-merit (FoM) is -207.4 dBc/Hz at the center frequency of 30.3 GHz.

References

[1] H. Zirath, T. Masuda, R. Kozhuharov, and M. Ferndahl, "Development of 60-GHz front-end circuits for a high-data-rate communication system," IEEE J. Solid-State Circuits, vol. 39, pp. 1640-1649, 2004.

[2] B. Piernas, K. Nishikawa, T. Nakagawa, and K. Araki, "A compact and low-phase-noise Ka-band pHEMT-based VCO," IEEE Trans. Microw. Theory Tech., vol. 51, pp. 778-783, 2003.

[3] H.-Y. Chang, Y.-S. Wu, and Y.-C. Wang, "A 38% tuning bandwidth low phase noise differential voltage controlled oscillator using a 0.5 m E/D-PHEMT process," IEEE Microw. Wireless Compon. Lett., vol. 19, pp. 467-469, 2009.

[4] F.-H. Huang, C.-K. Lin, and Y.-J. Chan, "V-band GaAs pHEMT cross-coupled sub-harmonic oscillator," IEEE Microw. Wireless Compon. Lett., vol. 16, pp. 473-475, 2006.

[5] J. Jeong and Y. Kwon, "A fully integrated V-band PLL MMIC using 0.15-μm GaAs pHEMT technology," IEEE J. Solid-State Circuits, vol. 41, pp. 1042-1050, 2006.

[6] Y. Chen, K. Mouthaan, and F. Lin, "Design of X-band and Ka-band Colpitts oscillators using a parasitic cancellation technique," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 57, pp. 1817-1828, 2010.

[7] C.-L. Chang, C.-H. Tseng, and H.-Y. Chang, "A New Monolithic Ka-Band Filter-Based Voltage-Controlled Oscillator Using 0.15 m GaAs pHEMT Technology," IEEE Microw. Wireless Compon. Lett., vol. 24, pp. 111-113, 2014.

[8] E. Hegazi, H. Sjöland, and A. Abidi, "A filtering technique to lower LC oscillator phase noise," IEEE J. Solid-State Circuits, vol. 36, pp. 1921-1930, 2001.

[9] R. L. Ross, S. P. Svensson, and P. Lugli, Pseudomorphic HEMT technology and applications, vol. 309: Springer Science & Business Media, 2012.

[10] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," Proc. IEEE, pp. 329-330, 1966.

[11] N. Mahalingam, K. Ma, K. S. Yeo, and W. M. Lim, "-band High-PAE Wide-Tuning-Range VCO Using Triple-Coupled Tanks," IEEE Trans. Circuits Syst. II: Express Briefs, vol. 60, pp. 736-740, 2013.