Ultra low phase noise and high output power monolithic microwave integrated circuit oscillator for 5G applications

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ABSTRACT
A novel structure of low phase noise and high output power monolithic microwave integrated circuit (MMIC) oscillator is presented in order to use it in 5G applications. The oscillator is based on the ED02AH process which allows us to design a microwave oscillator keeping a minimum size which is impossible to have it using other technologies since microwave oscillators are sensitive components above 20 GHz. The oscillator is studied, designed, and optimized on a GaAs substrate from the OMMIC foundry using the advanced design system (ADS) simulator in order to obtain a miniaturized oscillator (1.1×1.3 mm²) generating two signals of different frequencies \( f_{o1} = 26 \text{ GHz} \) and \( f_{o2} = 30 \text{ GHz} \). The objective is to design an oscillator with high output power and low phase noise while respecting its specifications. The optimization of the proposed microwave oscillator shows satisfying results. Indeed, at 26 GHz and 30 GHz, the output powers are respectively 13.33 dBm and 14.89 dBm. The oscillator produces a sinusoidal signal of 1.5 V and 1.75 V amplitude respectively at 26 GHz and 30 GHz. The oscillator phase noise at \( f_{o1} \) and \( f_{o2} \) resonance frequencies using the liquid crystal (LC) resonator shows respectively -109 dBc/Hz and -110 dBc/Hz at 10 MHz offset.

1. INTRODUCTION
A monolithic microwave integrated circuit (MMIC) [1]–[3] is a type of integrated circuit device that are dimensionally small (from around 1 mm² to 10 mm²) and can be mass-produced. MMICs used metal-semiconductor field-effect transistors (MESFETs) as the active device and more recently high electron mobility transistors (HEMTs), pseudomorphic HEMTs and hetero-junction bipolar transistors (HBTs). Indeed, transistors operating in microwaves have become very numerous and can be on different substrates like gallium arsenide (GaAs) and gallium nitride (GaN) in order to use them in the design of power amplifiers (PAs), low noise amplifiers (LNAs), switching, mixer, filters, and oscillator’s circuits.

Recently several studies have been done using the MMIC technology. The first step in the design of a circuit will have to be concerned with the choice of active component, so a technology [4]. Once the choice of the active component is made, it is necessary to have models which describe the performances corresponding to the circuit to be made and this according to the width of the grids for the field-effect transistors (FETs) or the length of the transistor for the hetero-junction bipolar transistor (HBT) [5]. For instance, in [6], the voltage controlled oscillator (VCO) is based on a liquid crystal (LC) resonator and can be implemented in a single MMIC and its characterized by low cost, low weight and so low size. However,
in [7] and [6], the continuously tunable bandwidth is limited and the phase noise only moderate. In [8], the push-push strategy is applied to coplanar MMIC with InGaP-GaAs-HBTs, which are known to combine 1/f noise with mm-wave capabilities. Moreover, the wideband, and low noise differential yttrium garnet (YIG) tuned oscillator is presented in [9]. It is based on SiGe MMIC and transmission type YIG resonator. This oscillator with a short transmission line offers oscillator frequencies with a tuning range from 23 to 48.2 GHz. Finally, in [10], the dual band oscillator using single ring resonator employs step impedance (SI) which contains two orthogonal resonant mode and two different frequencies as negative resistance devices.

Indeed, today, thanks to MMIC and 5G technologies, it is possible to integrate on the same substrate any satellite transmission-reception chain that works at very high frequencies [11], [12]. In such systems, the microwave sources consisting of a varied combination of oscillators [13], phase-locked circuits, amplifiers, multipliers [14], [15], occupy a place that is often fundamental. The main element is of course the oscillator. In fact, the microwave oscillator, which is a circuit that changes direct current (DC) power to radio frequency (RF) power, is one of the most important components in microwave systems [16], [17].

