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# Microwave Oscillator Design

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Oscillator now is taking one of the most important roles in RF and microwave engineering and it can be applied widely in many RF system in practice. The design of oscillator therefore is necessary in the study of electronics. This thesis work aimed to study an effective way in designing a functional and stable oscillator.

The first section of this paper gives a detailed theoretical background about microwave oscillator. Microwave oscillator operates on the principle of LC tank circuit and it is used in the electronic system to generate AC output signals without any input. The structure of microwave oscillator typically includes two main parts: an active device (two-port transistor) and a passive frequency-determining resonant element. Therefore, the discussions about transistor's stability factor and resonator's classification are given in details.

Besides that, after delivering the technical background of microwave oscillator in theory, the practical design was implemented to create an applicable layout for microwave oscillator which could be used at the given frequency of 1GHz. To implement the microwave oscillator a PCB was designed by NI AWR, a circuit design software which provides the simple design environment with integrated high-frequency circuits as well as good simulation technologies.

The final layout of the designed oscillator is applicable and useful. With further improvements in design and assembly process, it can be applied for other electronic projects.

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|---|---|
| Keywords | Radio Frequency, Oscillator design, Microstrip. |

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## List of Abbreviations

| | |
|---|---|
| MWO | Microwave Oscillator Office |
| RF | Radio Frequency |
| AC | Alternating Current |
| DC | Direct Current |
| LC | Resonant or Tank circuit |
| BJT | Bipolar Junction Transistor |
| FET | Field-effect Transistor |
| UJT | Unijunction Transistor |
| RLC | Tuned Circuit |
| RFC | Radio Frequency Choke |
| SOT | Small Outline Transistor |

# 1 Introduction

Nowadays, because of the high demand for higher bandwidth and frequencies in wireless and wireline application, it would increase the large pressure for RF engineers to design and deliver higher performance and higher functionality in new microwave components. Oscillators are the key components for such systems: wireless and mobiles communications, or test and measurement system. Therefore, it is important for RF designer to improve the performance of oscillators in both technology and design methodology. [1,1.]

Therefore, the purpose of this thesis is giving the general knowledge about microwave oscillator design. This paper will introduce the deep understanding about working theory of oscillator, as well as the effective approaching way to design and simulation microwave oscillator by using NI AWR.

Besides that, with the researching information inside this paper, this thesis can be useful for others who want to develop the oscillator by themselves, as well as gain the fundamental knowledge about the RF design, because the microwave oscillator technology continues to make strides in the availability of new active devices and resonator technologies. [1,6.]

# 2 Understanding an Oscillator

In this section, the detailed knowledge about oscillator will be presented in a clear order from the working theory of oscillator until the wide classification of oscillator in application. There are two main parts in this section: working theory of oscillator and classification of oscillator. Through this section, readers should understand how oscillator works and principal to create a good and stable oscillator circuit as well as how to apply the oscillator circuit in different field of high frequency electronics.

### 2.1 Working Theory

Basically, an oscillator is an electronic circuit which can generate a continuous or repetitive output waveform without any AC input signal. In the other words, oscillators transform current flow of DC power source into an alternating waveform at the specific frequency which can be decided by its circuit components. [2.]

The main fundamental of oscillator can be explained by analyzing the LC tank circuit, which includes an inductor L and totally pre-charged capacitor C as the Figure 1 below shows.

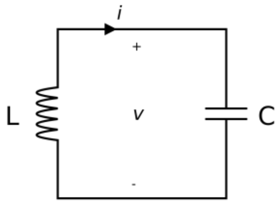

Figure 1: LC tank circuit. Modified from Oscillators: What Are They? (2019) [2].

When the LC circuit is closed, the conventional current flow moves from negative plates of the capacitor to positive one through the inductor coil L. Therefore, the strength of electric field inside the capacitor C decreases by time. Additionally, this current flow through the inductor will create a magnetic field around the inductor so the inductor starts to store the magnetic energy. When the capacitor is completely discharged, at this time, the magnetic field gets the maximum value and starts decaying and producing the counter emf. [2.]

This counter emf can generated the new current flow through LC tank and according to Len’s law, the capacitor C would be charged in the opposite polarity in comparison with the initial charging condition by that current flow. When the capacitor C is fully charged in the opposite direction, the magnetic field in the coil collapsed and converted into electric field inside the capacitor completely. At that time, the capacitor starts discharging once again and this whole process repeats continuously. [2.]

However, in practice, due to the resistance of the coil and connecting wire, the transferring process of energy from L to C and from C to L can dissipate power in the form of heat. As a result, the energy losses decrease the amplitude of oscillations until it damps in nature.

Therefore, in the purpose of keeping the oscillations continue endlessly at the constant amplitude, it is necessary to have a feedback circuit which can product the accurate amount of energy to compensate for the power loss. The figure 2 below shows the basic block diagram of a typical oscillator with its feedback network.

