A Low-Power High-Output-Efficiency Bipolar Colpitts VCO Using Base Inductive Feedback and Q-factor Enhancement for Analog Signal Acquisition

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Abstract  A low-power Colpitts VCO with high output efficiency that uses base inductive feedback and Q-factor enhancement techniques is proposed in this paper. The base inductive feedback technique employs an inductor at the base of the bipolar transistor to generate a feedback enhancement effect and reduce the start-up current. The Q-factor enhancement technique adopts a capacitor voltage divider at the output of the Colpitts VCO to improve the DC-to-RF efficiency. The mechanisms are theoretically analyzed, and then a 433 MHz Colpitts VCO is designed to verify the scheme. Its DC consumption is as low as 270 µW while the operating frequency is 433 MHz. Finally, the Colpitts VCO is applied in a wireless neural signal recording system and works well. Thus, the presented VCO is suitable for analog signal acquisition system in the extremely power-constrained wireless scenarios.

key words: Colpitts VCO, Inductive feedback, Q-factor enhancement, DC-to-RF efficiency, Low power

Classification: Devices, circuits and hardware for IoT and biomedical applications

1. Introduction

The low-power demand is becoming more and more significant as the development of portable wireless communication systems, such as the battery-powered nodes in the IoTs (Internet of Things) [1–4], short-range wireless biological signal acquisition devices [5–8], sensor networks [9,10]. In many wireless scenarios of external analog signal acquisition, the system’s power consumption is limited extremely to the microwatt level. As a power-hungry component in RF transceiver, voltage-controlled oscillators (VCOs) often contribute a large power dissipation of these portable wireless systems. Colpitts VCOs are widely applied in wireless communication systems because of their simple structures and good phase noise performance [11–14]. Because the noise and linearity performances of bipolar devices are always better than MOS devices, bipolar Colpitts VCOs attract more attention in the analog signal direct-transmission, such as radio microphones, wireless instruments and so on. Meanwhile, the collected analog signal can be modulated by using the bipolar Colpitts VCO and radiated via the antenna. Thus, this pure analog process method which omits the analog-to-digital converter and power amplifier further reduces the system’s energy consumption [15–17]. However, Colpitts VCOs usually suffer from poor start-up characteristics and require high power consumption to ensure reliable start-up. Meanwhile, its output power is another important performance indicator, which could ensure a relatively sufficient communication distance. The limitation of the active devices makes it difficult to design Colpitts VCOs with high output efficiency. The trade-off between low power consumption and high output power must be weighed carefully.

To overcome the above-mentioned difficulties, many works have been reported [18–26]. The differential Colpitts VCOs, which often use negative-conductance boosted and current switching techniques, are adopted to overcome the start-up difficulty [18,22,23]. By employing inductors for a negative-conductance boosted structure, the DC power consumption of the Colpitts VCO is effectively reduced [18]. A 7/24 GHz dual-band VCO using a current-source switching topology is designed to avoid additional losses in the resonator and lower its power consumption [23]. A low-power PMOS Colpitts VCO using the technique of gate inductive feedback is demonstrated to enhance the negative conductance and overcome the start-up difficulty [20]. The micro-electromechanical (MEM) technique is also adopted to realize low power VCOs, but its process is not compatible with CMOS process [27,28]. The DC power consumption of these VCOs are mainly in the milliwatt level, and the DC-to-RF efficiency is not efficient. These VCOs are hard to satisfy the transmission of analog signals in the extremely power-constrained acquisition systems. In this paper, the improved techniques of base inductive feedback and Q-factor enhancement are used in a low-power bipolar Colpitts VCO. Thus, the required start-up power consumption can be decreased to the microwatt level with the base inductive feedback structure, and the significant enhancement to the DC-to-RF efficiency can also be achieved by adding a capacitor voltage divider. Besides, the nonlinear analysis and verifications are applied for this Colpitts VCO, which accounts for the nonlinear ef-

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fect of the inductors, capacitors and active devices. This paper is organized as follows. In Section II, the proposed Colpitts VCO is introduced. The design considerations and nonlinear analysis of the improved techniques are presented. Section III describes the 433 MHz Colpitts VCO implementation with the DC power consumption of 270 μW and its application experiments. The experimental results and characterization of neural signal recording are also given to verify the proposed method. Finally, a conclusion is drawn as a summary of this paper.

