Design of Q-enhanced Class-C VCO with robust start-up and high oscillation stability

Mi Tian\(^1\), Zhigong Wang\(^{1a}\), Jian Xu\(^1\), and Changchun Zhang\(^2\)
\(^1\) Institute of RF- & OE-ICs, Southeast University, Nanjing 210096, China
\(^2\) College of Electronic Science and Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210003, China
\(^a\) zgwang@seu.edu.cn

Abstract: A novel topology of Q (quality factor)-enhanced dynamically self-biasing Class-C VCO is proposed in this article. It introduces a bridging capacitor to enhance the quality factor of the oscillator. The enhancement of the quality factor suppresses the squeeging phenomenon and the harmonic distortion, and thus improves the phase noise and oscillation stability. The prototype of the proposed circuit was fabricated in SMIC 0.18\(\mu\)m CMOS process and the measurement results showed a low phase noise of \(-125\) dBc/Hz at 1 MHz from 3.331 GHz carrier with a total power consumption of 3.36 mW from a 1.2 V supply. The proposed work exhibited an excellent Figure of Merit (FoM) of \(-190\) dBc/Hz.

Keywords: Class-C VCO, quality factor, phase noise, oscillation stability, squeeging phenomenon

Classification: Integrated circuits

References

1 Introduction

In recent years, as an optimal evolution for both of low power consumption and low phase noise in fully integrated CMOS voltage-controlled oscillator (VCO) design, Class-C harmonic VCO has attracted great interest [1, 2]. However, the low DC bias voltage $V_{\text{gbias}}$ of cross-coupled transistors in Class-C VCO decreases their trans-conduction $g_m$ and results in a difficulty in the start-up of oscillation. In order to solve this problem, a dynamically self-biasing Class-C VCO with a negative-envelope feedback structure was proposed in [2], and it realized a robust start-up. In order to solve the squegging phenomenon, a voltage summing circuit is used to raise $V_{\text{gbias}}$ in their design. In this article, we investigated the reason of the squegging phenomenon and harmonic distortion in the conventional Class-C VCO. Based on the investigation, we innovatively proposed a capacitor bridging topology to shunt the current passing the bias-resistors, thereby enhancing the quality factor of the oscillator. The enhancement of quality factor improves the phase noise performance while effectively suppressing the squegging phenomenon and harmonic distortion. Results of contrast simulations and measurements have proved that our design realizes an obvious improvement of phase noise performance and oscillation stability. The proposed work exhibited an excellent Figure of Merit (FoM) of $-190$ dBc/Hz.

2 Squegging phenomenon and harmonic distortion in Class-C VCO

2.1 Squegging phenomenon

According to Leeson’s proportionality, the phase noise of VCO can be expressed as [3]:

$$L(\Delta \omega) = 10 \cdot \log \left( \frac{\sum_i N_{L,i}}{2\Delta \omega^2 C^2 A_{\text{tank}}^2} \right)$$  \hspace{1cm} (1)

where $A_{\text{tank}}$ is the oscillation amplitude. From Eq. (1) we can see that a larger $A_{\text{tank}}$ introduces a lower phase noise. And in a Class-C VCO, the following in equation must be satisfied [1]:

$$A_{\text{tank}} < \frac{1}{2}(V_{\text{dd}} - (V_{\text{gbias}} - V_{\text{th}}))$$  \hspace{1cm} (2)

In equation (2) indicates that, to get a lower phase noise, a lower $V_{\text{gbias}}$ is required to obtain a larger oscillation amplitude. However, the adoption of an extremely low $V_{\text{gbias}}$ has two negative aspects. First, it decreases the reliability of oscillation start-up [2]. Second, because a lower $V_{\text{gbias}}$ drives the cross-coupled transistors to present a greater impedance, it raises the risk that the tail current transistor is squeezed into triode region. It has been formerly regarded as the reason of the squegging phenomenon [2].

In this article, we investigated the squegging phenomenon from a fresh perspective of quality factor. To realize Class-C operation, the large tail capacitor $C_{\text{tail}}$ is a key device [1]. However, the large $C_{\text{tail}}$ presents a very small AC impedance, and provides the oscillation signal a low impedance path to the ground. As shown in Fig. 1, a large amount of power leaks into this low impedance path in
the form of a large AC current $I_{\text{leakage}}$, rather than distributing in resonant cavity to establish oscillation. From the perspective of energy distribution, it means a serious deterioration to the quality factor of the oscillator. The large AC current $I_{\text{leakage}}$ charges $C_{\text{tail}}$, and obviously raises the voltage on it. It makes the gate-source voltage $V_{\text{gs}}$ of the cross-coupled transistors $M_1$ and $M_2$ drops to the value much lower than the threshold voltage. While both the cross-coupled transistors are cut off for a long period of time, the oscillation power in the resonant cavity cannot acquire sufficient supplement and the oscillation will attenuate or even quench. With the drop of the oscillation, $I_{\text{leakage}}$ gets smaller or even vanishes. And $C_{\text{tail}}$ will be discharged by the current $I_{\text{SS}}$ through the tail current transistor $M_6$. Then, $V_{\text{gs}}$ of the cross-coupled transistors rises and establishes the oscillation again. As this quasi-relaxation process repeats, the squegging phenomenon occurs.