For this, the main work of this paper is the study and the design of an oscillator in MMIC technology whose working frequencies are 26 GHz and 30 GHz using pseudomorphic high electron mobility transistor (pHEMT). In fact, satellite earth stations in 26 GHz band are used for receiving earth observation data, for example satellite imagery and climate data, from earth exploration satellite systems. And in 30 GHz they are used for communications satellite systems [18]. The paper is organized as follows. Section 2 describes the procedure and research method of the studied oscillator. Section 3 presents the results found and also performs a comparative study with other recently published works. Finally, a conclusion is made to summarize the whole work.

2. DESIGN PROCEDURE AND RESEARCH METHOD OF MMIC OSCILLATOR

We are facing a challenge whose goal is to design an oscillator capable of generating two different signals at 26 GHz and 30 GHz and characterized by low phase noise and high output power comparing it with previous works. The first step is the choice of the appropriate technology and the size of active element as well as the bias network, and the second one consists of study of stability circuit. In our case, to be able to meet the needs of our specifications and to achieve our goal, we used LC resonator that it contribute generally for having good performances at high frequencies as well as the OMMIC technology, something that will add value to our work in term of phase noise and output power. In what follows, we will detail the design procedure and method followed by the results as well as the discussion. The circuit is designed in MMIC technology in ED02AH process from OMMIC foundry using advanced design system (ADS) software from Agilent. This MMIC oscillator based on LC resonator will be suitable for wireless communication systems of the next generation 5G mm-wave band.

2.1. Choice of active element

The most important part of the active component is the choice of transistor to be used with the adequate size. The transistor plays a vital role in the power output and the amount of phase noise in the final oscillator; therefore, the choice of transistor needs careful consideration. In this respect, the selected process in this work is developed by OMMIC foundry and we choice ED02OH pHEMT process with gate length equal to 0.18 μm and total size is \( n \times w \) as shown in Figure 1, and it is based on a GaAs technology.

![Figure 1. Layout of fED02ONl transistor for ED02OH process (6x15 μm)](image-url)
2.2. Design of LC resonator

LC oscillator is a type of oscillator where an inductor-capacitor resonant circuit is used for giving the required positive feedback for sustaining the oscillations as shown in Figure 2. Moreover, according to the Barkhausen criterion for sustained oscillations, a circuit will sustain stable oscillations only for frequencies at which the loop gain of the system is equal to or greater than 1 and the phase shift between input and output is 0 or an integral multiple of $2\pi$. LC oscillators can be realized using bipolar junction transistor (BJT), field effect transistor (FET), metal oxide semiconductor field effect transistor (MOSFET), and metal-semiconductor field effect transistor (MESFET). In our case, we will use ED02OH pHEMT as mentioned in the previous part.

![Resistor, inductor, and capacitor (RLC) resonator circuit](image)

Furthermore, this type of oscillators is commonly used at very high frequencies comparing it with the lumped elements. They are not suitable for use as very low frequency because the inductors and the capacitors would be large in size, heavy and costly to manufacture. The input impedance $Z_{in}$ of the resonator can be written using RLC network components:

$$Z_{in} = \frac{s^2 C}{s^2 + s\left(\frac{1}{LC} + \frac{1}{RC}\right)}$$  \hspace{1cm} (1)

The resonance and quality factor are calculated by determining the poles of the expression (1) where $w_0$ is the resonance frequency and $Q$ is the quality factor of the resonator.

$$\frac{w_0}{Q} = \frac{1}{CR}$$  \hspace{1cm} (2)

$$w_0 = \frac{1}{\sqrt{LC}}$$  \hspace{1cm} (3)

$$Q = \frac{R}{w_0L} = w_0RC$$  \hspace{1cm} (4)

To sum up, the quality factor can be considered as a measure of the energy storage efficiency of the LC circuit. The equations from (1) to (4) describe the fundamental response of parallel RLC circuit. The power dissipated in the circuit is the result of losses in the resonator due to the non-ideality of the circuit elements. To overcome them, an applied energy must be introduced. This can be done by the negative resistance resulting from the transconductance ($g_m$) of an amplifier in order to maintain the oscillations. Table 1 shows the values of ideal elements of LC resonator using the equations mentioned above at 26 GHz and 30 GHz. Typical applications of LC oscillators include RF signal generators, frequency mixers, tuners, sine wave generators, and RF modulators.

