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AN ADVANCED ANALYSIS METHOD OF COLPITTS OSCILLATOR CIRCUIT

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Abstract. Oscillator circuits are one of the most important components in communication devices. Although oscillator circuits have been widely used in practice, their analytical theories still have more errors when calculating the design of oscillator circuits in the high-frequency region. In this paper, we review current theoretical analysis methods of the Colpitts oscillator circuit and point out the limitations of these methods. From there, we propose an advanced analysis method to increase the accuracy of calculating the oscillation frequency in the high-frequency domain.

Keywords. Radio frequency, high-frequency oscillator circuit, Colpitts oscillator.

1 INTRODUCTION

1.1 Introduction about oscillator

An oscillator generates stable periodic signals at a certain frequency. High-frequency oscillator circuits are the main component of most electronic devices for various applications, such as:

- Radio frequency (RF) communication: In radios, cell phones, and Wi-Fi routers, oscillators provide the carrier signal for transmitting and receiving wireless signals.
- Clock generation: Computers, microcontrollers, and other digital devices rely on oscillators to keep time and synchronize operations.

1.2 The operation principle of a radio frequency oscillator

Oscillator circuits are formed from two basic components, an amplifier with gain $A(\omega)$ and a feedback circuit with its transform $B(\omega)$, as shown in Figure 1. The amplifier supplies the power for the feedback circuit. We call x_a is the input signal of the amplifier at the first time t_0, and x_b is the output signal of the feedback circuit at the second time t_1. It is assumed that x_a transmits through the amplifier and feedback circuit from the time t_0 to t_1. Hence, we have an analysis as follows,

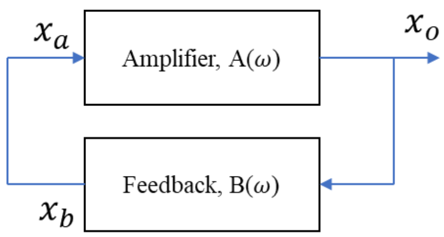

Figure 1. A general block diagram of an oscillator circuit.

$$x_o = Ax_a \quad (1)$$

$$x_b = Bx_0 \quad (2)$$

If $(x_b < x_a)$ then oscillation gradually subsides or If $(x_b \geq x_a)$ then the circuit will automatically oscillate.

From eq (1) and eq (2), we get the loop-gain transform of the oscillator circuit as,

$$A_f = \frac{x_b}{x_a} = AB \quad (3)$$

So, the loop-gain condition of the oscillator circuits at $\omega = \omega_0$,

$$A_f \geq 1. \quad (4)$$

The above analysis for the oscillator circuit was also presented by Gonzales in [1] and some other authors in [2] and [3]. We get the loop-gain condition of the oscillator circuit at $\omega = \omega_0$,

$$\leftrightarrow \begin{cases} A_f \geq 1 \\ \theta_{A_f} = \pm k2\pi, \ k \in (0,1) \end{cases} \quad (5)$$

With θ_{A_f} is the phase responding of the loop-gain transform.

1.3 The art of analysis theories

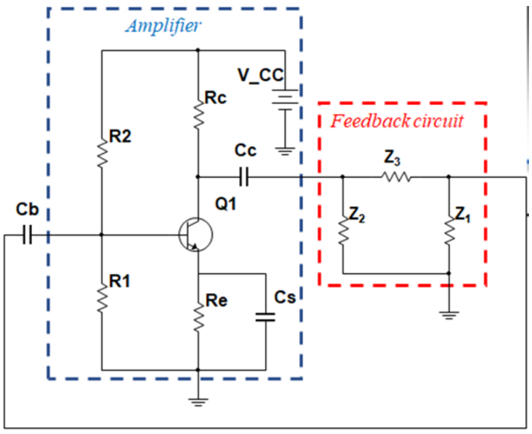

Figure 2. A general model for high-frequency oscillating circuits.

A general high-frequency oscillator using BJT is presented in Figure 2, which is the combination of a BJT amplification circuit, and a feedback circuit. We use the π filter circuit for the feedback circuit which the equivalent impedances of components are Z_1, Z_2, and Z_3. As systemized in [3], It is up to the configuration of L and Cs of the feedback circuit, we have three popular types of RF oscillator circuits, Colpitts, Hartley, or Clapp, as shown in Figure 3.

