A Ku-Band SSB Subharmonically Pumped Mixer designed using a 100nm GaN-on-Si process

M. San-Miguel-Montesdeoca, D. Mayor-Duarte, S. Mateos-Angulo, S.L. Khemchandani and J. del Pino
Institute for Applied Microelectronics (IUMA), Departamento de Ingeniería Electrónica y Automática
Universidad de Las Palmas de Gran Canaria
Las Palmas de Gran Canaria, Spain

***Abstract*—This paper presents a Ku-band single-sideband mixer (SSB). The design is based on subharmonically pumped IQ mixers (SHP), designed using a GaN on Silicon process of the French foundry OMMIC. The mixer uses an in-phase Wilkinson divider for the LO, two SHP mixers implemented using antiparallel diode pairs (APDPs) and a 90° combiner for the RF signal. To minimise the area of the circuits, the quasi-lumped technique was applied to the design. The mixer was designed to provide an output RF frequency range between 13.75-14.5 GHz. The mixer occupies an area of 2268µm x 1408µm, with a conversion loss of 21.18 dB and a sideband rejection of 29.32dBc.**

Index terms: IQ mixer, Ku-band, MMIC, GaN, OMMIC, SSB mixers, SHP mixers, quasi-lumped stubs, layout.

I. INTRODUCTION

In the last few years, the demand for communication systems that operate at higher frequency bands and provide greater speeds has increased exponentially. To cater to these requirements, communication systems must evolve and become more complex, while guaranteeing a good power efficiency/cost ratio. Gallium nitride (GaN) processes are the key to designing circuits that meet these demands. A good candidate is the D0XGH process of the French supplier OMMIC. This recently introduced (September 2017) GaN on Si process offers 6-inch wafers that can work at high frequencies with a high output power.

To test the viability of this process for Ku-band applications, a subharmonically pumped mixer (SHP mixer) was designed to provide an output signal frequency range of 13.75-14.5 GHz. This IQ mixer is intended for its use in transmitter circuits in antennas that operate in the Ku band. The mixer uses antiparallel diode pairs (APDPs). This topology uses the second harmonic of the local oscillator (LO) frequency, which allows the use of an LO source operating at half the frequency required for the mixing without the need for a frequency multiplier. However, this topology requires the fundamental LO frequency to be supressed. In addition, APDPs do not require DC power to operate [1][2]. Single-sideband mixers (SSB mixers) can be an adequate solution for circuits that require a low conversion loss and a high image-rejection performance, although their dividers/ combiners must be extremely accurate in amplitude and phase. Conventional SSB mixers require an LO in-phase divider and two quadrature hybrids at the IF and RF ports [3]. Usually, the IF frequency is lower than the RF and LO, which forces the IF hybrid to be implemented externally, so the resulting SSB mixer monolithic microwave integrated circuit (MMIC) does not occupy a large area. The RF hybrid also occupies a large area, although its size can be reduced using several techniques at the cost of a bandwidth decrease [3]-[5].

In this paper, a SSB SHP IQ mixer MMIC is proposed and analysed. To reduce the area of the MMIC, the quasi-lumped technique has been applied. The design process of the mixer and the theory behind its operation are described in Section II. Section III covers the layout implementation of the MMIC and the achieved results of the mixer are shown in Section IV. Finally, some conclusions are given in Section V.

II. DESIGN OF THE SSB SHP MIXER

As it was mentioned previously, SSB mixers typically use an RF quadrature hybrid implemented with a branch-line hybrid as a divider/combiner, to reduce the total circuit area [6]. However, these hybrids only work in a narrow band, so their implementation is not recommended for wideband applications. On the contrary, Wilkinson dividers/combiners provide well-balanced signals in both amplitude and phase and with a low insertion loss for a wide bandwidth. Therefore, the use of Wilkinson dividers/combiners is recommended for these mixers [1].