2. VCO Design

Fig. 1 shows the topologies of analog signal acquisition and the circuit of the proposed Colpitts VCO. The analog signal is amplified and injected to the proposed VCO which modulates the analog signal and outputs the RF signal. In the traditional Colpitts VCO circuit, the resonant tank consists of inductor \((L_1)\), capacitors \((C_1, C_2)\) and parasitic components. The negative resistance cell comprises of capacitors \((C_1, C_2)\) and bipolar transistor \((T)\). A base inductor \((L_b)\) is added to reduce the start-up current and makes the oscillator start up easily, and its action is named as the base inductor feedback effect. A capacitor voltage divider is made up of capacitors \((C_1, C_2\text{ and additional } C_c)\), and it helps to reduce the energy loss of the resonant ring. It improves the DC-to-RF efficiency of the Colpitts VCO, whose action is named as the Q-factor enhancement effect. The operating mechanisms, nonlinear analysis and simulation verifications of these two methods are discussed in detail as follows.

![Fig. 1. Schematic of the proposed Colpitts VCO](image)

2.1 Base inductor feedback

To reveal its inner mechanisms, the Colpitts VCO with feedback inductor and its small-signal equivalent \(\pi\)-model are shown in Fig. 2. In Fig. 2(a), the negative conductance should be greater than the load conductance in its one-port network when the oscillator starts up. The operating frequency is determined by inductors and capacitors generated from its one-port network [29]. The negative conductance is always generated by using a positive feedback amplifier, which is used to maintain the sustained oscillation. The positive feedback path is formed by using \(C_2\), which feeds some of the resonant energy to the input of the transistor, and sustains the oscillation. The oscillator could work at a relatively lower quiescent current and thereby the static power consumption could be reduced when the positive feedback is enhanced by optimizing the circuit structure or the start-up conditions. Thus, a feedback inductor \((L_f)\) is added at the input of Colpitts VCO to supply a feedback path and the negative resistance network is constituted by capacitors \((C_1, C_2)\), feedback inductor \((L_f)\) and bipolar transistor \((T)\). Then it boosted the negative conductance to enhance the positive feedback effect. As a result, the start-up current and power consumption are reduced.

![Fig. 2. Schematic of the Colpitts VCO using base inductive feedback and its small-signal equivalent \(\pi\)-model](image)

According to the Eq. (1) in the condition for self-sustained oscillation [30], the Y-matric can be derived as shown in Eq. (2) to Eq. (6).

\[
\begin{bmatrix}
Y_{11} + sC_2 + sC_1 & Y_{12} - sC_1 \\
Y_{21} - sC_1 & Y_{22} + sC_1 + Y_L
\end{bmatrix} = 0 \quad (1)
\]

\[
Y_{11} = \frac{1}{R_e} + g_m r_{be} + sL_g + s^2 r_{be} C_{be} L_g + \frac{r_{be}}{1 + s C_{be} r_{be} + s L_g r_{be} + s C_{ce}} \quad (2)
\]

\[
Y_{12} = -sC_{ce} \quad (3)
\]

\[
Y_{21} = -g_m \frac{r_{be}}{r_{be} + s L_g + s^2 r_{be} C_{be} L_g} - sC_{ce} \quad (4)
\]

\[
Y_{22} = sC_{ce} \quad (5)
\]

\[
Y_L = \frac{1}{s L_1} + \frac{1}{s L_p} \quad (6)
\]

By substituting Eq. (2)–Eq. (6) into Eq. (1), it is drawn that

\[
Y_{out} = Y_{22} + sC_1 - \frac{(Y_{12} - sC_1) (Y_{21} - sC_1)}{Y_{11} + sC_1 + sC_2} \quad (7)
\]

The start-up conditions should be satisfied while Real\((Y_{out}) + \text{Real}(Y_L) < 0\) and Imag\((Y_{out}) + \text{Imag}(Y_L) = 0\), where Real\((Y_{out})\) is the output conductance, and Imag\((Y_L)\) is the load reactance. It can be seen that the larger the
amplitude of the negative conductance \( \text{Real}(Y_{out}) \) is, the easier the oscillator starts up. The larger amplitude of \( \text{Real}(Y_{out}) \) always means more DC power consumption. The feedback inductor increases the amplitude of \( \text{Real}(Y_{out}) \). As a result, the start-up conditions become easier and the power consumption reduces.