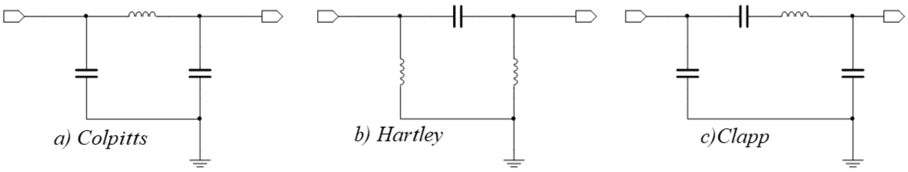

Figure 3. Three configuration types of feedback circuits of the RF oscillator circuits.

In this paper, we select the Colpitts oscillator using BJT for building the analysis method. The schematic of the Colpitts oscillator circuit is shown in Figure 4. The BJT transistor has its parameters, amplification factor β, parasitic capacitors c_{be} and c_{bc}, as described in Figure 5.

The brief equivalent circuit of the Colpitts oscillator is shown in Figure 6, in which:

- Z_i is the input equivalent impedance of the amplifier circuit.
- Z_o is the output equivalent impedance of the amplifier circuit.
- Z_1 is the equivalent impedance of C_1.
- Z_2 is the equivalent impedance of C_2.
- Z_3 is the equivalent impedance of $\{L_3 \ serial \ r_S\}$, with r_S is the internal resistance of L_3.

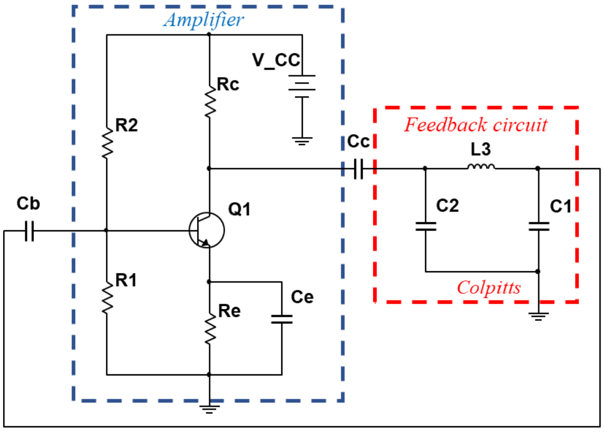

Figure 4. The schematic circuit of Colpitts oscillator.

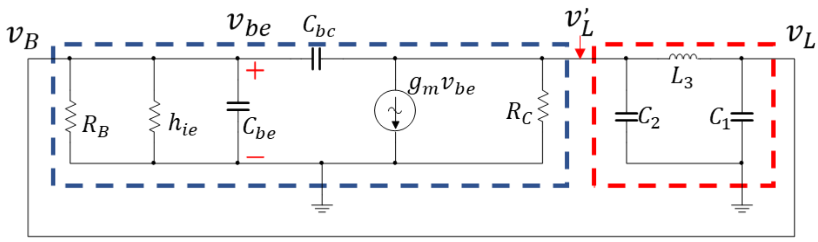

Figure 5. The high-frequency small signal equivalent circuit of the Colpitts oscillator circuit.

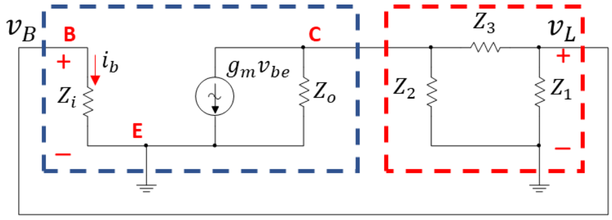

Figure 6. The simple equivalent circuit of the Colpitts oscillator.

The open-again of the amplifier circuit is inferred by removing the feed-back circuit and C_{bc} as follows,

$$A_v = \frac{v'_L}{v_b} = \frac{g_m v_{be} R_C}{v_{be}} = g_m R_C \tag{6}$$

Write the loop-again transform equation, and we obtain,

$$A_{vf} = \frac{v_L}{v_b} = \frac{v_L}{v_c} \times \frac{v_c}{g_m v_{be}} \times \frac{g_m v_{be}}{v_b}$$

$$A_{vf} = \frac{g_m (Z_1//Z_i)}{Z_1//Z_i + Z_3} \times \left(-Z_o//Z_2//(Z_1//Z_i + Z_3)\right) \tag{7}$$

Discovering basic theories for analyzing Colpitts oscillating circuits revealed two groups of analysis methods, the simple methods and the Miller equivalent methods.

a) Simple methods

Because expanding eq (7) is very complex to find the loop-gain condition of the oscillator circuit, as concerned in [2], [3], and [4], the authors skipped the parasite capacitors of transistors. In practice, the parasite capacitor of BC junction, C_{bc}, is small, from pF to several dozen pF; and the parasite capacitor of BE junctions, C_{be}, can be assumed too small to compare C_1, so they could be ignored in the equivalent circuit of the Colpitts oscillator.