The block diagram of the designed mixer is shown in Figure 1. As it can be seen in the figure, the IF frequency ranges from 1.5 to 2.7 GHz and the LO from 5.9 to 6.1 GHz. The mixer follows an approach that has been covered in several papers found in the literature ([2][7][8]), with an in-phase Wilkinson divider for the LO, two SHP mixers and a 90° combiner for the RF signal. In this structure, the IF signals are divided in the 90° external hybrid and fed into each mixer with a $\pi/2$ phase mismatch. The LO power is divided into two in-phase signals. The mixers generate the up-converted signals with a frequency of $2f_{LO}\pm f_{IF}$, which are then combined in the 90° combiner.

The SHP mixer was implemented using APDPs, as it was mentioned in the Introduction. The schematic for a SHP mixer is shown in Figure 2. As it can be seen, the mixer has a low-pass filter and a high-pass filter to isolate the IF and RF ports. In addition, the SHP mixer includes a $\lambda_{LO}/4$ short stub and a $\lambda_{LO}/4$ open stub. The $\lambda_{LO}/4$ short stub is intended to behave as an "open" circuit at f_{LO} and as a "short" circuit at f_{RF}. This way, there is no leakage of the RF signal towards the LO. Likewise, the $\lambda_{LO}/4$ open stub behaves as an "open" circuit for the f_{RF}, whereas it is seen as a "short" for the f_{LO}.

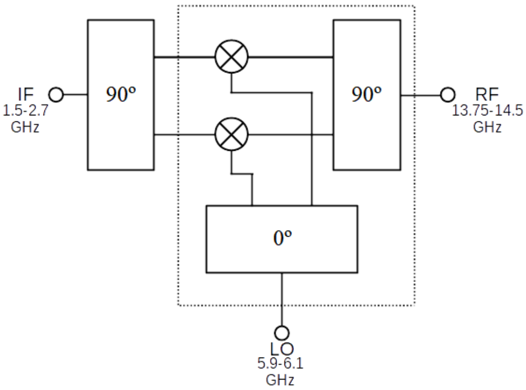

Figure 1. Block diagrams of the SSB SHP mixer.

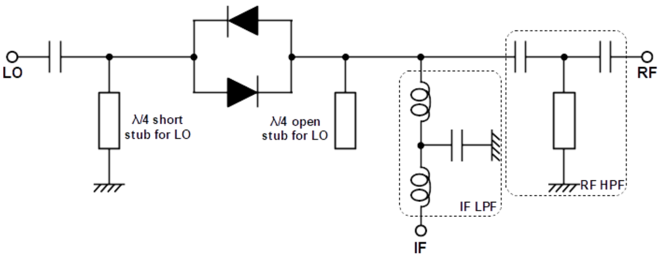

Figure 2. SHP mixer schematic.

The main issue of the $\lambda_{LO}/4$ short and open stubs is the fact that in this technology and at this frequency (f_{LO}=6 GHz), the transmission line required for their implementation takes up a large area (4591µm long and 85µm wide). To make the stubs shorter, the quasi-lumped method was applied. This technique consists on the substitution of the $\lambda_{LO}/4$ stubs for the structures formed by lumped components shown in Figure 3.

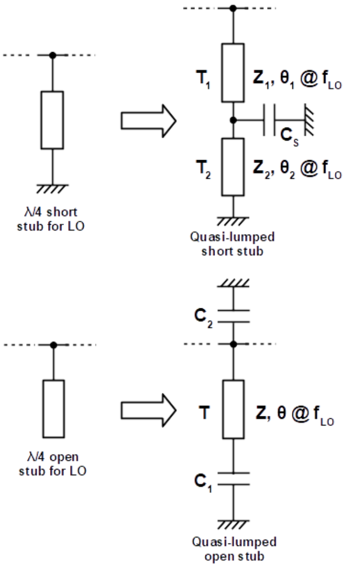

Figure 3. $\lambda_{LO}/4$ quasi-lumped stubs equivalent circuits.