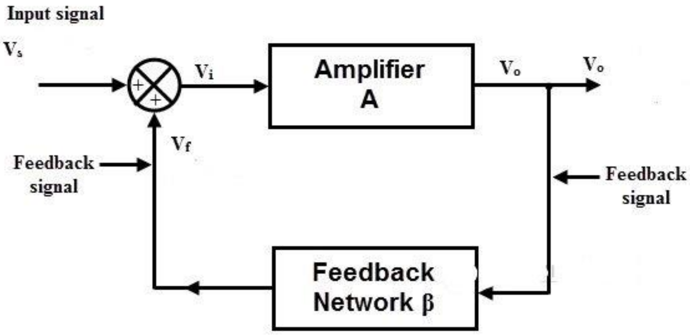

Figure 2: A typical oscillator. Copied from Oscillator Basics [3].

Nevertheless, it is critical to be noted that the energy supplied by feedback circuit should be strictly controlled and must be accurately equal to the amount of the lost energy to keep the oscillations at the constant amplitude. If the energy supplied is more than the lost energy, the oscillations will increase steadily and lead to a distorted signal at the output. On the other hands, if the energy supplied is less than the lost energy, the oscillations will decrease and collapse by time. [3.]

Therefore, the oscillator circuit always includes two main part in practice: amplifier (normally using transistor or vacuum tube) to generate AC output signal without requirement of any input and positive feedback network to get a portion of the amplifier output and feed it back to the oscillator in a correct phase and accurate magnitude. [3.]

As Figure 2 above shows, $V_S$ is assumed as sinusoid input signal and because the amplifier is non-inverting, the output signal $V_O$ is in phase with $V_S$. Besides that, the feedback network feeds $V_F$ to the input and the amount of $V_F$ depends on the feedback gain β.

When the loop is open, the gain A of the amplifier is defined by the ratio of input and output voltage of amplifier

$$A = \frac{V_O}{V_I} \tag{1}$$

When the loop is closed, under the effect of feedback circuit, the close loop gain is defined as below

$$G = \frac{V_O}{V_S} \tag{2}$$

Where $V_S$ is the substitution of $V_I$ to $V_F$ since the feedback signal is in phase with the input signal.

In addition, the value of the feedback voltage depends on the feedback gain β and the amount of output voltage $V_O$ so $V_F$ can be expressed as

$$V_F = \beta * V_O \tag{3}$$

Therefore, the close loop gain G can be expressed as

$$G = \frac{V_O}{V_S} = \frac{V_O}{V_I - V_F} = \frac{V_O}{V_I - \beta V_O} \tag{4}$$

By dividing both numerator and denominator by Vi, we can get

$$G = \frac{\frac{V_O}{V_I}}{\frac{V_I}{V_I} - \frac{\beta V_O}{V_I}} = \frac{A}{1 - A\beta} \tag{5}$$

(since $A = \frac{V_O}{V_I}$ as the equation (1))

As the expression above shows, it is clear to notice that the close loop gain G is infinity only when Aβ = 1. In other words, the oscillations can generate the output signal constantly and continuously when and only when the condition of Aβ = 1 is satisfied.

## 2.2 Oscillator Classification

There are several ways to classify oscillators into different types. However, in practice, oscillators can be divided based on two main factors.

First, the most common way is classification based on the usage of feedback. According to feedback network, there are two main types of oscillators: feedback and non-feedback oscillators. Oscillators use feedback network in order to satisfy required conditions of the oscillation is called the feedback oscillators. While other oscillators can operate functionally without feedback network is called the non-feedback oscillators. [3.]

In the feedback oscillator type, there are also many of different types which can be classified by the components of feedback circuit such as LC feedback oscillators (Hartley, Colpitts and Claps), RC phase-shift oscillators (Wein-bridge), negative-resistance oscillators and crystal oscillators. [3.]

The figures 3,4 and 5 below illustrate the typical circuit of Harley, Colpitts and Wein-bridge oscillators.

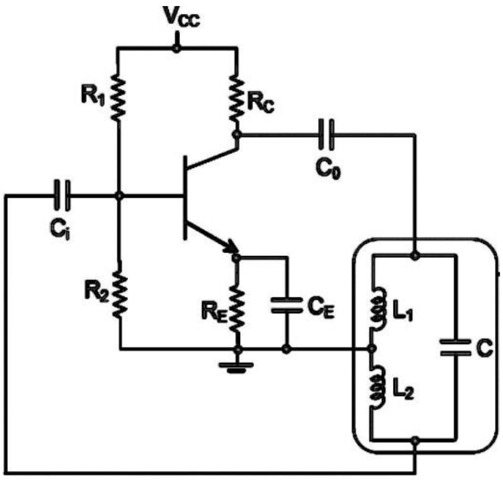

Figure 3: An example of feedback oscillator (Hartley oscillator). Copied from Anju Radhakrishnan (2018) [4].