Moreover, r_S is often too small so we can omit it. This simple method assumed that $R_1//R_2$ is designed too larger than h_{ie} so we have $Z_i = h_{ie}//R_1//R_2 \approx h_{ie}$. Therefore, the high-frequency small signal equivalent circuit of the simple method is described in Figure 7, in which $Z_1 = 1/j\omega C_1$, $Z_2 = 1/j\omega C_2$, and $Z_3 = j\omega L_3$. And, another brief way, we call $Z_1 = jX_1$, $Z_2 = jX_2$ và $Z_3 = jX_3$.

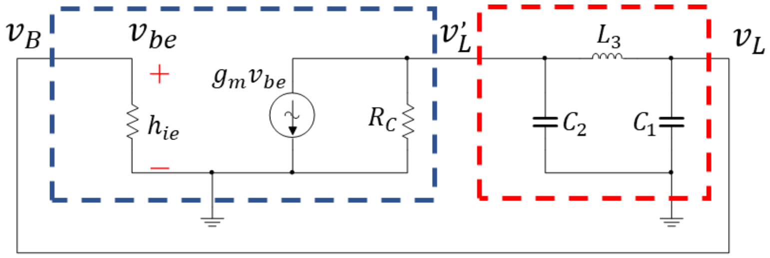

Figure 7. The high-frequency small signal equivalent circuit of the simple method.

To simplify the design problem, we assumed that,

$$|Z_0| \gg |Z_2| \;=> R_C \gg \left|\frac{1}{j\omega C_2}\right|$$

$$=> C_2 \gg \frac{1}{\omega R_C} \tag{8}$$

So,

$$Z_2//Z_0 \approx Z_2 \tag{9}$$

From eq (7) and eq (9), we expand and obtain,

$$A_{vf} = \frac{-g_m Z_i Z_1 Z_2}{Z_i(Z_1+Z_2+Z_3)+Z_1(Z_2+Z_3)} \tag{10}$$

$$A_{vf} = \frac{g_m Z_i X_1 X_2}{j\{Z_i(X_1+X_2+X_3)\}-X_1(X_2+X_3)} \tag{11}$$

Based on the condition of the oscillator in [5], we get

$$A_{vf} \geq 1 \;<=> \begin{cases} Im(A_{vf}) = 0 \\ Re(A_{vf}) \geq 1 \end{cases} \tag{12}$$

$$<=> \begin{cases} jR_c(X_1 + X_2 + X_3) = 0 \\ \dfrac{g_m h_{ie} X_1 X_2}{-X_1(X_2+X_3)} \geq 1 \end{cases} \tag{13}$$

$$<=> \begin{cases} X_1 + X_2 + X_3 = 0 \\ \dfrac{\beta X_2}{X_1} \geq 1 \end{cases} \tag{14}$$

$$<=> \begin{cases} \dfrac{-1}{\omega C_1} + \omega L_3 = \dfrac{1}{\omega C_2} \\ \beta \geq \dfrac{C_2}{C_1} \end{cases} \tag{15}$$

From eq (15), we define the oscillator frequency at,

$$f_0 = \frac{1}{2\pi\sqrt{L_3 C_T}}, \text{ with } C_T = \frac{C_1 C_2}{C_1+C_2} \tag{16}$$

We also define the oscillator condition at,

$$\beta \geq \frac{C_2}{C_1} \tag{17}$$

Some methods have approached matrix parameters Z, Y, and H to solve the problem with the same results in the oscillator frequency and the oscillator condition as in [1], [6], [7], and [8].