As shown in Figure 3, the quasi-lumped $\lambda_{LO}/4$ short stub consists of two transmission lines (T_1 and T_2) and a shunt capacitor (C_S). Z_1 and Z_2 are the impedances and θ_1 and θ_2 are the electrical lengths of the lines. The calculation of these parameters is performed following equations (1)-(4), which are valid only when $\alpha\beta > 2$.

$$\alpha = \frac{1 + 3 \cdot tan^2(\theta_1)}{2\pi \cdot \tan(\theta_1)} \tag{1}$$

$$\beta = \frac{Z_2}{Z_1} \tag{4}$$

$$\tan(\theta_2) = \alpha\beta - \sqrt{\alpha^2\beta^2 - 3} \tag{2}$$

$$C_S = \frac{1}{2\pi f_{LO} \cdot Z_2}\left(\frac{1}{\tan(\theta_2)} - \beta \cdot \tan(\theta_1)\right) \tag{3}$$

Figure 4 shows a comparison between an ideal $\lambda_{LO}/4$ short stub, one implemented with a T-Line of the OMMIC D0XGH process and a quasi-lumped short stub. As it can be seen, the quasi-lumped short stub loses 2.27dB at 6 GHz, which is acceptable, but it has a better rejection at the second harmonic of the LO (37 dB rejection @ 12 GHz) and the RF frecuency (15.5 dB loss @ 14.125 GHz) than the $\lambda_{LO}/4$ short stub made with the OMMIC T-Line (0.133 dB loss @ 6 GHz, 20.7 dB loss @ 12 GHz, 2.4 dB loss @ 14.125 GHz).

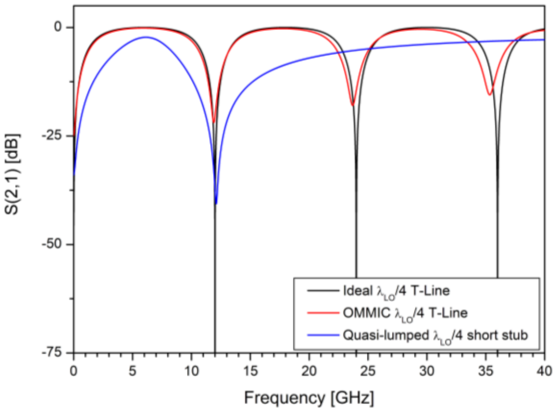

Figure 4. Comparative of the S(2,1) of the ideal $\lambda_{LO}/4$ short stub vs the OMMIC $\lambda_{LO}/4$ shortened T-Line vs the $\lambda_{LO}/4$ quasi-lumped short stub.

Regarding the quasi-lumped $\lambda_{LO}/4$ open stub, its structure consists on a transmission line (T) and two capacitors (C_1 and C_2). For a line impedance of Z and an electrical length $0 < \theta < \pi/2$, the capacitors are calculated following equations (5) and (6).

$$C_1 = \frac{1}{2\pi f_{LO} \cdot Z \cdot tan(\theta)} \tag{6}$$

$$C_2 = \frac{C_1}{3 + tan^2(\theta)} \tag{5}$$

As done for the short stub, Figure 5 shows a comparison between the behaviour of a $\lambda_{LO}/4$ open stub implemented with an ideal transmission line, with an OMMIC T-Line and the quasi-lumped methodology. As it can be observed, the quasi-lumped open stub effectively supresses the LO signal (32.3 dB rejection @ 6GHz) while letting through the RF signal (0.23 dB loss @ 14.125 GHz). These results are very positive, considering the performance of the stub implemented with the ideal T-Line (45.6 dB rejection @ 6 GHz and 0.4 dB loss @ 14.125 GHz) and the OMMIC T-Line (24.87 dB rejection @ 6 GHz and 0.76 dB loss @ 14.125 GHz).

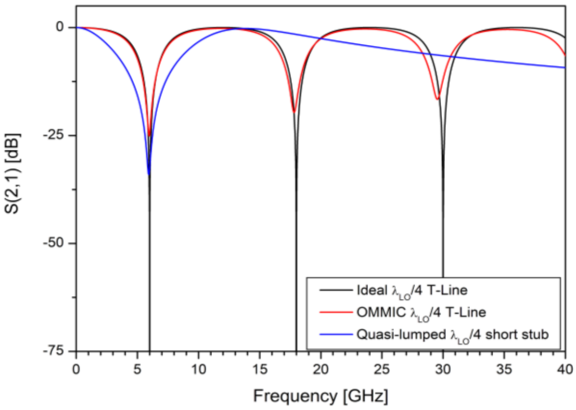

Figure 5. Comparative of the S(2,1) of the ideal $\lambda_{LO}/4$ open stub vs the OMMIC $\lambda_{LO}/4$ open T-Line vs the $\lambda_{LO}/4$ quasi-lumped open stub.