<table>
<thead>
<tr>
<th>Table 1. Value of ideal elements of LC resonator</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Q</td>
</tr>
<tr>
<td>R (Ω)</td>
</tr>
<tr>
<td>L (pH)</td>
</tr>
<tr>
<td>C (pF)</td>
</tr>
</tbody>
</table>

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2.3. Study of circuit stability

The S-parameter formulation was introduced by Ohira et al. [11] which states that for absolute stability, two conditions must apply:

\[
K < 1 \text{ and } B < 0
\]  

(5)

K and B are respectively the stability factor and measurement stability, in practice K<1 is taken by the vast microwave community as the condition for absolute stability [19], [20].

\[
k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{12}S_{21}|}{2|S_{12}S_{21}|} > 1
\]  

(6)

\[
B = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2
\]  

(7)

Where

\[
\Delta = S_{22}S_{11} - S_{12}S_{21}
\]  

(8)

2.4. Phase noise

All the components of an oscillator produce noise and more precisely it comes from the active component. Therefore, the sources combine to form amplitude and phase modulation noise. Generally, phase noise is the most considered because it directly affects the stability of the oscillation frequency. The phase noise performance described in Leeson’s formula [21]:

\[
L(\Delta f) \propto F \frac{4KT_{\text{tank}}}{v_0^2} \left( \frac{w_0}{2\Delta f Q_{\text{tank}}} \right)
\]  

(9)

where F is noise factor, K is boltzman constant, T is temperature, \(v_0\) is signal amplitude, \(w_0\) is Center frequency, \(Q_{\text{tank}}\), load quality factor.

3. RESULTS AND DISCUSSION

In order to verify the MMIC oscillator performance in terms of stability factor, oscillator frequency, phase noise and output power, a set of simulations are performed in harmonic balance simulator using ADS software from Agilent. The oscillator proposed in Figure 3 is mounted on a GaAs substrate with a thickness of 100 μm. The size (nxw) of the fED02ONL transistor in GaAs-pHEMT technology is determined so as to have a minimum stability factor. The advantage of using this type of transistor is to have a low phase noise oscillator. The drain-to-source voltage of the transistor is \(V_d=3.4\) V and the DC power consumption is about 340 mW.

From Figure 4(a), we observe that the stability factor decreases by adding the number of fingers. Therefore, the optimal number of fingers is \(n_{\text{opt}}=8\). And by setting n to 8, the width of the transistor is varied. As shown in Figure 4(b), the results show that the optimal value of w is 30 μm. It should be noted that the optimal value is chosen in such a way as to obtain a minimum stability factor and of very small dimensions. Therefore, the size of the studied transistor fED02ONL pHEMT is: \(n_{\text{opt}}xw=8x30\) μm.

The ideal localized elements of the resonators RiLiCi are replaced by real elements supplied by the OMMIC foundry. Resistors, capacitors, and inductors are successively of the NiCr type (tRwED2AH), lumped MIM Si3N4 capacitors model (CbetaED2) and spiral inductor model (indED02EH). The resonant frequency of R1L1C1 is 26 GHz while the resonant frequency of R2L2C2 is 30 GHz. The optimized values of these elements are shown in the Table 2.

In order to generate an RF signal to the load, the oscillator must be unstable. However, the use of the inductance in series with source of the transistor allowed us to create a conditionally stable circuit at a narrow frequency. For this, we had to add a capacity Csi in parallel with the inductance Lsi to have an unstable circuit. In Figures 5(a) and (b), the results show that the previous condition of stability is satisfied (K<1 and B<0) at both of studied frequencies (26 GHz and 30 GHz).