b) Miller equivalent methods

To increase the accuracy of Colpitts oscillator circuit analysis, the parasitic capacitor C_{be} has been used for analysis in [9] but omitted C_{bc} in this method.
The feedback parasitic capacitor C_{bc} creates the Miller effect [10] in the BJT transistor amplifier at high frequency. The Miller effect is also mentioned in a review paper about common Colpitts oscillator circuits [11]. So, removing C_{bc} in the Colpitts oscillator circuit analysis theories also increase the error for calculating the oscillator frequency.
To decrease the Miller effect and increase the accuracy of analysis theory, the authors in [12] used Miller equivalent capacitance, $C_M = (1 + g_m R_C // h_{ie}) C_{bc}$, to replace the parasitic capacitor C_{bc}, as in Figure 8. C_M is connected in parallel with C_{be}.
The final equivalent circuit of the Miller equivalent method is present in Figure 9, with $C_1^* = C_1 + C_{be} + C_M$. Hence, we have a small change, $Z_1 = 1/j\omega C_1^*$.

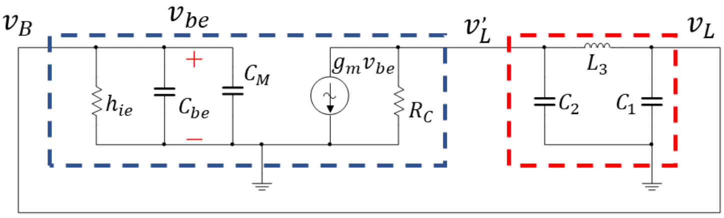

Figure 8. The high-frequency small signal equivalent circuit of the Miller equivalent method.

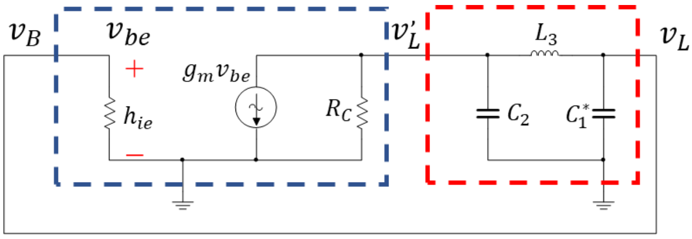

Figure 9. The final equivalent circuit of the Miller equivalent method.

Furthermore, they assumed that Z_i is designed so that $Z_i \gg |Z_1|$. Therefore, Z_i is omitted in eq (7), and we obtain the loop again equation,

$$A_{vf} = \frac{-g_m Z_o Z_1 Z_2}{Z_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)} \tag{18}$$

Apply the condition of the oscillator circuit referred from [12],

$$A_{vf} \geq 1 \ <=> \begin{cases} Im(A_{vf}) = 0 \\ Re(A_{vf}) \geq 1 \end{cases} \tag{19}$$

$$<=> \begin{cases} jR_c(X_1 + X_2 + X_3) = 0 \\ \dfrac{g_m R_c X_1 X_2}{-X_2(X_1+X_3)} \geq 1 \end{cases} \tag{20}$$

$$<=> \begin{cases} \dfrac{-1}{\omega C_1^*} + \omega L_3 = \dfrac{1}{\omega C_2} \\ g_m R_c \geq \dfrac{C_1^*}{C_2} \end{cases} \tag{21}$$

From eq (22), we define the oscillator frequency at,

$$f_0 = \frac{1}{2\pi\sqrt{L_3 C_T^*}}, \text{ with } C_T^* = \frac{C_1^* C_2}{C_1^* + C_2} \tag{22}$$

We also define the oscillator condition at,

$$g_m R_c \geq \frac{C_1^*}{C_2} \tag{23}$$

c) The idea of this paper

In the simple methods, the parasitic capacitors C_{bc} and C_{be} are skipped, for it is assumed that it has a small value from some pF to several dozen pF. This can be accepted at low frequencies, but in the high-frequency domain, ignoring C_{bc} and C_{be} will increase the error between the real oscillator frequency and the calculated frequency.

With the Miller equivalent method, to increase the accuracy of analysis theory, the authors didn't skip the parasite capacitor between BE junctions, C_{be}, and the parasite capacitor between BC junctions, C_{bc}. Instead, they used a Miller capacitor to replace C_{bc}. However, in the high-frequency small signal equivalent circuit of the Colpitts oscillator as in Figure 10, there are two feedback branches, C_{bc} and the Colpitts feedback circuit. Therefore, applying Miller's theory in [12] will be not enough correct. It will create the error between the real oscillator frequency and the calculated frequency based on theory in the high-frequency domain.

