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High rejection self-oscillating up-conversion mixer for fifth-generation communications

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ABSTRACT

This paper presents the design of a pseudomorphic high electron mobility transistor (pHEMT) self-oscillating mixer (SOM) for millimeter wave wireless communication systems. The 180° out-of-phase technique is chosen to both improve the desired lower sideband (LSB) signal and to achieve a satisfactory rejection of the unwanted signals (LO, USB and IF). This SOM is designed on the PH15 process of UMS foundry which is based on 0.15 µm GaAs pHEMT. The signal is up-converted from 2 GHz-IF frequency to 26 GHz-LSB frequency, using an autogenerated 28 GHz-LO signal. Simulations were performed using the advanced design system (ADS) workflow. They show 6.4 dB conversion gain and a signal rejection rate of 29.7 dB for the unwanted USB signal. the chip size is 3.6 mm^2.

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1. INTRODUCTION

In these times of pandemic caused by coronavirus disease 2019 (COVID-19), communities' way of life has been changed [1]. During social distancing, connectivity allows us to keep informed, continue working and maintain our mental and physical health balance [2]. As current communication systems cannot meet our needs, developing new communication systems for fifth-generation (5G) has become a great necessity [3]–[5]. And to achieve the performance promised by this new generation, new design approaches and semiconductor technologies are being adopted.

Radio frequency (RF) transceivers must be as compact as possible to effectively reduce power consumption in 5G millimeter-wave systems [6]. High integration also leads to a tangible reduction in the costs of semiconductor technologies [7], [8]. In this context, the research presented in Winkler *et al.* [8] and Lee *et al.* [9] is carried out. They propose the design of self-oscillating mixer (SOM) circuit, which combines the harmonic generation, and the frequency conversion functions in a single RF chip.

Sawada and Imai [10] propose the design of an optoelectronic self-oscillating using a heterojunction bipolar transistor (HBT). The designed circuit performs the up-conversion of the 1 GHz-IF signal to a 10.6 GHz-RF signal, using a 9.6 GHz LO. On the other hand, low-power injection-locked zero-IF SOM for 40 GHz-RF frequency is developed in Burasa *et al.* [11]. The experimental results exhibit a conversion gain of -30 dB under -38 dBm input power. An up-conversion SOM for 77 GHz applications is presented in the paper [9]. This circuit has a high conversion gain of 3.87 dB. However, both lower sideband (LSB) and universal serial bus (USB) signals have the same output power, meaning no image frequency rejection exists. In [8], an integrated receiver using a balanced SOM for 5.8 GHz-RF frequency is presented.

The purpose of this paper is to analyze and design a SOM circuit. It consists of a low-phase noise voltage controlled oscillator (VCO) and a double-balanced mixer with high LO and USB signal rejections. The mixer circuit, introducing couplers and phase-shifting lines, allows a conversion gain of 6.385 dB. Thus, among published SOMs, this work exhibits the best GC around 26 GHz, with a high rejection of unwanted harmonics, making it more attractive for 5G wireless systems.

This paper is organized as follows. The pseudomorphic high electron mobility transistor (pHEMT) is introduced in section 2. In section 3, the double-balanced mixer architecture is studied and designed. While in section 4, the designed SOM circuit and its simulation results are discussed. Then a conclusion is reported in section 5.

2. PHEMT TECHNOLOGY

There is explosive growth in mobile traffic demand, broadband transmissions and improved system performances are required [12]–[14]. Circuit designers are then focused on the device technology [15]: transistors with high transducer gain and low noise are privileged in our study. GaAs pHEMTs are nowadays the basis for monolithic microwave integrated circuits (MMIC) circuits [16]. Thanks to the development of these SC devices, researchers have succeeded in designing very efficient communication systems for the next generation 5G [17]–[24].

The circuit presented in this paper is designed with a 0.15 µm GaAs pHEMT transistor from the UMS foundry. A cutoff frequency characterizes this device f_T of 110 GHz, a maximum transconductance g_m of 640 (mS)/mm, a maximum Ids current of 220 mA/mm, a pinch-off voltage V_{pinch} of -0.7 V, and a gate-drain breakdown voltage of more than 4.5 V [25]. The transistor gate length is 0.15 µm, associated with a gate width of 30 µm. The pHEMT structure is shown in Figure 1. The typical electrical parameters of the used pHEMT are summarized in Table 1.