As the feedback inductor changes, the variations of \( \text{Real}(Y_{out}) \) and \( \text{Imag}(Y_{out}) \) are plotted in Fig. 3(a) and Fig. 3(b), respectively. The influence of \( r_{ds} \) is also taken into account in the Colpitts VCO design. The value of \( \text{Real}(Y_{out}) \) is improved when \( L_g \) is increased within a certain range for a fixed \( r_{ds} \). The maximal value of the amplitude appears at the resonance point of its one-port network. However, the value of \( L_g \) at the resonance point can not be used in the design of the Colpitts VCO. As shown in Fig. 3(b), \( \text{Imag}(Y_{out}) \) varies dramatically near the resonance point. Therefore, it would make the frequency of the Colpitts VCO shift from its design goal or even make it not oscillate as the PVT varies when the value of \( L_g \) is used at the resonance point or near it. In order to avoid this condition, the value of \( L_g \) is determined as that is discussed in [29]. As a result, \( L_g \) used in this design is at the left side of the curve as shown in Fig. 3 and slightly far away from the resonance point.

![Fig. 3. The values of \( Y_{out} \) as a function of the feedback inductor within a certain range for a fixed \( r_{ds} \) (a) \( \text{Real}(Y_{out}) \) versus \( L_g \) (b) \( \text{Imag}(Y_{out}) \) versus \( L_g \)](image)

### 2.2 Q-factor enhancement technique

It differs from the conventional Colpitts VCO on that a capacitor \( (C_c) \) is added at the connector terminal of the bipolar transistor in the proposed Colpitts VCO. Fig. 4 gives the equivalent T-model of the proposed VCO with the additional capacitor. The capacitors \( (C_c, C_1 \text{ and } C_2) \) constitute a capacitor voltage divider. By using this capacitor voltage divider, \( C_{\text{total}} \) used in the LC tank is relatively reduced without changing the values of \( C_1 \text{ and } C_2 \), where \( C_{\text{total}} \) is composed of \( C_1, C_2 \) and the parasitic capacitors of the bipolar transistor. \( L_{\text{total}} \) used in the tank includes \( L_1 \text{ and } L_g \). As the frequency of the oscillator is specified by the formula \( \omega=1/(C_{\text{total}}L_{\text{total}})^{1/2} \) and set to a fixed value, the value of the inductor loaded in LC tank should be enlarged and the Q-factor of the LC tank increases. Thus, the power loss of the LC tank reduces and the phase noise performance of the Colpitts VCO improves. As a result, the DC-to-RF efficiency of the Colpitts VCO is enlarged.

When the VCO comes into a stable oscillation state, the turn-on time of the transistor is only a small fraction of the entire period (\( \omega_1 \)). The large pulse current is generated from the collector terminal of the bipolar transistor during the turn-on time. The fundamental component of the large pulse current is filtered out by the LC loop and fed back to the base terminal of the bipolar transistor. The average current generated during the entire cycle should be equal to the bias current \( (I_{bias}) \), as shown in Eq. (8).

![Fig. 4. Equivalent T-model of the proposed VCO with the additional capacitor (a) The equivalent T-model1 (b) The equivalent T-model2 that simplifies the equivalent T-model1](image)

\[
i_c = \frac{1}{T} \int_0^T i_c(t) \, dt = I_{bias}
\]  

(8)

The pulse current formula is expanded by using Fourier series, and it is

\[
i_c(t) = I_{c,0} + \sum_{n=1}^{\infty} I_{c,n} \cos(\frac{n\pi t}{T})
\]

(9)

\[
I_{c,1} = \frac{2}{T} \int_0^T i_c(t) \cos(\omega t) \, dt
\]

(10)

The turn-on time of the pulse current \( i_c(t) \) is very small, and \( \cos(\omega t) \) can be approximated as a constant unit value, so the fundamental current can be simplified to

\[
i_{c,1} \approx \frac{2}{T} \int_0^T i_c(t) \, dt = 2I_{bias}
\]

(11)

And then, it is got as

\[
G_m = \frac{I_{c,1}}{V_1} = \frac{2I_{bias}}{V_1}
\]

(12)