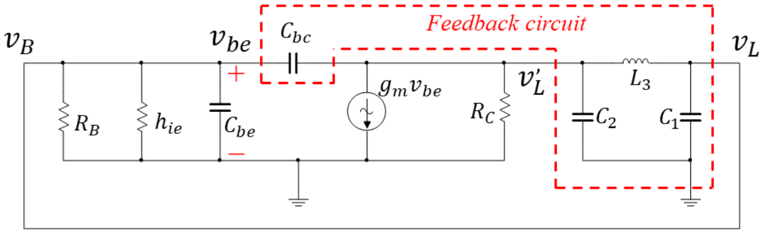

Figure 10. Presentation of the high-frequency small signal equivalent Colpitts oscillator with full feedback.

Hence, to address the limitations of current Colpitts oscillator analysis theories, this paper proposes an enhanced analysis method by using all practical components such as C_{bc}, the Colpitts feedback circuit, and adding some hypotheses to simplify and increase the accuracy of the analysis theory.

2 A PROPOSED METHOD FOR ANALYZING COLPITTS OSCILLATOR CIRCUIT

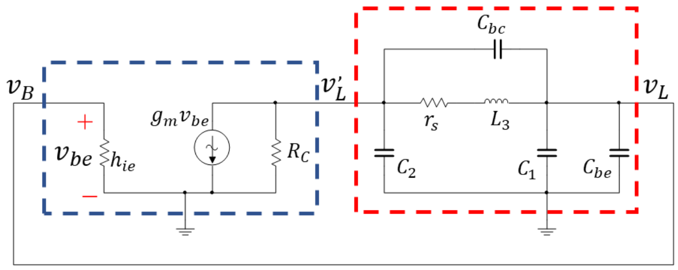

Figure 11. The final equivalent circuit of the proposed method for the Colpitts oscillator.

The final equivalent circuit using the proposed method of the Colpitts is shown in Figure 11. We can see:

- Z_1 is the equivalent impedance of $C_1 // C_{be}$.
- Z_2 is the impedance of C_2.
- Z_3 is the equivalent impedance of $\{[L_3 \; serial \; r_S] // C_{bc}\}$, with r_S being the internal resistance of L_3.

Expanding eq (7) in the case of an equivalent circuit in Figure 11 is very complex. Therefore, we add some hypotheses to simplify and increase the accuracy of the analysis theory.

The first hypothesis, the input impedance is too small to compare with the impedance of C_1 or,

$$|Z_i| \gg |Z_1| \;=> h_{ie} \gg \left|\frac{1}{j\omega(C_1+C_{be})}\right|$$

$$=> C_1 \gg \frac{1}{\omega h_{ie}} - C_{be} \tag{24}$$

So that,

$$Z_1//Z_i \approx Z_1 \tag{25}$$

The second hypothesis, the impedance of L_3 is too small to compare with the resistance of r_S or,

$$\left|Z_{L_3}\right| \gg r_S => L_3 \gg \frac{r_S}{\omega} \tag{26}$$

So that $Z_3 \approx Z_{(L_3//\,C_{bc})}$ or

$$Z_3 = j\left(\frac{\omega L_3}{1-\omega^2 L_3 C_{bc}}\right) \tag{27}$$

From there, we apply eq (25) into eq (7), we get the loop gain of the oscillator circuit,

$$A_{vf} = \frac{-g_m Z_o Z_1 Z_2}{Z_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)} \tag{28}$$

We also call $Z_1 = jX_1$, $Z_2 = jX_2$ và $Z_3 = jX_3$ with Z_1 and Z_2 are capacitors. Then, we get:

$$A_{vf} = \frac{g_m R_c X_1 X_2}{jR_c(X_1+X_2+X_3)-X_2(X_1+X_3)} \tag{29}$$

To satisfy the characteristic of the Colpitts oscillator circuit, we add the third hypothesis that Z_3 is an inductor or $X_3 > 0$. Hence, we can infer from eq (27):

$$\leftrightarrow \frac{\omega L_3}{1-\omega^2 L_3 C_{bc}} > 0 \tag{30}$$

$$L_3 < \frac{1}{4\pi^2 f_o^2 C_{bc}} \tag{31}$$

Apply the condition of the oscillator circuit, and we get:

$$A_{vf} \geq 1 \;<=> \begin{cases} Im\left(A_{vf}\right) = 0 \\ Re\left(A_{vf}\right) \geq 1 \end{cases} \tag{32}$$