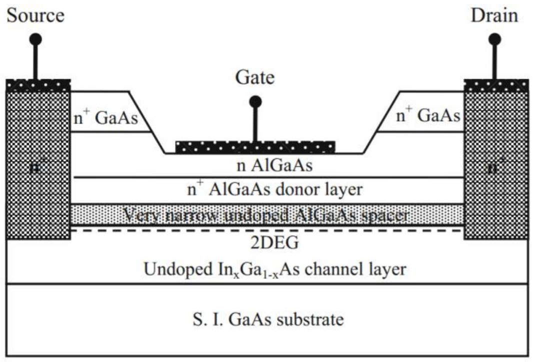

Figure 1. Structure of the pHEMT Technology [26]

Table 1. Typical electrical parameters of the pHEMT technology

Parameters	Values
Power density	300 mW/mm
Gate length	0.15 µm
Idssat	220 mA/mm
V_{BDS}	> 4.5 V
Cutoff frequency	110 GHz
pinch-off voltage	- 0.7 V
Gm max	640 ms/mm
Noise/Gain	1.9/6 dB @ 60 GHz

3. DOUBLE BALANCED MIXER DESIGN

3.1. Proposed architecture

LO, IF, and USB rejections are performed by filtering, in the case of a carrier frequency in a few hundred MHz, or by the method of phase opposition, especially for a carrier frequency in the millimeter-wave band, where filtering becomes difficult because of the impedance matching difference at the different ports of a balanced structure and in a large bandwidth. Two input signals that are phase opposite and with the same amplitude cancel each other at the output when added.

As shown in Figure 2, the signals LO1, LO2, LO3, and LO4, successively shifted in phase by 90°, drive the four transistor gates of four cascode cells acting as mixer cells. The other four transistor gates are excited by the signals IF1, IF2, IF3, and IF4, successively phase shifted by 90°, to. Table 2 presents the phase balance of the main signals present at each output of the four cascode cells, corresponding to transistor drains. Vector addition of the signals RF1, RF2, RF3 and RF4, leads to eliminating the signals in the opposite phase, i.e., IF, LO, and USB, while it amplifies the LSB signal in the millimeter-waves for 5G.

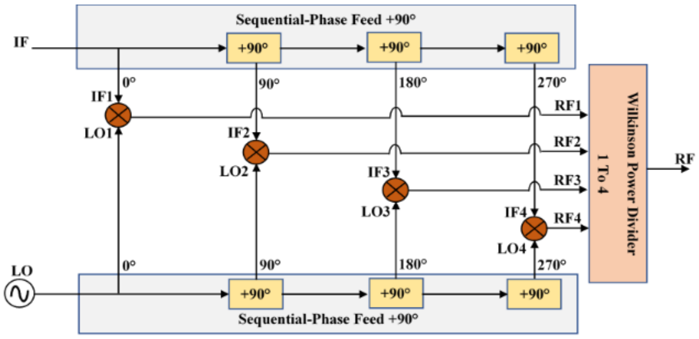

Figure 2. Synoptic diagram of the proposed double balanced mixer

Table 2. Phase balance of the signals present on the drains of the four cascode cells

Signal / Output	FI	OL	LSB	USB
RF1	0°	0°	0°	0°
RF2	90°	90°	0°	180°
RF3	180°	180°	0°	0°
RF4	270°	270°	0°	180°

3.2. Post-layout simulations

The mixer presented in this paper can generate RF signal in the first millimeter-wave band assigned to 5G by the International Telecommunication Union (from 24.25 to 27.5 GHz). Figure 3 shows the conversion gain CG as a function of LO frequency, varying from 26.25 to 29.5 GHz. CG is positive and higher than 2 dB. In addition, to verify the harmonic rejection at IF, LO, and USB frequencies, its output power spectrum is presented in Figure 4. In the LO frequency bandwidth, the mixer has a good level of rejection. The rejection of the USB signal is maximum and about 25 dB for a LO frequency of 28.25 GHz. And the rejection of the IF signal exceeds 30 dB in the LO bandwidth. At 27.4 GHz-LO frequency, the LO rejection reaches its maximum value of 15 dB at the mixer output, and it decreases for the other frequencies, higher than 4 dB for the worst case.