Once the quasi-lumped stubs were ready for implementation, the rest of the mixers was designed. Each diode of the APDPs was implemented by connecting the source and drain of a 4x50µm GaN transistor. With this, the SHP mixers were ready for testing. Figure 6 shows the simulated output spectrum of the two SSB SHP mixers implemented with ideal hybrids, an IF input signal of -10 dBm at 2.1 GHz and a LO signal of 20 dBm at 6 GHz.

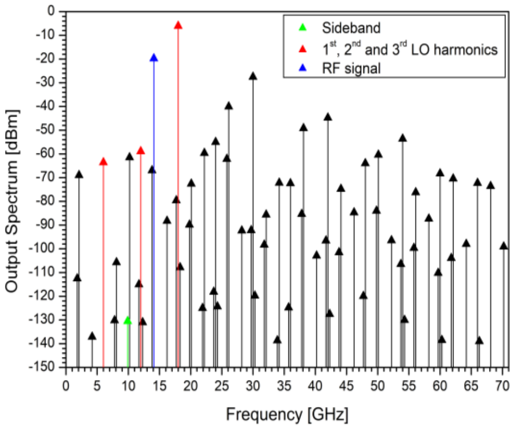

Figure 6. Simulated frequency response of the SSB SHP mixers implemented with ideal hybrids.

As it can be seen, the RF output signal (-19.7 dBm @ 14.1 GHz) is far greater than the side band (-130.5dBm @ 9.9 GHz), which means that the mixer has a sideband rejection of 110.8 dBc. The conversion loss for this mixer is 9.7 dB.

Although the results are promising (even if it must be considered that most elements on these mixers are still ideal), the output spectrum of the mixer shows a large peak at third LO harmonic, 18 GHz (-6 dBm). This spurious signal had to be filtered to prevent negative effects on other elements connected after the mixer. In order to do so, an additional quasi-lumped short stub had to be added to the SHP mixers to prevent the 18 GHz signal passing through. With that addition, the final structure of the SHP mixer is the one shown in Figure 7.

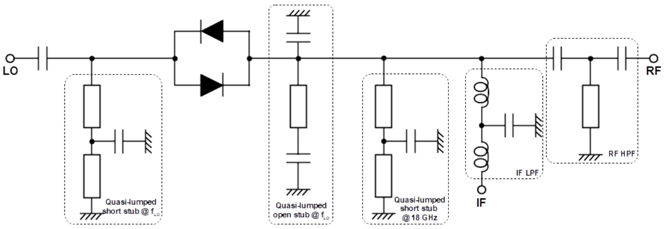

Figure 7. Final schematic of the SHP mixer

The new quasi-lumped short stub had to be optimised so it would not have a serious impact at the RF frequency. The output power spectrums for both SSB SHP mixers is shown in Figure 8. As it can be observed, the power of the signal at 18 GHz has been minimised (-36.3 dBm). As a downside, this suppression of the third harmonic of the LO also means a reduction of the RF power (-22.7 dBm). This means that the conversion loss has been reduced to 12.7 dB. The sideband rejection was also slightly diminished (114 dBc).

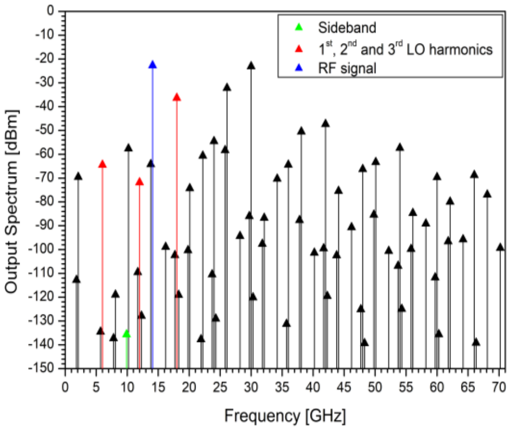

Figure 8. Simulated frequency response of the SSB SHP mixer with the additional quasi-lumped short stub.