$$<=> \begin{cases} jR_c(X_1+X_2+X_3) = 0 \\ \dfrac{g_m R_c X_1 X_2}{-X_2(X_1+X_3)} \geq 1 \end{cases} \tag{33}$$

$$<=> \begin{cases} X_1 + X_2 + X_3 = 0 \\ \dfrac{g_m R_c X_1}{X_2} \geq 1 \end{cases} \tag{34}$$

$$<=> \begin{cases} f_o = \dfrac{1}{2\pi\sqrt{L_3(C_{12}+C_{bc})}} \text{ , với } C_{12} = \dfrac{(C_1+C_{be})C_2}{C_1+C_{be}+C_2} \\ g_m R_c \geq \dfrac{(C_1+C_{be})}{C_2} \end{cases} \tag{35}$$

Hence, from the eq (26) and eq (35), we infer from the second hypothesis as below, eq (36) and eq (37).

$$L_3 \gg \frac{r_S}{\omega} \quad \leftrightarrow \quad \frac{1}{4\pi^2 f_o^2 (C_{12}+C_{bc})} \gg \frac{r_s}{2\pi f_o}$$

$$\leftrightarrow \quad \frac{1}{2\pi f_o r_s} - C_{bc} \gg C_{12} \tag{36}$$

And,

$$C_2 \geq \frac{C_1+C_{be}}{g_m R_c} \tag{37}$$

It is also from eq (35), we withdraw the oscillating frequency of the Colpitts oscillator is,

$$f_o = \frac{1}{2\pi\sqrt{L_3(C_{12}+C_{bc})}} \tag{38}$$

Finally, to make it easy for the above Colpitts oscillator circuit analysis theory, we summarize the conditions from the hypotheses as follows,

1) $C_1 \gg \frac{1}{2\pi f_o R_{be}} - C_{be}$
2) $C_2 \geq \frac{C_1+C_{be}}{g_m R_c}$
3) $C_{12} \ll \frac{1}{2\pi f_o r_s} - C_{bc}$
4) $L_3 < \frac{1}{4\pi^2 f_o^2 C_{bc}}$

3 RESULTS

We performed simulations using MULTISIM software for the Colpitts oscillator circuit, as shown in Figure 6. In practice, the value of parasitic capacitors C_{bc} can be only supplied in a range from some pF to several dozen pF, as seen in [13]. To measure exactly the parasitic capacitor value of each transistor, a specialized equipment such as a vector network analyzer is used, as mentioned in [14]. In the case of this paper, we use transistor BJT 2SC1815 to have simulating parameters, C_{be}= C_{bc}= 10.2pF, amplification factor β =113, and base resistance r_b= 2.5Ω.

Next, we select the oscillator frequencies as in the column f_o at the proposed method in Table 1. Then, while changing the values pair of values C_1 and C_2, we calculate the values of L_3 by using eq (39) and check the conditions by using the proposed method. After that, based on the values of C_1, C_2, and L_3, we solve the oscillator frequencies and check their corresponding conditions by using the simple method and the Miller equivalent method. The results of different methods are shown in Table 1 and Figure 12. The simulation method column illustrates the oscillator frequencies measured on simulation by MULTISIM software; The simple method column presents the oscillator frequencies calculated by the theory of this method and the percentage errors between the oscillator frequencies calculated and the simulation frequencies; The Miller equivalent method column presents the oscillator frequencies calculated by the theory of this method and the percentage errors between the oscillator frequencies calculated and the simulation frequencies. We can see that the average error of the proposed method at 4.8% is much less than other methods, the simple method at 36.4%, and the Miller equivalent method at 27.8%.

To evaluate the percentage errors on the frequency scale, we perform statistical Table 2 and Figure 13. It revealed that the higher the frequency we performed in the oscillator circuit, the larger the errors of the calculated frequency we get by the recent methods except the proposed method. For example, at the oscillator frequency 526.7 MHZ, the percentage error is 82.4% for the simple method, and 66.5% for the Miller equivalent method, while that of the proposed method is only 5.0%. Moreover, when observing the graph for percentage errors between the different methods, we see that the proposed method has very small errors and is more stable than that of others, especially in the high-frequency domain.