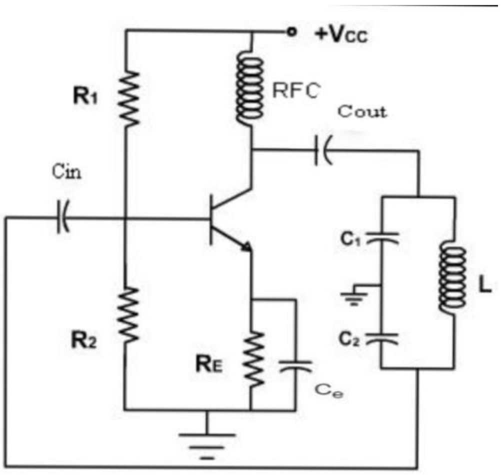

Figure 4: An example of feedback oscillator (Colpitts oscillator). Copied from Anju Radhakrishnan (2017) [5].

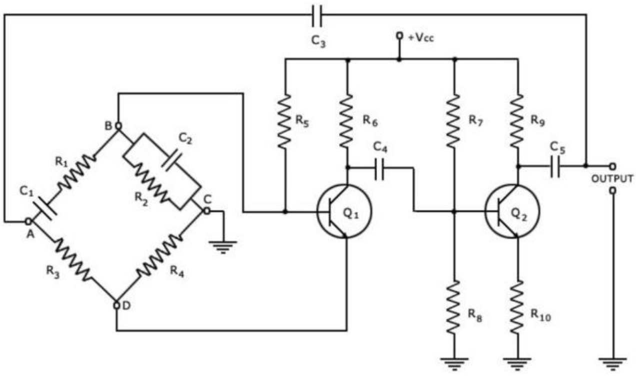

Figure 5: An example of feedback oscillator (Wein Bridge oscillator). Copied from Anish.K, Rakesh Bute, Avaneet Ranjan (2010) [6].

Besides that, the typical example for non-feedback oscillator is UJT relaxation oscillator which uses a negative resistance region of the characteristic of the device. The figure 6 below shows the illustration of UJT oscillator.

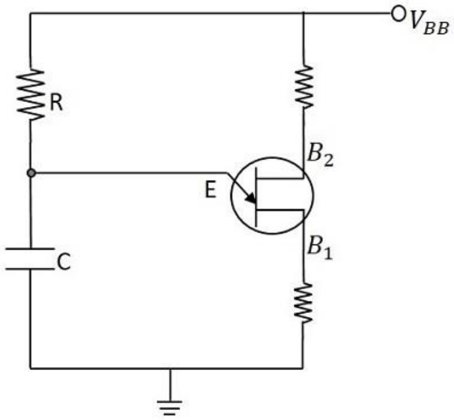

Figure 6: An example of non-feedback oscillator (UJT oscillator). Copied from UJT as relaxation oscillator [7].

Secondly, oscillators can be classified based on the frequency generated. According to the principle of oscillators, oscillators can be used to produce the output waveform at specific frequencies ranging from low to very high level.

Oscillators which are used to generate the oscillations at low frequencies range (from 20 Hz to 200 kHz) are called low – frequency oscillators or audio oscillators. In practice, RC oscillators are normally used at that low frequency range. [3.]

Moreover, oscillators which are used at frequencies more than 200 kHz to gigahertz are called high – frequency oscillators or radio oscillators or microwave oscillators. LC oscillators are typical type of oscillators which are practically used at that high range of frequency. [3.]

## 3 Microwave Oscillator

Because of many different types of oscillator, this paper cannot cover all of design for oscillator in general. Therefore, from this section, the focus of the paper is microwave oscillator and how to design a functional oscillator in practice. The section includes three small parts. The first part will present the basic understanding about microwave oscillator as well as the application of this type oscillator in the real life. The second part will give the deep understanding about one of the important aspects in microwave oscillator design – stability factor. Then after understanding about what we aim to design, the last part will describe a simple but effective approach to design a RF oscillator.

## 3.1 Microwave Oscillator Background

Nowadays, microwave oscillators take the most important role in determining key characteristics of any electronic systems, especially in the field of RF and microwave. On the low-end of microwave frequency spectrum, the development of microwave oscillator is affecting on enhancing cellular wireless communication systems. On the other hands, on the high-end of the spectrum, high-performance oscillators are in high demand to perform “out of the ordinary” functions in the field of automotive radars or high-speed optical communications. Therefore, in general, microwave oscillator now is one of the most effective and necessary electronic devices in any RF systems. Moreover, in practice, microwave oscillators can be divided into many different types based on frequency bandwidth, type of resonator used, or type of active device used. [1,2.]