It remains to verify the oscillation condition in relation to the reflection coefficients for the two input and output ports for the two blocks. The Figure 6 shows that the reflection coefficients S11 and S22 for the two blocks at both frequencies 26 GHz and 30 GHz at port 1 and port 2 are greater than unity, which satisfies the maintenance of the oscillation at these two studied frequencies. From this study we can see that all the oscillation conditions are satisfied to generate two RF signals at the two ports P1 and P2 of respective frequencies 26 and 30 GHz.
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Table 2. Values of real elements of RLC resonators (li in μm)

<table>
<thead>
<tr>
<th></th>
<th>26 GHz</th>
<th>30 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R_1(Ω)</td>
<td>L_1(pH)</td>
</tr>
<tr>
<td>l_1</td>
<td>272</td>
<td>950</td>
</tr>
<tr>
<td>l_2</td>
<td>272</td>
<td>950</td>
</tr>
<tr>
<td>l_3</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>l_4</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>l_5</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>l_6</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

Figure 3. RLC resonator circuit

Figure 4. Transistor stability factor for different values of (a) number of fingers and (b) length of fingers
The transistor fED0ON1 is a nonlinear element which is capable to generate harmonics which affect the output signal causing it a possible distortion as seen in Figure 7 which shows us the spectrum of the output with the $2f_0$ and $3f_0$ harmonics at Figure 7(a) and time domain output signal of the studies oscillator of the two ports at Figure 7(b). For this, resonators of $\frac{\lambda}{4}$ length are added to the output of the two ports in order to suppress these unwanted harmonics. Table 3 shows the results of factor stability $K$ and measured stability $B$ of studied oscillator at both of 26 GHz and 30 GHz and Table 4 shows the length of resonators.
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Table 3. Factor stability and measured stability at 26 GHz and 30 GHz

<table>
<thead>
<tr>
<th></th>
<th>Stability@ 26 GHz</th>
<th>Stability@ 30 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( K_1 )</td>
<td>( B_1 )</td>
</tr>
<tr>
<td>( L_{S1} )</td>
<td>-0.919</td>
<td>-74</td>
</tr>
<tr>
<td>( C_{S1} )</td>
<td>0.75 pF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( K_2 )</td>
<td>( B_2 )</td>
</tr>
<tr>
<td>( L_{S2} )</td>
<td>-0.95</td>
<td>-53</td>
</tr>
<tr>
<td>( C_{S2} )</td>
<td>0.5 pF</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Length of \( \lambda/4 \) resonators

<table>
<thead>
<tr>
<th>Resonator</th>
<th>( L_{\lambda/4} ) at 52 GHz</th>
<th>( L_{\lambda/4} ) at 60 GHz</th>
<th>( L_{\lambda/4} ) at 90 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400 μm</td>
<td>300 μm</td>
<td>141 μm</td>
</tr>
</tbody>
</table>

After adding the \( \lambda/4 \) resonators, the result becomes as shown in Figure 8. The Figure 8(a) shows the spectrum of output signal while Figure 8(b) shows the time domain output signal for the two ports at both studied frequencies 26 GHz and 30 GHz. As shown in Figure 9, the proposed circuit achieves an ultra-low phase noise (PN) in the two ports \( P_1 \) and \( P_2 \). The PN at \( P_1 \) for \( f_{o1} = 26 \) GHz is -88 dBc/Hz, -109 dBc/Hz and -129 dBc/Hz respectively at 100 KHz, 1 MHz and 10 MHz. However, for \( f_{o2} = 30 \) GHz at the port \( P_2 \), the PN is -98.08 dBc/Hz, -110 dBc/Hz and -130 dBc/Hz at the same frequencies.

Figure 8. Final output signal of proposed MMIC oscillator (a) signal spectrum and (b) time domain

Figure 9. Phase noise of proposed MMIC oscillator

For sum up, as seen in Table 5, if we compare this work with others like [22]–[26], we find that our oscillator meets our needs and specifications; it’s more relevant with regard to phase noise (-88 dBc/Hz, -109 dBc/Hz and -129 dBc/Hz for 26 GHz and -98.08 dBc/Hz, -110 dBc/Hz and -130 dBc/Hz for 30 GHz respectively at 100 KHz, 1 MHz and 100 MHz) and output supplied \( P_{out} \) (13.33 dBm for 26 GHz and 14.89 dBm for 30 GHz ). Indeed, we observe a significant difference of its values by comparing it with
previous works. As well as for example, the work [27] is based on the same technology that we used in this MMIC oscillator, however, it got a very low achieved power at the output compared to our work.