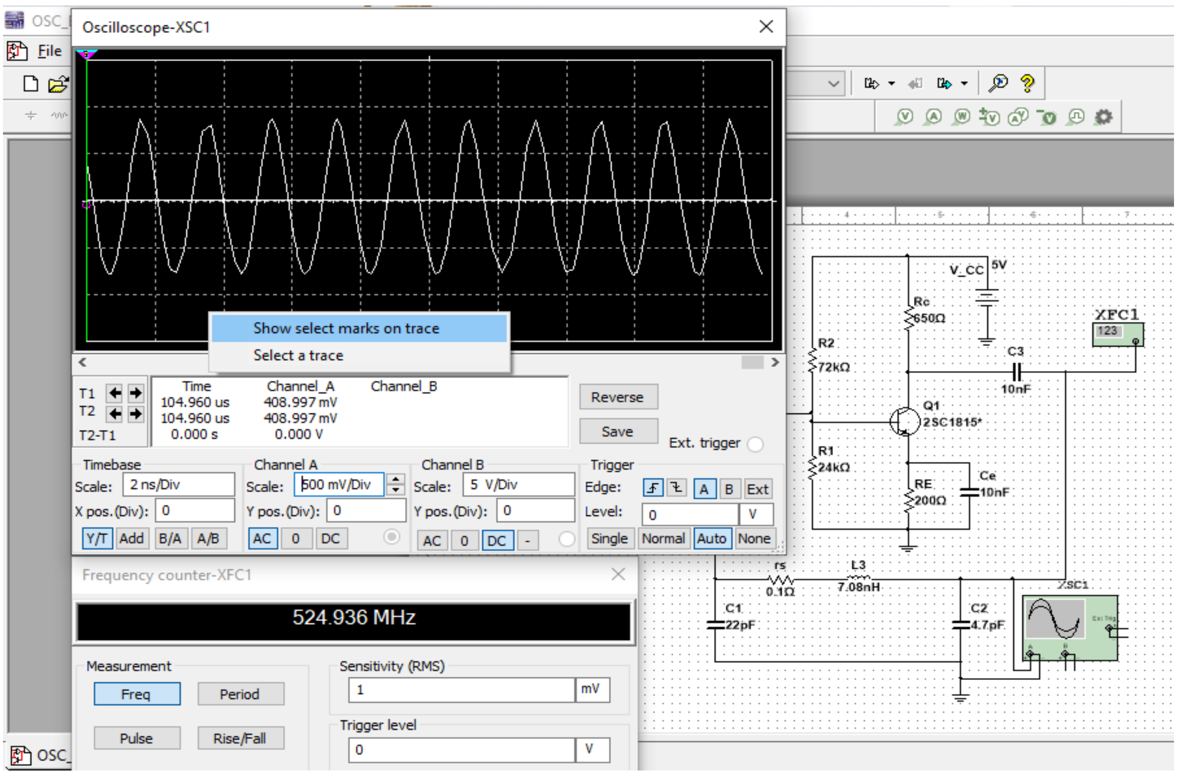

Figure 12. Simulation of a Colpitts oscillator circuit.

Table 1. The statistical results of the different Colpitts oscillator analysis methods.

Values of C_1, C_2, and L_3	Simulation method	Simple method		Miller equivalent method		Proposed method	
	f_o (MHz)	f_o (MHz)	Error (%)	f_o (MHz)	Error (%)	f_o (MHz)	Error (%)
$1nF$, $100pF$, and $2.5\mu H$	10,0	10,6	6,00	10,4	4,00	10	0,00
$1nF$, $100pF$, and $0.278\mu H$	29,5	31,6	7,12	31,2	5,76	30	1,69
$100pF$, $33pF$, and $0.197\mu H$	63,4	71,8	13,25	64,4	1,58	60	5,36
$100pF$, $22pF$, and $88.76nH$	106,3	125,8	18,34	116,4	9,50	100	5,93
$100pF$, $22pF$, and $22.19nH$	209,1	251,6	20,33	232,9	11,38	200	4,35
$33ppF$, $4.7pF$, and $19.49nH$	333,3	562	68,62	528,7	58,63	300	9,99
$33pF$, $4.7pF$, and $10.96nH$	427,2	749,3	75,40	705,0	65,03	400	6,37
$22pF$, $4.7pF$, and $7.08nH$	526,7	960,8	82,42	877,2	66,55	500	5,07
Everage errors			**36,43**		**27,80**		**4,85**

Table 2. The error statistic results of the different Colpitts oscillator analysis methods.