As other types of oscillator, microwave oscillators also function as DC-to-AC converters. A typical microwave oscillator usually includes two main parts: an active device and a passive frequency-determining resonant element. First, commonly there are two types of the active device inside oscillator circuit: two-terminal device like a Gunn diode and three-terminal device such as a junction bipolar transistor or FET or other devices which use newer semiconductor materials. Besides that, in order to make the oscillator circuit work functionally, basic oscillation conditions, which was mentioned in the previous part, need to be satisfied and one of those conditions is signalling an active device with acceptable gain to back-up for feedback loop losses in a high frequency. Therefore, in microwave oscillators, there are two different topologies which are used to satisfy that condition. The figure 7 below shows both of topologies in their generalized form. In the parallel topology, the frequency-determining element is used as a feedback element between the input and the output of oscillator. The purpose of this topology is enhancing the necessary instability of the whole system. Otherwise, a negative resistance oscillator is the one where reflection gain at the output terminal is used to satisfy the oscillation condition when connecting to the resonator in the proper phase condition. While the parallel feedback approach is more suitable for narrowband, lower noise tuneable oscillators in practice, the negative resistance feedback approach is used for wideband tuneable oscillators. [1,2-3.]

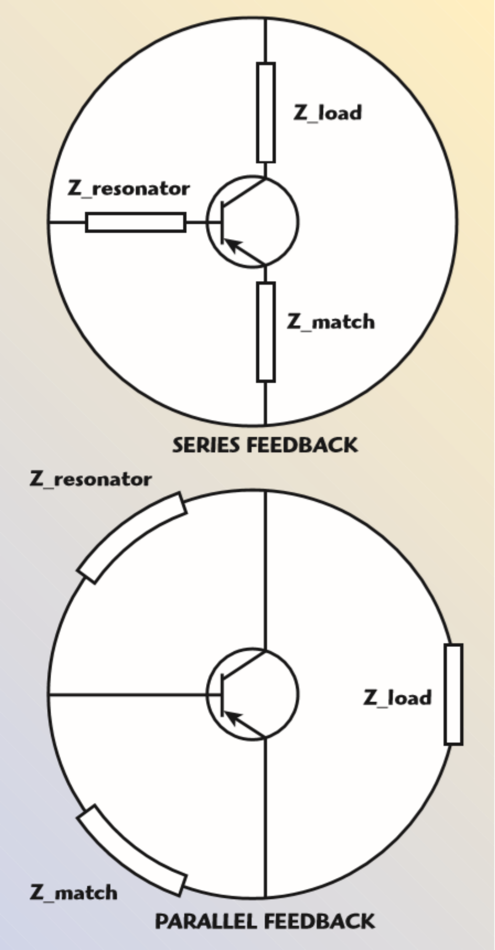

Figure 7: Generalized oscillator configurations using three-terminal devices. Copied from Khanna APS (2006) [1,2].

## 3.2 Stability Factor

In radio frequency design, stability is one of the most important factors which must be considered. Generally, stability determines what load and source impedance should be connected to two-port device for stable amplifier or potentially unstable oscillator. Ideally, all active devices are unilateral devices. It means signals only transform in the forward direction (from input to output) but not in reserved direction, so theoretically $S_{12}$ should be zero. However, in practice, $S_{12}$ parameter of two-port transistor usually feeds a small amount of output power back to the input port and it will combine with reflection coefficient $S_{11}$ at the input port. After the combination, the magnitude of the reflection coefficient might exceed unity. Therefore, the transistor will experience the exceed gain and it will make the transistor cause self-oscillations. In the other words, a change in the load impedance presented to the network can cause a change in the input impedance of the network and vice versa. Therefore, in application, the transistor still be stable or unstable in specific frequency range. Hence it is essential to analyse the stability of transistors or active devices in RF network beforehand. In the other words, by checking the stability of transistor based on its S-parameter or specifications, the transistor can be decided to function as stable amplifier or unstable oscillator in the chosen frequency range. [8; 9,1].

The figure 8 below presents the simple block diagram of two-port network of transistor.