Thus, the small signal equivalent circuit shown in Fig. 4(a) could be simplified to Fig. 4(b). Where \( G_m=2I_{bias}/V_1 \) and \( V_c=2I_{bias}R_{total} \). Then the output power is

\[
P_{out} = \frac{(V_c')^2}{2R_L}
\]

(13)

Where \( V_c'=\eta_2V_c, \quad V_c=\eta_1V_c', \quad \eta_1=C_I/(C_1+C_2), \quad \text{and} \quad \eta_2=C_c/(C_c+C_1+C_2) \). Then the output power can be written as

\[
P_{out} = \frac{(2\eta_2I_{bias}R_{total})^2}{2R_L}
\]

(14)

According to Eq. (14), the output power varies as the value of \( C_c \) changes and the output power can be maximized by
selecting the proper value of $C_c$. Fig. 5(a) shows the numerical calculation results and circuit simulation results of the output power with different capacitances of $C_c$. The addition of $C_c$ significantly changes the output power and the output power reaches the maximal value when $C_c \approx C_1||C_2$. It is also seen that the simulation results are nearly consistent with the numerical calculation results via Eq. (14). As shown in Fig. 5(b), the output power is also improved by the addition of $C_c$ while the value of the load resistance changes. The output power of the proposed Colpitts VCO using $C_c$ larger than that without $C_c$. It is also shown that the output power achieves the maximal value when the value of $C_c$ is 1 pF.

3. Experimental verification

3.1 433 MHz Colpitts VCO design
A bipolar Colpitts VCO operating at 433 MHz is designed to verify the techniques of base inductor feedback and Q-factor enhancement which are proposed in this paper. The testing environment is shown in Fig. 6(a). The bipolar transistor named MMBR941 from MOTOROLA and the passive components from MURATA are used in the VCO design. The output power spectrum was measured by the spectrum analyzer N9010A (Agilent). The photograph of the measured output power spectrum is shown in Fig. 6(b).

3.2 Performance of Colpitts VCO
The results of three types of quiescent currents are obtained when the inductor ($L_g$) changes, as shown in Fig. 7(a). The upper and lower curves in Fig. 7(a) are the measured quiescent currents of critical oscillation state and critical un-oscillation state, respectively. The middle curve is the startup current from software emulation. Because the values of the current-limited resistors are unable to be selected arbitrarily in the practical measurements, there is a certain gap between the critical oscillation quiescent current and the corresponding critical un-oscillation quiescent current with a certain inductor. It is observed that the startup current of the VCO with the feedback inductor is about 21% lower than that without the feedback inductor when the value of $L_g$ is 25 nH.

3.3 Colpitts VCO used in neural signal recording
To confirm the applicability of the bipolar Colpitts VCO for analog signal acquisition, a low power neural signal acquisition module that consists of the analog amplifier, the bipolar Colpitts VCO and the antenna is proposed to record the neural signals of small animals. Due to the requirements

### Table I. Performance summary of the proposed Colpitts VCO in comparison with other reported VCOs recently

| Power (mW) | Supply (V) | Frequency (GHz) | DC-to-RF efficiency (%) |
|------------|------------|-----------------|-------------------------|
| [20]       | [25]       | [26]            | [31]                    | [32] | This work |
| 4.9        | 1.5        | 7.9             | 0.62                    | N/A  | N/A       | 3.0 |
| 0.34       | 3.0        | 0.8             | 3.0                     | N/A  | N/A       | 3.1 |
| 1.4        | 1.1        | 2.4             | 1.4                     | N/A  | N/A       | N/A |
| 4.2        | 1.4        | 2.4             | 0.75                    | 0.75 | 0.75      | 0.30 |
| 1.1        | 0.75       | 0.75            | 0.43                    |      | 0.43      |      |
| 0.27       |            |                 |                         |      |           |      |

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of long-time and free-activity in the neural signal recording experiments, the module should have low power consumption, lightweight and wireless transmission. Fig. 8 shows the structure of the low-power neural signal acquisition module and the verification flow of its application. At last, the original neural signals in an area of the honeybee brain are acquired, and it is shown that the spike signals and field potential signals are mixed up (Fig. 8). According to the test results, the power consumption of the module is about 743 µW in a 3 V power supply, and its effective communication distance is up to 20 cm with the 5×5 mm² PCB antenna. Compared with other acquisition modules (Table II), the design scheme of the bipolar Colpitts VCO proposed for analog signal acquisition is feasible.