Frequency points for simulation	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Simulation frequencies (MHz)	**9,96**	**29,5**	**63,4**	**107**	**209,1**	**333,3**	**427,2**	**526,7**
Errors of the simple method (%)	6,00	2,1	13,25	18,34	20,33	68,62	75,40	82,42
Errors of the Miller equivalent method (%)	4,00	5,76	1,58	9,50	11,38	58,63	65,03	66,55
Errors of the proposed method (%)	0,00	1,69	5,36	5,93	4,35	9,99	6,37	5,07

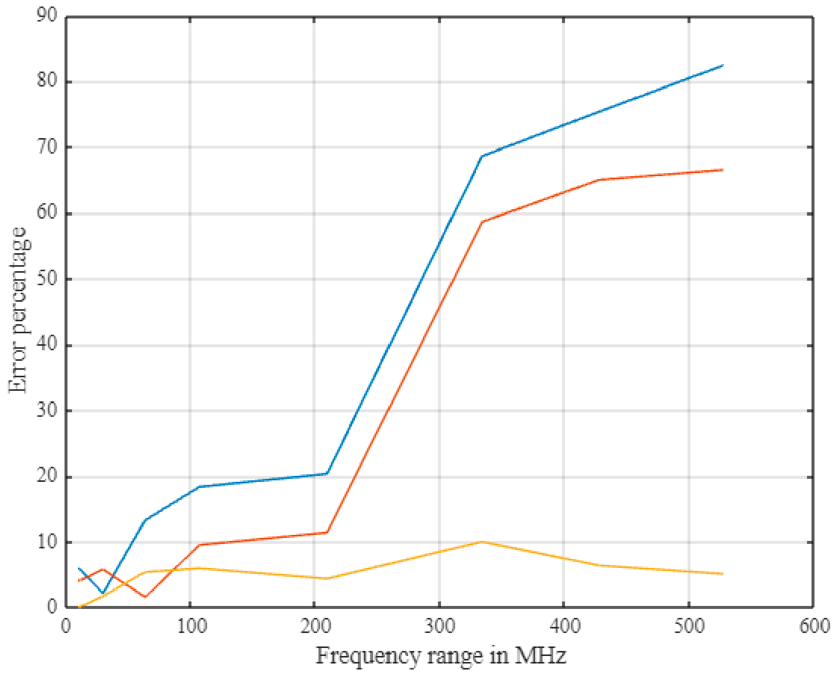

Figure 13. Illustrate the graph for percentage errors of the different methods. The blue line is the result of the simple method, the red line is that of the Miller equivalent method, and the yellow line is that of the proposed method.

4 CONCLUSIONS

The analysis theory of RF oscillator circuits is a crucial step in designing communication devices, but current analytical theories still have certain limitations. This makes it more difficult to calculate and design high-frequency oscillator circuits to get an accuracy value. In this paper, we reviewed current theory methods about Colpitts oscillator circuits and pointed out the limitations of these methods. From there, we proposed an advanced analysis method to increase the accuracy of the design method by adding parasitic capacitors c_{bc} and c_{be}, and hypotheses to make the analysis process easier for the Colpitts oscillator circuits using transistor BJT. The results have shown that the oscillator frequencies of the proposed method are more accurate and stabler than other methods, especially at high-frequency domain.

This paper has two contributes as follows,

- Systemized analysis theories for the Colpitts oscillator circuit.
- Proposition of an advanced analysis method to increase the accuracy of theory calculating at high-frequency domain.

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PHƯƠNG PHÁP PHÂN TÍCH NÂNG CAO CHO MẠCH DAO ĐỘNG COLPITTS

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Tóm tắt. Mạch dao động là một trong những thành phần quan trọng nhất trong các thiết bị truyền thông. Mặc dù các mạch dao động đã được sử dụng rộng rãi trong thực tế nhưng các lý thuyết phân tích của chúng vẫn còn nhiều sai số khi tính toán thiết kế mạch dao động ở vùng tần số cao. Trong bài báo này, chúng tôi xem xét lại các phương pháp phân tích lý thuyết của mạch dao động Colpitts hiện nay và chỉ ra những hạn chế của các phương pháp này. Từ đó, chúng tôi đề xuất một phương pháp phân tích nâng cao nhằm tăng độ chính xác khi tính toán tần số dao động trong miền tần số cao.
Từ khóa. Tần số vô tuyến, mạch dao động tần số cao, mạch dao động Colpitts.

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