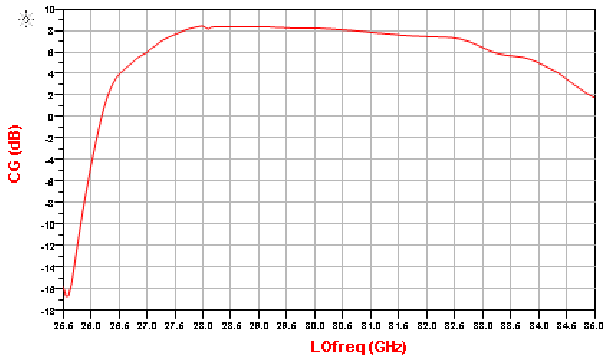

Figure 3. Variation of the conversion gain versus LO frequency (for IF_power=-11.5 dBm and LO_power=7.5 dBm and IF_freq=2 GHz)

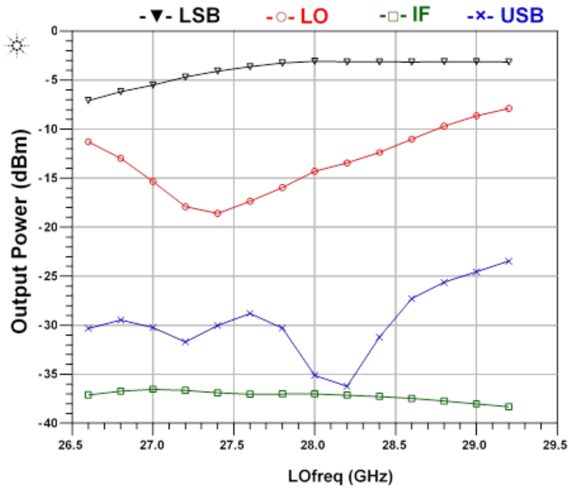

Figure 4. Variation of IF, LO, USB and LSB power versus LO frequency (for IF_power=-11.5 dBm and LO_power=7.5 dBm and IF_freq=2 GHz)

The same frequency analysis was performed, varying the IF frequency. Figure 5 shows the CG curve versus IF frequency. It shows a conversion gain ripple of 3 dB for an IF frequency variation of 100 MHz (between 1.95 and 2.05 GHz). The output power spectrum is presented in Figure 6, showing a good rejection all over the IF frequency band: IF signal rejection is higher than 30 dB, the maximum USB rejection is 22 dB, whereas its minimum value is 5 dB, and finally, the LO rejection varies from 8 to 32 dB.

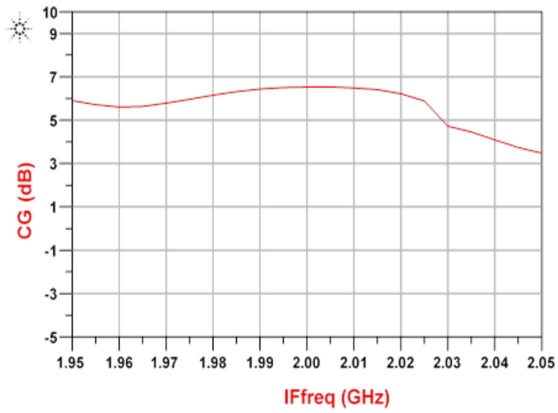

Figure 5. Variation of the conversion gain versus IF frequency (for IF_power=-11.5 dBm and LO_power=7.5 dBm and LO_freq=27 GHz)

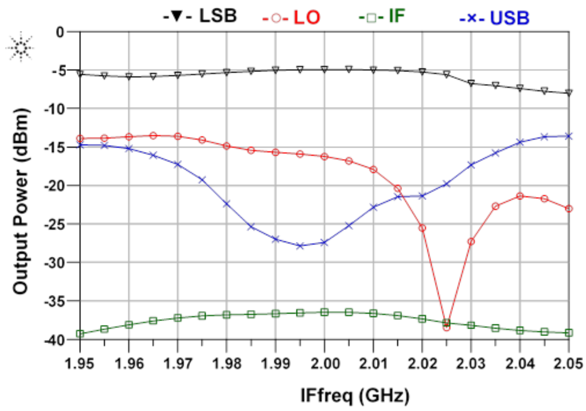

Figure 6. Variation of IF, LO, USB and LSB power versus IF frequency (for IF_power=-11.5 dBm and LO_power=7.5 dBm and LO_freq=27 GHz)

4. SELF-OSCILLATING MIXER DESIGN

4.1. Layout design

To ensure the LO signal generation and the IF signal conversion inside the same circuit, we integrate the mixer circuit into a VCO. Figure 7 illustrates the process of this integration. Figure 7(a) shows the LO and Mixer blocks before the integration and Figure 7(b) shows the resulting SOM block. The VCO circuit has been presented and studied in detail in the paper [25]. It is a perfectly symmetrical circuit based on "pHEMT varactor" to vary the capacitance value of the resonator and thus control the oscillation frequency.