![Fig. 8](image-url)

Fig. 8. The verification flow of the Colpitts VCO applied in neural signal recording

| Power Supply (V) | ±1.55 | ±3 | ±1.5 | ±1.5 | ±1.5 | N/A | 3.7 | 3.0 |
|-----------------|-------|----|------|------|------|-----|-----|-----|
| RF frequency (MHz) | 433 | 916 | 94-98 | 433 | 915 | 13.56 | 6400 | 433 |
| No. of channels | 4 | 6 | 1 | 4 | 8 | 1 | 2 | 1 |
| Power Consumption (mW) | 28 | 66 | 1.66 | 26.9 | 51.4 | 1.9 | 45.5 | 0.74 |
| Size (mm²) | 39×44×12 | 25×25×10 | 17×12×1.6 | N/A | 35×25×8 | 28×24×14.4 | 44.5×16.6×9.9 | 20×25×5 |
| AFE gain (dB) | 70 | 46 | 43.7 | 51.5-65.5 | 40 | 46-71 | N/A | 58 |
| AFE bandwidth (Hz) | 0.01–20k | 1–1k | 0.1–10k | 1–12k | 1–8k | N/A | 0.1–5k | 0.5–10k |
| CMRR (dB) | 90 | N/A | N/A | N/A | 56.4 | N/A | 100 |

**Table II. Performance comparison of neural signal acquisition modules**

| No. of channels | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
|-----------------|---|---|---|---|---|---|---|---|
| Size (mm²) | 39×44×12 | 25×25×10 | 17×12×1.6 | N/A | 35×25×8 | 28×24×14.4 | 44.5×16.6×9.9 | 20×25×5 |
| AFE gain (dB) | 70 | 46 | 43.7 | 51.5-65.5 | 40 | 46-71 | N/A | 58 |
| AFE bandwidth (Hz) | 0.01–20k | 1–1k | 0.1–10k | 1–12k | 1–8k | N/A | 0.1–5k | 0.5–10k |
| CMRR (dB) | 90 | N/A | N/A | N/A | 56.4 | N/A | 100 |

**4. Conclusion**

A circuit optimization method is proposed to improve the power consumption and DC-to-RF efficiency of bipolar Colpitts VCO in this paper. Two techniques named base inductive feedback and Q-factor enhancement are used to reduce the start-up current and the energy loss of the bipolar Colpitts VCO, respectively. In the 433 MHz bipolar Colpitts VCO design, the start-up current with feedback inductor is about 21% lower than that without feedback inductor, and the maximal DC-to-RF efficiency is about 51% higher than that without using a capacitor voltage divider. The practical verifications of the Colpitts VCO and its application in neural signal recording proved that the design scheme of the proposed bipolar Colpitts VCO is available for analog signal acquisition applications.

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**References**

[1] O. Elsayed, et al.: “An ultra low-power RF wireless receiver with RF blocker energy recycling for IoT applications,” IEEE Trans. Microwave Theory and Techniques 66 (2018) 4927 (DOI: 10.1109/TMTT.2018.2868683).

[2] B. Thoen, et al.: “A deployable LPWAN platform for low-cost and energy-constrained IoT applications,” Sensors 19 (2019) 585 (DOI: 10.3390/s19030585).

[3] H. Morimura, et al.: “Ultra-low-power circuit techniques for mm-size wireless sensor nodes with energy harvesting,” IEICE Electron. Express 11 (2014) 20142009 (DOI: 10.1587/elex.11.20142009).

[4] J. Jeong, et al.: “A 42nd/conversion on-demand state-of-charge indicator for miniature IoT li-ion batteries,” IEEE J. Solid-State Circuits (2019) 524 (DOI: 10.1109/JSSC.2018.2876472).

[5] G. D. y Alvarez, et al.: “Wireless EEG system achieving high throughput and reduced energy consumption through lossless and near-lossless compression,” IEEE Trans. Biomedical Circuits and Systems 12 (2018) 231 (DOI: 10.1109/TBCAS.2017.2779324).

[6] D. Huo, et al.: “A compact and low-power wireless receiver for implanted medical backscatter,” IEICE Electron. Express 16 (2019) 20190501 (10.1587/elex.16.20190501).