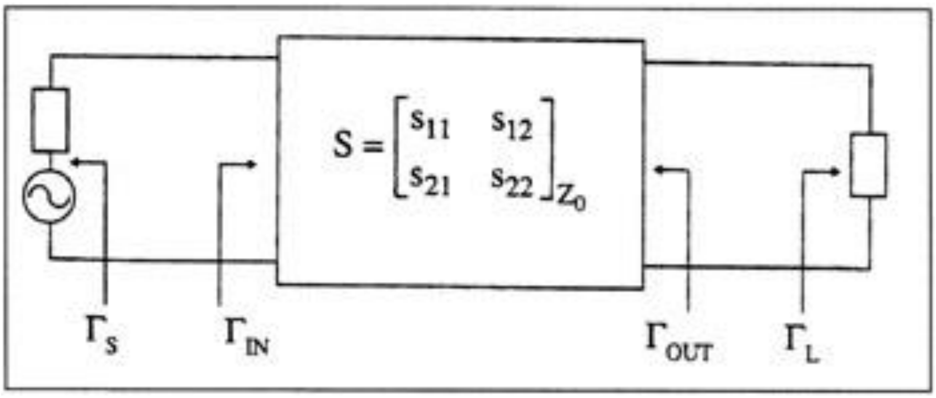

**Figure 8: Two-port network**

There are two important terms which should be understood before analysing the stability factor of two-port network. The first term is unconditional stability or potential instability. This term describes a situation when the transistor will be stable or not oscillate for all load and source connection. This condition only happens when the real part of input and output impedances are always greater than zero and smaller than unity. ($0<|\varphi_S|<1$ and $0<|\varphi_L|<1$). [8; 9,3.]

Secondly, conditional stability describes a transistor which can be stable for some, but not all load and source connections. This means that the two-port network can be stable when a matched output circuit is connected but the network also can self-oscillate when connecting to a mismatch output circuit. Therefore, conditional stability term is also known under the name “potential instability”. [8; 9,3.]

There are two factors that can be used to analyse the stability of a two-port device. The stability factor K is derived from S-parameter of a linear two-port transistor. K factor is defined as below:

$$K = \frac{1-|S11|^2-|S22|^2+|\Delta|^2}{2|S12\times S21|} \tag{6}$$

With $\Delta = S11 \times S22 - S12 \times S21$

The unconditional stability in transistor occurs only when $K \geq 1$. When $K \geq 1$ then there are a unique set of source and impedance, $\varphi_{ms}$ and $\varphi_{ml}$, which will permit for a conjugate match at the input and output of the device. When $K > 1$, the magnitude of conjugate S11* and S22* are lying inside the outer circumference of Smith Chart. When $K = 1$, the real part of those conjugate is lying exactly on the outer circumference of Smith Chart. [10,6.] Beside K factor, the other stability factor B1 must be considered to insure unconditional stability for a two-port network [9,2]. B1 is defined as below:

$$B1 = 1 + |S11|^2 - |S22|^2 - |S11 \times S22 - S21 \times S12|^2 \tag{7}$$

To insure the two-port network in unconditional stability region, B1 must be larger than zero. Additionally, B1 and K factors are both available to be checked and calculated in Microwave Office (MWO).

Secondly, the potential instability in transistor can happen when $K < 1$. As $K < 1$, the $\varphi_{ms}$ and $\varphi_{ml}$ will become negative impedances with their real part lying beyond the circumference of Smith Chart and two-port network will no longer in unconditional stability region. [9,2.]

Generally, in RF design, there are two stability circle which should be considered beforehand. The input stability circle is a limit line in the input plane that show the source impedance values which make the output reflection coefficient have a unity magnitude. Besides that, the output stability circle similarly represents a contour in the output plane that indicates load impedance values which make the magnitude of input reflection coefficient equals to 1. For both stability circles, the real part of reflection coefficient is equal or less than 1, the device is absolutely lying on the stable region, while if the real part is more than 1, the device can become potentially unstable. When using MWO, the stability circle will express two regions in each single frequency. The first region is unstable region which can be drawn with a dashed line and the second region is stable region which can be expressed by the solid line. If the dashed circle is inside the solid one, the outside of the circle shows the stable region, while if the dashed line is outside the solid one, the inside of the circle shows the stable region. Moreover, normally the stability of two-port device is calculated based on S-parameter which were measured in a 50-ohm system, so if the source or load impedance is 50 ohms, then the output and input reflection coefficient will be S22 and S11 respectively. Therefore, the region of stability circle that includes 50 ohms is also the stable region. [9,3.]

To sum up, there are two conditions for generating oscillations: stability factor $K < 1$ and the input and output reflection coefficients are larger than unity ($|\varphi_{in}| > 1$ and $|\varphi_{out}| > 1$)

## 3.3 Microwave Oscillator Design

After having a basic understanding about microwave oscillators as well as its basic topologies, this session will focus on the approach method to design the microwave oscillator in practice. However, there are quite many types of microwave oscillator in RF market, this session only focuses on bipolar transistor oscillator design in high frequencies.

Before starting the design for microwave oscillator, it is compulsory to apply a simple analytic method for transistor oscillator. With this analytic method, the optimum values of feedback circuit and load can be found by explicit expressions through bipolar transistor z-parameters. Depending on the applications of oscillators, the technical requirements for oscillator design can be different in each application. However, in general, it is essential for electronics designer to define the configuration of the oscillator circuit diagram. There are three compulsory steps in defining the configuration of the oscillator: choosing the suitable transistor type, analyzing and calculating all parameters in small-signal and large-signal equivalent circuits of the transistor and then measuring all electrical characteristics of the oscillator. [11,1.]