The circuit diagram of the first SSB mixer proposed in this paper is shown in Figure 9.

The LO Wilkinson divider was made with lumped elements to reduce its area. The 90° hybrid combiner is a branch line coupler where the λ/4 transmission lines have been replaced by C-L-C pi networks. The inductors and capacitors can be calculated following equations (7) to (9).

$$L_1 = \frac{Z_O}{\omega} \tag{7}$$

$$L_2 = \frac{Z_O}{\omega\sqrt{2}} \tag{8}$$

$$C_1 = \frac{(1+\sqrt{2})}{\omega Z_O} \tag{9}$$

The 50 Ω resistance is used to ground the isolated port of the branch-line coupler. The SSB mixer performed adequately from a simulation point-of-view. The mixer requires 6 inductors and 8 capacitors for its implementation. In the following section, the layout implementation and the final simulation results will be analysed.

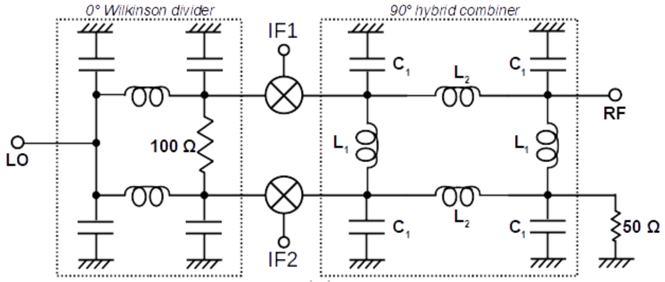

Figure 9. Circuit diagram of the SSB SHP Mixer.

III. LAYOUT IMPLEMENTATION OF THE SSB SHP MIXER

In order to obtain the layout implementation of the SSB SHP mixer, the software Advanced Design System (ADS), developed by Keysight was used. Several changes had to be made to guarantee an adequate performance while occupying the smallest area possible. The layout of the design can be seen in Figure 10.

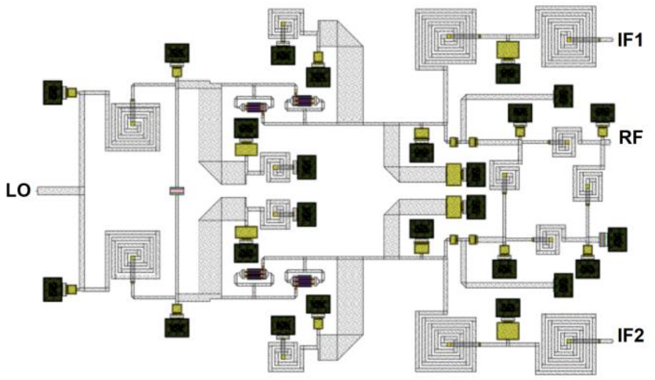

Figure 10. Layout diagram of the SSB SHP Mixer.

Some of the modifications that were made consist on bending the T-Lines of the quasi-lumped stubs in order to better accommodate them in the design. The second T-Lines of the $\lambda_{LO}/4$ short stubs were replaced by inductors to minimise the area.

The SSB SHP mixer takes up an area of 2268µm x 1408µm. This is due to the fact that the branch-line coupler forces the APDPs to be further apart, which leaves a blank space between both pairs. This space was later on used to place the first quasi-lumped short stub and reduce the total height of the layout.

IV. SIMULATION RESULTS OF THE SSB SHP MIXER

Regarding the performance of the mixer once the layout was complete, some adjustments had to be made to keep it operating. First of all, the LO power had to be augmented to compensate the losses of the mixer. Figure 11 shows the RF output of the mixer when the LO power is swept for an IF input power of -10dBm. From the results of this figure, the LO power was set to 20 dBm. With this LO power, the conversion losses for the SSB mixer are 21.2 dB.