To avoid this squegging phenomenon, the power leakage into the low impedance path must be restrained. From the perspective of energy distribution, that means, it is of great necessity and importance to enhance the quality factor of the oscillator, thereby maximizing the oscillation power while adopting low $V_{\text{gbias}}$ and large $C_{\text{tail}}$ to maintain deep Class-C operation.

### 2.2 Harmonic distortion

As shown in Fig. 2, because of the very low conduction angle $2\Phi$ in Class-C operation, an obvious harmonic distortion can be seen in the output waveform. This asymmetric multi-harmonic waveform brings unwanted harmonic interference and exacerbates the mismatch between the differential output signals. Therefore, it also requires high-Q frequency selection for the oscillator to restrain this harmonic distortion.

### 3 Design of Q-enhanced Class-C VCO

In this article, a novel Q-enhanced Class-C VCO in Fig. 3 is proposed to improve the quality factor. In Fig. 3, part I is a typical Class-C VCO structure, where “CAP Array” is a 2-bit sub-band selection capacitor array. Part II is the negative-envelope
feedback structure which provides robust start-up [2]. According to the above analysis in Section 2, in order to achieve maximal oscillation amplitude, the gate bias voltage $V_{gbias}$ of the cross-coupled transistors $M_1$ and $M_2$ should be set at a relatively low value. Therefore, we use the dynamical output voltage $V_{C1}$ of the negative-envelope feedback structure as $V_{gbias}$ directly without raising it. To solve the squegging problem introduced by the low bias voltage, a bridging capacitor topology is innovatively introduced in our design. As shown in Fig. 3, a bridging capacitor $C_{bridge}$ is set in parallel with the bias resistors $R_1$ and $R_2$, bridging the gates of the cross-coupled transistors $M_1$ and $M_2$.

The bridging capacitor $C_{bridge}$ has two important functions as shown in Fig. 4. First, it is equivalent to two capacitors in series and gives a virtual AC ground node at the midpoint. With the resistors $R_1$ and $R_2$, a low pass filter is formed to eliminate the ripple on $V_{gbias}$. Therefore, the jitter in the output signal is reduced. Second, capacitors $C_2$ and $C_3$, in series with resistors $R_1$ and $R_2$, provide a current path in parallel with the resonant cavity. As the current of the oscillation signal passes
through the resistors $R_1$ and $R_2$, energy loss occurs and degrades the quality factor of the oscillator. The introduction of $C_{\text{bridge}}$ shunts the current that flows through the resistors, thereby reducing the energy loss on them and enhancing the quality factor. The enhancement of quality factor brings the Class-C VCO a lower phase noise and more stable oscillation with low harmonic distortion.

4 Contrast simulations

Fig. 5 gives the transient simulation to exhibit the dynamically self-biasing process. At the beginning of oscillation, the bias voltage $V_{\text{bias}}$ is set at $V_{\text{dd}}$, which ensures a robust start-up. With the building-up of the oscillation, $V_{\text{bias}}$ decreases and the oscillator enters into Class-C operation, where good phase noise and high current efficiency can be achieved.

The contrast simulation of the output impedance of the two-port network into the resonant cavity is shown in Fig. 6. As can be seen, the network exhibits a much larger impedance at the resonant frequency with $C_{\text{bridge}}$ introduced. The module of the impedance as well as the steepness of the module curve is greatly boosted, proving that the quality factor has been greatly improved.

Fig. 7 gives the contrast simulation result of the output waveform between the Class-C VCO with and without $C_{\text{bridge}}$ introduced. It can be seen from Fig. 7(a) that
Fig. 6. Simulated output impedance of the two-port network into the resonant cavity; (a) is the module curve with $C_{\text{bridge}}$ introduced; (b) is that without $C_{\text{bridge}}$ introduced.

Fig. 7. Transient simulation of the output waveform with $C_{\text{bridge}}$ introduced; (a) elimination of squegging phenomenon; (b) suppression of harmonic distortion.
the occurrence of squegging phenomenon is eliminated by $C_{\text{bridge}}$. Fig. 7(b) shows that the harmonic distortion in output waveform is greatly suppressed by $C_{\text{bridge}}$ as well. It reveals that the enhancement of quality factor introduced by $C_{\text{bridge}}$ improves the oscillation stability effectively.