Firstly, operating frequency and noise frequency control are two concerning factors which is used to select the fitting transistor type for oscillator circuit. Typically, BJT devices can operate excellently in both fixed tuned and tunable oscillators at frequencies up to 20 GHz with low noise characteristic. On the other hand, FET transistor have been demonstrated to generate stable oscillations at frequencies beyond 100GHz. Besides that, BJT transistors can offer 10dB better phase noise close to the carrier in comparison with FET ones. [11,1.]

Secondly, to evaluate the basic parameters of transistor equivalent circuits, it is possible to measure directly or using experimental data with acceptable accuracy at a designing frequency [11,1]. Moreover, if the selected transistor in microwave oscillator circuit is expressed as two-port network, it is available to calculate all compulsory elements in equivalent circuits by using Microwave Office (MWO) software.

Finally, it is desirable to have a short analytic method in calculating optimal values for feedback elements, load impedance as well as maximum output power in terms of transistor-equivalent elements and their current-voltage characteristics. A maximum small-signal negative resistance is taken in account to define the optimal combination of feedback circuit which will take a key role in permitting oscillations at the largest amplitude. Besides that, a small-signal circuit of transistor is also used to find the optimal load value for the whole circuit of oscillator. Moreover, the large-signal nonlinearity of transistor equivalent circuit can determine the maximum output power configuration of oscillator. [11,1.]

To sum up, if a simple analytic approach is considered before designing a microwave oscillator, it will be helpful to simplify the design procedure as well as speed up the whole design process.

After completing the simple analytic approach above, two-port oscillator design process includes five steps.

Firstly, the suitable transistor should be selected based on the application of oscillator. Then, the appropriate transistor configurations should be checked carefully.

Secondly, the stability factor of the transistor should be calculated or computed to check whether the transistor can be potentially unstable or not ($K < 1$). If the device is not potentially unstable, the configuration of transistor should be changed from common-emitter into common-base and the lumped elements such as an inductor should be added between the base and ground to make the device become more potentially unstable. Moreover, the shunt or series feedback also can be used to increase the magnitude of input and output reflection coefficient. It means the instability of the device can be increased as well.

Thirdly, the output matching circuit is designed by choosing the appropriate value for $\varphi_L$. The $\varphi_L$ should be lying far away in the unstable region of the output stability circle to make the magnitude of input reflection coefficient be larger than 1 ($|\varphi_{in}| > 1$). Besides that, the value of $\varphi_L$ should be chosen wisely to create the largest possible resistance at input of the transistor $R_{in} < 0$. Normally the optimal value for $R_{in}$ is around -100Ω.

After that, the fourth step is designing the source network to define $Z_{in}$ and $X_{in}$. Basically, the value of $Z_{in}$ and $X_{in}$ must be satisfied the equations below:

$$X_{in} = -X_S \tag{8}$$

$$R_{in} = -3 \times R_S \tag{9}$$

The value of $R_{in}$ should be chosen wisely and carefully so the oscillations will not cease until it reaches the steady condition.

Both of source tuning network and terminating network can be matched or created by adding the suitable lumped or distributed elements.

# 4 Resonators

In this section, the focus is about resonators because it will take the most important role in RF oscillator design. In RF design, the resonator will take the role of creating and stabilizing the center frequency for the whole circuit. Therefore, in this section, it is helpful to understand the function as well as working theory of resonator in RF circuit and then have the general knowledge about different types of resonators which can be applied in RF circuit in real system.

## 4.1 Resonator's Concept

Resonance is an important term in microwave oscillator design, especially in filter theory. The definition of resonance is a term which describe the ability in which a microwave network can present a maximum or minimum impedance at a frequency. One of simple and common forms of resonator is a lumped element RLC circuit which is also known as tank circuit. The resonance of tank circuit happens when the inductive and capacitive reactance have the same magnitude but have 180 degree different in phase shift. Therefore, they will cancel each other due to the opposite direction in phase. In the other words, at resonant frequency (central frequency), the imaginary component of circuit's admittance is zero, and only the real part component is observed. In practice, the resonator can provide reliable, fundamental mode and frequency stabilization in the application of transmitters or local oscillator. [12.]

## 4.2 Type of Resonators

As mentioned above, the resonator takes the important role in oscillator design. Moreover, based on the working condition as well as used purposes, the potential applications of resonator are various widely. Therefore, nowadays, there are many different types of resonators created by electronic companies. Each type of resonator is suitable for different applications. It is necessary to have a deep understanding about the performance characteristics of each resonator type before choosing the correct one for the circuit.