The layout of the SOM circuit is presented in Figure 8. Its area dimension is 3.6 mm^2. It consists of the doubly balanced mixer (Part I), the VCO whose oscillation frequency is controlled by the control voltage Vtune (Part II), and the impedance matching circuit (Part III). The matching circuits are provided to achieve impedance matching between the output of the VCO and the LO port of the mixer.

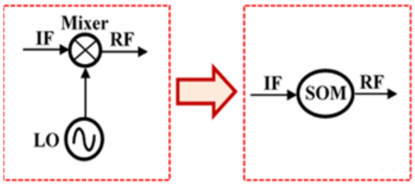

Figure 7. LO and Mixer blocks (a) before integration and (b) after integration

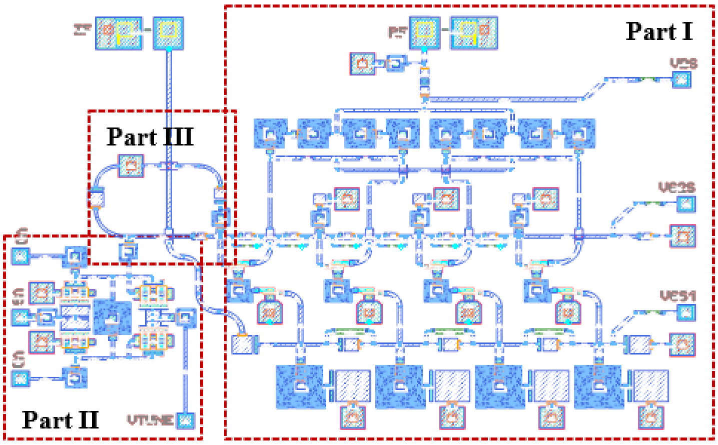

Figure 8. 5G mm-wave SOM layout

4.2. Post-layout simulations

The conversion gain of the SOM circuit is presented in Figure 9. For an IF power of -15.4 dBm, the CG equals 6.385 dB. On the other hand, the variation of the LSB output power is presented in Figure 10. For an IF power of -12.5 dBm, it is equal to -7.394 dBm.

To verify the rejection of IF, LO and USB harmonics, the Figure 11 presente the power spectrum at the SOM output. In the LO frequency bandwidth, the SOM has a good level of rejection. The rejection of LO signal is better than 8 dB in the entire bandwidth. In addition, the rejection of IF signal exceeds 22 dB. And the USB rejection reaches its maximum value of 29.7 dB for a voltage Vtune lower than 1 V. Whereas it is about 20 dB for the other values of Vtune. Finally, the effect of technological dispersion is evaluated. Figure 12 shows the Monte Carlo analysis of IF, LO, USB and LSB signals. This analysis is performed at 100 iterations.

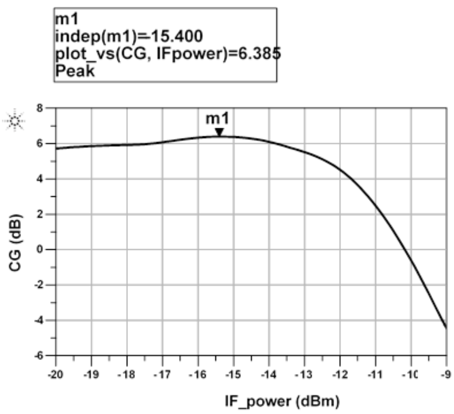

Figure 9. Variation of the conversion gain versus IF power (for IF_frequ=2 GHz, and LO_power=7.5 dBm and Vtune=0.8 V)