Finally, Figure 10 shows the layout of the proposed ultra-low phase noise dual band MMIC oscillator which is characterized by its miniature size compared to other works which only support a single oscillation frequency, on the other hand in our work, the studied oscillator is designed for the generation of two RF signals at 26 GHz and at 30 GHz keeping a miniature size which is 1.43 mm$^2$. It is to highlight that the realization of this type of oscillators can only be done exclusively through the OMMIC foundry.

![Figure 10. Layout of the proposed ultra-low phase noise dual band MMIC oscillator (1.1x1.3 mm$^2$)](image)

### Table 5. Performance comparison of different oscillators

<table>
<thead>
<tr>
<th>Techno</th>
<th>Freq (GHz)</th>
<th>F0 res</th>
<th>Dissipated power (mW)</th>
<th>Pout (dBm)</th>
<th>Size mm$^2$</th>
<th>Phase noise dBc/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>@100 KHz @1 MHz @10 MHz</td>
</tr>
<tr>
<td>[21] 28 nm-CMOS</td>
<td>27.3</td>
<td>11.58</td>
<td>0.15</td>
<td>-8</td>
<td>2 x 1</td>
<td>-83</td>
</tr>
<tr>
<td>[22] 65 nm-CMOS</td>
<td>27.5</td>
<td>23</td>
<td>NA</td>
<td>1.2x1</td>
<td>-72</td>
<td>-100</td>
</tr>
<tr>
<td>[23] 0.25 μm-GaN HEMT</td>
<td>15.05</td>
<td>63</td>
<td>-6</td>
<td>2 x 1</td>
<td>-106</td>
<td>-133</td>
</tr>
<tr>
<td>[24] 0.13 μm-SiGe HEMT</td>
<td>29.6</td>
<td>18</td>
<td>NA</td>
<td>0.1</td>
<td>NA</td>
<td>-100</td>
</tr>
<tr>
<td>[25] 0.13 μm-SiGe HBT</td>
<td>36.5</td>
<td>132</td>
<td>NA</td>
<td>0.1x0.12</td>
<td>NA</td>
<td>-75</td>
</tr>
<tr>
<td>[26] 0.15 μm-GaAs pHEMT</td>
<td>37.608</td>
<td>129.9</td>
<td>10.46</td>
<td>NA</td>
<td>-82.2</td>
<td>-112</td>
</tr>
<tr>
<td>This work</td>
<td>38.06</td>
<td>129.9</td>
<td>10.46</td>
<td>NA</td>
<td>-82.2</td>
<td>-112</td>
</tr>
</tbody>
</table>

**CONCLUSION**

The MMIC technique in oscillator applications is used for a low cost and low phase noise performance. For this, in this paper we studied and designed a novel miniaturized oscillator with MMIC technology for 5G applications in order to generate two RF signals at 26 and 30 GHz using Agilent ADS. The results obtained during the study satisfied all the oscillation conditions necessary at these two frequencies and are satisfactory with regard to phase noise, output spectrum and output time domain signal. Indeed, to conclude, we can say that we were able to realize an oscillator capable of generating two sinusoidal RF signals while keeping a minimal surface by comparing it with the old works and which is
1.43 mm². In addition, this MMIC oscillator is characterized by maximum output power equal to 13.33 dBm for 26 GHz and 14.89 dBm for 30 GHz which is seen as an added value to this work.

REFERENCES


BIOGRAPHIES OF AUTHORS

Hanae El Ftouh was born in 1987, Tetouan, Morocco. She received a Master degree in telecommunication systems engineering from Abdelmalek Essaâdi University, Tetouan, Morocco, in 2010. She received Ph.D. degree in microwave circuits in 2016 at the same university. Her research interests on miniaturization of printed linear microwave circuits, antennas, filters and power divider and oscillators. She has authored and co-authored several papers in different international indexed journals and conferences in the field of microwave communications Technology. She can be contacted at email: elftouhhanae2@gmail.com.

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