[7] L.-H. Wang, et al.: “Implementation of a wireless ECG acquisition SoC for IEEE 802.15.4 (ZigBee) applications,” IEEE J. Biomedical and Health Informatics 19 (2015) 247 (DOI: 10.1109/JBHI.2014.2311232).

[8] S. Yoshimoto, et al.: “Flexible electronics for biosignal monitoring in implantable applications,” IEICE Electron. Express 14 (2017) 20172003 (DOI: 10.1587/elex.14.20172003).

[9] C. S. Abella, et al.: “Autonomous energy-efficient wireless sensor network platform for home/office automation,” IEEE Sensors J. 19 (2019) 3501 (DOI: 10.1109/JSEN.2019.2892604).

[10] R. S. Dilmaghani, et al.: “Wireless sensor networks for monitoring physiological signals of multiple patients,” IEEE Trans. Biomedical Circuits and Systems 5 (2011) 347 (DOI: 10.1109/TBCAS.2011.2114661).

[11] F. Boscolo, et al.: “A 21GHz 20.5%-tuning range Colpitts VCO with -119 dBc/Hz phase noise at 1MHz offset,” IEEE European Solid State Circuits Conference (2017) 91 (DOI: 10.1109/ESSCIRC.2017.8094533).
[12] X. Cheng, et al.: "A low phase noise InGap–GaAs HBT Colpitts VCO with a high quality differential inductor," Analog Integrated Circuits and Signal Processing 100 (2019) 469 (DOI: 10.1007/s10470-019-01426-w).

[13] F. Quadrelli, et al.: "A 18.2-29.3 GHz Colpitts VCOs bank with -119.5 dBc/Hz phase noise at 1 MHz offset for 5G communications," IEEE Radio Frequency Integrated Circuits Symposium (2019) 167 (DOI: 10.1109/RFIC.2019.8701813).

[14] J.-P. Hong: "A low supply voltage and wide-tuned CMOS Colpitts VCO," IEICE Electron. Express 11 (2014) 20140428 (DOI: 10.1587/ex.11.20140428).

[15] T. Li, et al.: "A novel direct sequence spread spectrum CDMA system with analog frequency modulation," International J. Wireless Information Networks 7 (2000) 43 (DOI: 10.1023/a:1009592101249).

[16] T. Rahkonen, et al.: "A 3-V analog FM-modulator based on a delay-modulated PLL synthesizer," IEEE Midwest Symposium on Circuits and Systems (1997) 553 (DOI: 10.1109/MWSCAS.1997.666196).

[17] C. Hewitt and D. Wang: "Surviving the digital transition: Maintaining UHF microphone systems for the future," International Symposium on Industrial Electronics (2014) 1056 (DOI: 10.1109/ISIE.2014.6864759).

[18] T.-P. Wang: "A CMOS Colpitts VCO using negative-conductance boosted technology," IEEE Trans. Circuits and Systems-I: Regular Papers 58 (2011) 2623 (DOI: 10.1109/TCSI.2011.2143270).

[19] K.-W. Ha, et al.: "Transformer-based current-reuse armstrong and armstrong-Colpitts VCOs," IEEE Trans. Circuits and Systems-II: Express Briefs 61 (2014) 676 (DOI: 10.1109/TCSII.2014.2331112).

[20] J.-A. Hou and Y.-H. Wang: "A 7.9 GHz low-power PMOS Colpitts VCO using the gate inductive feedback," IEEE Microwave and Wireless Components Letters 20 (2010) 223 (DOI: 10.1109/LMWC.2010.2042559).

[21] C.-I. Shie, et al.: "Low power and high efficiency VCO and quadrature VCO circuits constructed with transconductance-enhanced Colpitts oscillator feature," IEICE Trans. Electron. E91-C (2008) 193 (DOI: 10.1093/ietele/e91-c.2.193).

[22] J.-A. Hou and Y.-H. Wang: "A 5 GHz differential Colpitts VCO using the bottom PMOS cross-coupled source," IEEE Microwave and Wireless Components Letters 19 (2009) 401 (DOI: 10.1109/LMWC.2009.2020038).