Fig. 8 gives the contrast simulation result of phase noise with and without $C_{\text{bridge}}$. The contrast result proves that the enhancement of quality factor introduced by $C_{\text{bridge}}$ brings an optimization of $2 \text{ dBC/Hz} @ 1 \text{ MHz}$ to the phase noise performance.

5 Measurement results

The prototype of the proposed circuit was fabricated in SMIC 0.18 $\mu$m CMOS process. Fig. 9 shows the die photograph. The chip area was $0.7 \text{ mm} \times 0.5 \text{ mm}$ with monitor buffer included. The total power consumption was only 3.36 mW with a single 1.2 V supply.
An Agilent E4448A PSA series spectrum analyzer was used to measure the frequency characteristics of the output signal. Fig. 10 gives the measured phase noise of $-125 \text{ dBc/Hz}$ at 1 MHz off 3.331 GHz carrier. The linear tuning voltage range was from 0.6 V to 1.8 V. The linear tuning frequency range was 120 MHz in one single sub-band with a VCO gain of 100 MHz/V, and the whole tuning frequency range including all the 4 sub-bands was from 3.25 GHz to 3.55 GHz.

![Carrier Freq 3.330706333 GHz](image)

**Fig. 10.** The measured phase noise of $-125 \text{ dBc/Hz@1 MHz}$ from 3.331 GHz carrier

Table I gives a comparison between our work and other previous studies [4, 5, 6, 7, 8, 9]. A widely used FoM that permits a fair comparison of oscillators is adopted here:

$$\text{FoM} = L(f_{\text{offset}}) - 20 \cdot \log\left(\frac{f_0}{f_{\text{offset}}}\right) + 10 \cdot \log\left(\frac{P_{dc}}{1 \text{ mW}}\right)$$

(3)

where $f_0$ is the oscillation frequency, $f_{\text{offset}}$ is the offset frequency from the oscillation carrier, $L(f_{\text{offset}})$ is the phase noise at the offset frequency, $P_{dc}$ is the power consumption. As shown in Table I, the proposed work has the highest FoM of $-190 \text{ dBc/Hz}$, which proves its excellent performance.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Process (nm)</th>
<th>Freq. (GHz)</th>
<th>Vdd (V)</th>
<th>Pdc (mW)</th>
<th>Phase noise (dBc/Hz @1 MHz)</th>
<th>Tuning range (%)</th>
<th>Chip area (mm$^2$)</th>
<th>FoM (dBc/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>250</td>
<td>2.3</td>
<td>2.5</td>
<td>10</td>
<td>$-124$</td>
<td>31.4</td>
<td>NA</td>
<td>$-181$</td>
</tr>
<tr>
<td>[5]</td>
<td>90</td>
<td>5</td>
<td>1.2</td>
<td>2.52</td>
<td>$-98.8$</td>
<td>30</td>
<td>0.0665</td>
<td>$-169$</td>
</tr>
<tr>
<td>[6]</td>
<td>180</td>
<td>10.52</td>
<td>1.5</td>
<td>20.4</td>
<td>$-122$</td>
<td>8</td>
<td>0.392</td>
<td>$-189$</td>
</tr>
<tr>
<td>[7]</td>
<td>350</td>
<td>2.45</td>
<td>3</td>
<td>10.7</td>
<td>$-111$</td>
<td>8.2</td>
<td>0.028</td>
<td>$-168$</td>
</tr>
<tr>
<td>[8]</td>
<td>180</td>
<td>10</td>
<td>0.9</td>
<td>3.15</td>
<td>$-114$</td>
<td>10.9</td>
<td>1.2856</td>
<td>$-189$</td>
</tr>
<tr>
<td>[9]</td>
<td>90</td>
<td>10.13</td>
<td>0.4</td>
<td>1.32</td>
<td>$-108.8$</td>
<td>33</td>
<td>0.3408</td>
<td>$-188$</td>
</tr>
<tr>
<td>This work</td>
<td>180</td>
<td>3.4</td>
<td>1.2</td>
<td>3.36</td>
<td>$-125.02$</td>
<td>8.8</td>
<td>0.35</td>
<td>$-190$</td>
</tr>
</tbody>
</table>

© IEICE 2014
DOI: 10.1587/elex.11.20140982
Received October 15, 2014
Accepted October 23, 2014
Publicized November 7, 2014
Copyedited November 25, 2014
6 Conclusion

In this article, a Q-enhanced Class-C VCO with dynamically self-biasing feedback loop is proposed. A bridging capacitor is introduced to improve the phase noise and oscillation stability in deep Class-C operation. Results of contrast simulations and measurements have demonstrated that the proposed structure improves the quality factor and realizes an excellent performance with low power consumption.