### 4.2.1 Coaxial Resonator

The first type of resonator is coaxial resonator. This type of resonator is used in the application of voltage-controlled oscillators or filters. Coaxial resonators usually function as high-quality-factor inductors inside an oscillator. Therefore, whenever coaxial resonator is connected to a capacitor or varactor diode, it will create a resonant circuit. Besides that, the structure of coaxial resonators includes two parts: the outer conductor in the form of square-shaped cross-section and a central conductor in the form of a cylindrical shape. There are two main types of coaxial resonators: a half-wavelength resonator with both ends which is open and a quarter-wavelength resonator with one end shorted and the opposite end open. In the application, this type of resonator can be function effectively in the frequency range from 200MHz to 10GHz. [13.]

The figure 9 below illustrates both types of coaxial resonators as well as its structure.

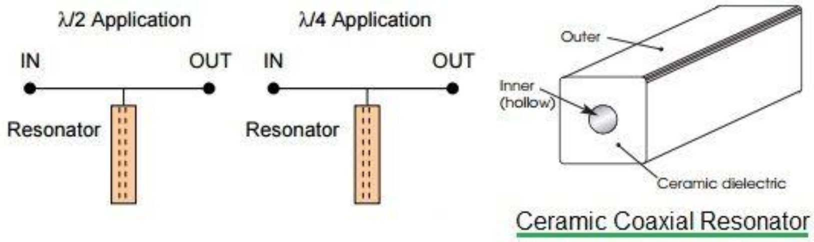

Figure 9: Coaxial resonator. Copied from RF Wireless World [14].

### 4.2.2 Dielectric Resonator

A dielectric resonator is a disc-shaped material with a high εr value. With the high εr value, the air-filled cavity inside resonator is cancelled so the size of the circuit will be significantly smaller. Moreover, with the dielectric resonator, the radiation losses will be reduced extremely, and a high-quality-factor can be achieved because of the huge restriction electromagnetic fields within a dielectric resonator. There are several modes of dielectric resonator, but the most common mode of this type of resonator is transverse-electric mode. In this mode, a dielectric resonator may be matched to a circuit by several different methods. One of the most common methods is to connect the resonator to a microstrip line. In practice, the dielectric resonator can be functional effectively in the range of frequency up to 50 GHz. Finally, the dielectric resonator can be applied in oscillators, microwave filters, microwave combiners, satellite equipment. [13.]

The figure 10 below shows the small elements of dielectric resonator’s structure.

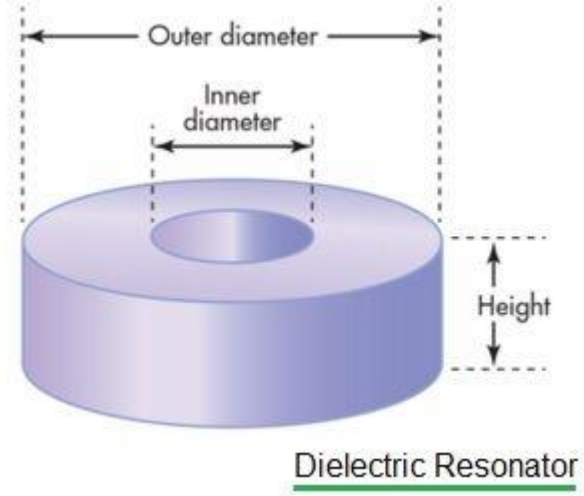

Figure 10: Dielectric resonator. Copied from RF Wireless World [14].

### 4.2.3 Crystal Resonator

Quartz crystals can offer high Q and high frequency stability for oscillator because of their piezoelectric properties. Therefore, in practice, the crystal oscillators are often used instead of LC oscillators. Besides that, the piezoelectric materials of crystal resonators cam convert mechanical energy into electrical energy and vice versa. Therefore, an electric energy can be generated by and proportional to the applied mechanical stress. The maximum operational frequency of this type of resonator is 250MHz. This type of resonator can be used in the design of satellites, mobile devices, TVs, home appliances and automotive device. [13.]

The basic circuit of crystal resonator would be presented as the figure 11 below.