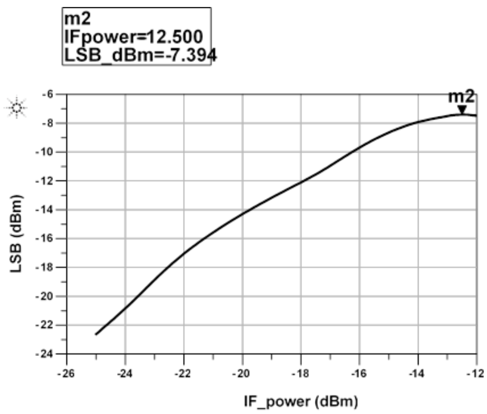

Figure 10. LSB power versus IF power (for IF_frequ=2 GHz, and LO_power=7.5 dBm and vtune=0.8 V)

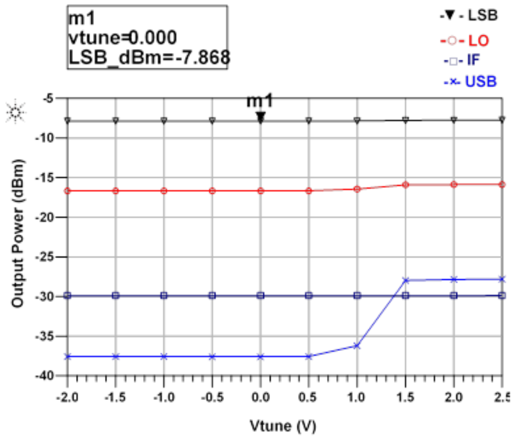

Figure 11. Variation of IF, LO, USB and LSB power versus vtune (for IF_power=-11.5 dBm and IFfreq=2 GHz)

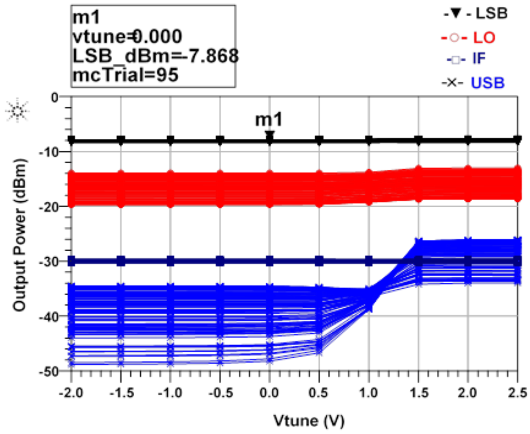

Figure 12. Monte Carlo analysis of IF, LO, USB and LSB power (for IF_power=-11.5 dBm and IFfreq=2 GHz)

Table 3 summarizes the main characteristic parameters of SOMs published in the literature. The conversion gain of our SOM is 6.385 dB which is greater than the one of the structures studied in [9], [11], [27], [28]. In addition, our circuit allows high rejection of unwanted harmonics at its output. This allows to eliminate IF, LO and USB harmonics without the use of a bandpass filter. Therefore, this circuit meets the requirements of the new communication systems.

Table 3. Performance summary and comparison of SOMs

	Technology	RF freq (GHz)	IF freq (GHz)	CG (dB)	Chip size (mm^2)
This work	0.15 µm GaAs pHEMT	26	2	6.385	3.6
[11]	65 nm CMOS	40	NA	-30	0.24
[27]	0.13 µm CMOS	30	0.5	-30	NA
[9]	0.10 µm GaAs pHEMT	38.5/77.38	0.3	3.87	5.98
[28]	0.20 µm GaAs pHEMT	10	1.57	-19	NA

5. CONCLUSION

New design approaches are needed to achieve the performance promised by 5G, which relies on millimeter wave frequencies. This paper shows the efficiency and feasibility of an up-conversion SOM with IF, LO, and USB rejection for 5G millimeter-wave systems. The circuit enables up-conversion of a 2 GHz IF signal to a 26 GHz LSB signal. The circuit has a conversion gain of 6.385 dB. The rejection of the LO signal is better than 8 dB in the entire bandwidth. In addition, the rejection of IF signal exceeds 22 dB. And the USB rejection reaches a maximum value of 29.7 dB. The circuit layout occupies an area of 3.6 mm^2; it is designed based on 0.15 µm GaAs pHEMT of PH15 process from UMS foundry. This circuit will constitute the core of a fully integrated communication system that we intend to design based on pHEMT Technology.

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