A similar study was performed by sweeping the power of the input signal. As it can be seen on Figure 12, there is a linear response in the conversion gain of the mixer for input powers ranging from -20dBm to 10dBm.

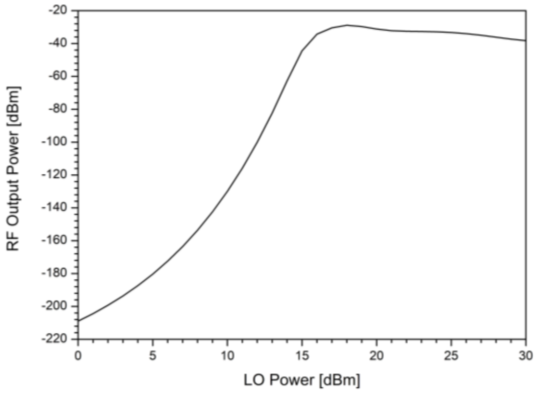

Figure 11. RF Output power vs LO Power of the two SSB SHP mixers.

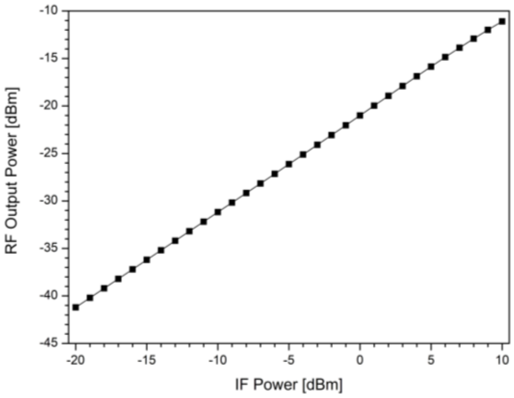

Figure 12. RF Output Power vs IF input power of the two SSB SHP mixers.

The frequency response of the SSB SHP mixer proposed in this paper can be seen in Figure 13. As it can be observed, the RF Output signal has a power of -28.18 dBm, which means that there is a conversion loss of 18.18 dB at that frequency. The sideband rejection is 29.32dBc (-57.5 dB power @ 9.9 GHz). When implementing the layout, the first LO harmonic has risen (-29.6 dBm @ 6GHz), while the second and third harmonics have been reduced (-51.5 dBm @ 12 GHz and -34.8 dBm @ 18 GHz). A slight modification of the quasi-lumped $\lambda_{LO}/4$ open stub could solve this issue. However, if the circuits that follow the mixer (driver amplifiers and power amplifiers) are selective enough, that modification may not be necessary.

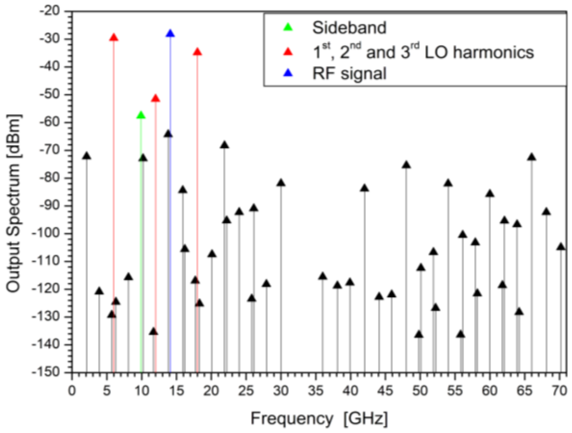

Figure 13. Frequency response of the SSB SHP mixer.

The performance of the mixer is adequate and meets the goals set in this paper, showing that these designs implemented with OMMIC’s D0XGH process can operate at these frequencies while providing good results.

V. CONCLUSIONS

A Ku-band SSB SHP IQ mixer implemented using the D0XGH process of the French foundry OMMIC have been presented in this paper. The mixer used an in-phase Wilkinson divider for the LO, two SHP mixers and a 90° combiner for the RF signal. The mixer occupies an area of 2268µm x 1408µm, with conversion losses of 18.18 dB and a sideband rejection is 29.32 dBc. These results are very positive and they can be taken as proof of the reliability of the D0XGH process for the implementation of Ku-band mixers.

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