[23] S. Wang and C.-Y. Xiao: "A 7/24 GHz CMOS VCO with high band ratio using a current-source switching topology," IEEE Trans. Ultrasonics Ferroelectrics and Frequency Control 63 (2016) 790 (DOI: 10.1109/TUFFC.2016.2536702).

[24] W. C. Lai, et al.: "Ultra low power Colpitts VCO with body-bias voltage controlled technique," IEEE International Symposium on Radio-Frequency Integration Technology (2016) 1 (DOI: 10.1109/RFFIT.2016.7578127).

[25] L. W. Chek, et al.: "Multiple output LC tank varactor VCO with ultra-low power consumption and low-phase noise," IEEE Malaysia International Conference on Communications (2015) 310 (DOI: 10.1109/MICC.2015.7725453).

[26] K.-W. Cheng, et al.: "Low-power and low-phase-noise Gm -enhanced current-reuse differential Colpitts VCO," IEEE Trans. Circuits and Systems-II: Express Briefs 66 (2019) 733 (DOI: 10.1109/TCSII.2019.2908423).

[27] B. O. Otis and J. M. Rabaei: "A 300-µW 1.9 GHz CMOS oscillator utilizing micromachined resonators," IEEE J. Solid-State Circuits 38 (2003) 1271 (DOI: 10.1109/JSSC.2003.813219).

[28] J. Koo, et al.: "A 2-GHz FBAR-based transformer coupled oscillator design with phase noise reduction," IEEE Trans. Circuits and Systems-II: Express Briefs 66 (2019) 542 (DOI: 10.1109/TCSII.2018.2867563).

[29] R. E. Rottava, et al.: "Ultra-low-power, ultra-low-voltage 2.12 GHz Colpitts oscillator using inductive gate degeneration," IEEE International New Circuits and Systems Conference (2013) 1 (DOI: 10.1109/NewCAS.2013.6573614).

[30] O.-P. Lunde, et al.: "A simple closed-form analysis of Clapp oscillator output power using a novel quasi-linear transistor model," IEEE Radio and Wireless Symposium (2014) 88 (DOI: 10.1109/RWS.2014.6830073).

[31] A. Mostajeran, et al.: "A 2.4 GHz VCO with FOM of 190MB/Hz at 10kHz-to-2MHz offset frequencies in 0.13 µm CMOS using an ISF manipulation technique," ISSCC Dig. Tech. Papers (2015) 452 (DOI: 10.1109/ISSCC.2015.7063121).

[32] K. A. Sankaragomathi, et al.: "A ±3ppm 1.1 mW FBAR frequency reference with 750MHz output and 750V supply," ISSCC Dig. Tech. Papers (2015) 454 (DOI: 10.1109/ISSCC.2015.7063122).

[33] M. Chae, et al.: "A 4-channel wearable wireless neural recording system," IEEE International Symposium on Circuits and Systems (2008) 1760 (DOI: 10.1109/ISCAS.2008.4541779).

[34] S. Farshchi, et al.: "A tinyOS-enabled MICA2-based wireless neural interface," IEEE Trans. Biomedical Engineering 53 (2006) 1416 (DOI: 10.1109/TBME.2006.873760).

[35] P. Mohseni, et al.: "Wireless multichannel biopotential recording using an integrated FM telemetry circuit," IEEE Trans. Neural Systems and Rehabilitation Engineering 13 (2005) 263 (DOI: 10.1109/TNSRE.2005.853625).

[36] M. Azin, et al.: "A battery-powered activity-dependent intracrortical microstimulation IC for brain-machine-brain interface," IEEE J. Solid-State Circuits 46 (2011) 731 (DOI: 10.1109/JSSC.2011.2108770).

[37] S. B. Lee, et al.: "An inductively-powered wireless neural recording system with a charge sampling analog front-end," IEEE Sensors J. 16 (2016) 475 (DOI: 10.1109/TSENS.2015.2483747).

[38] Z. He, et al.: "A wireless powered implantable and flexible neural recording and stimulating system based on NFC protocol," IEEE International Conference on Integrated Circuits, Technologies and Applications (2018) 100 (DOI: 10.1109/CICTA.2018.8706062).

[39] M. A. Kanchwala, et al.: "A miniature wireless neural recording system for chronic implantation in freely moving animals," IEEE Biomedical Circuits and Systems Conference (2018) 335 (DOI: 10.1109/BIOCAS.2018.8584701).