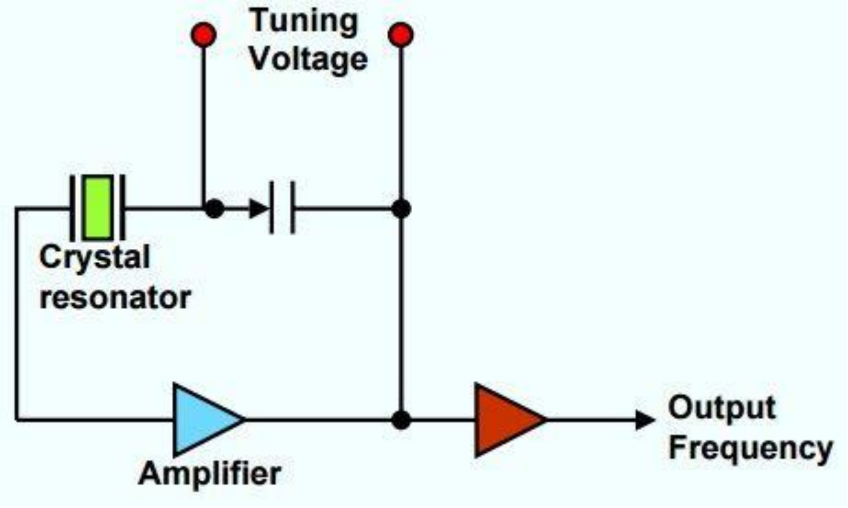

Figure 11: Crystal resonator's circuit. Copied from RF Wireless World [14].

### 4.2.4 Ceramic Resonator

Ceramic resonators have the similar working theory as the quartz crystals, so in practice, it is obviously the alternative option for quartz crystals. However, they still have some different advantages and disadvantages. For example, they can offer in smaller packages and at lower costs. Additionally, other advantage of ceramic resonators is providing a lower start-up time than crystals. On the other hands, as the results of some laboratory experiments, their function is less accurate than quartz crystals. The structures of ceramic resonators include two metro electrodes which are place on the top and bottom of the ceramic substrate. The resonant frequency will be decided by the thickness of the substrate because the substrate will vibrate between the electrodes when the supplied voltage is fed up into the resonant circuit. [13.]

The figure 12 below would present the basic circuit of ceramic resonator in application.

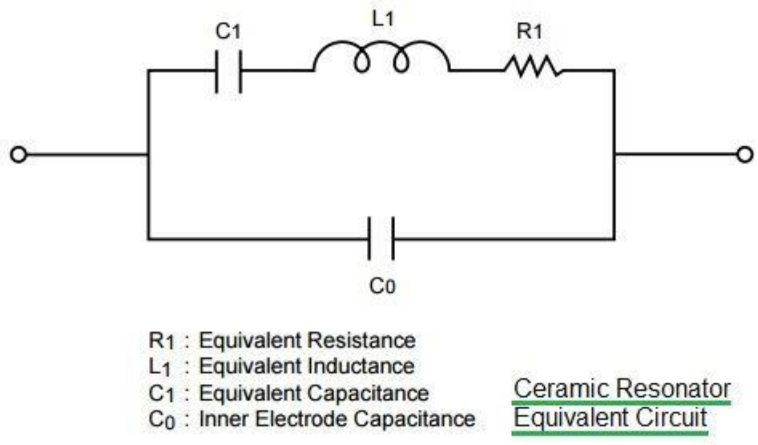

Figure 12: Ceramic resonator's circuit. Copied from RF Wireless World [14].

# 5 Circuit Calculation

Because the purpose of this paper is creating and testing the microwave oscillator at the center frequency at 1GHz, it is important to choose the appropriate transistor which can work as potentially unstable oscillator. Therefore, after checking some options, the BFR92A transistor was chosen for the whole project.

For this project of creating a microwave oscillator, the fixed base biasing circuit was applied as the DC biasing circuit of the transistor BFR92A. The reason for choosing this type of DC biasing circuit is that $I_B$, the base current would keep constant for all of values of supply voltage $V_{CC}$. In the other words, it means the operating point of the transistor also remain fixed for various values of supply voltage. The figure 13 below illustrates the fixed base biasing circuit which would be applied for this project.

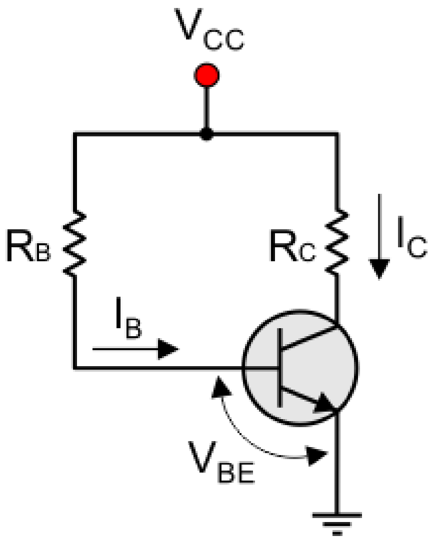

Figure 13: DC biasing circuit

As the figure 13 above, there were only two resistors used inside the biasing network. The purpose of those two resistors was establishing the initial operating region of the transistor.

With the emitter connected directly to the ground, so the voltage at emitter should be zero.

$$V_E = 0 \tag{10}$$

Besides that, the collect-emitter voltage is defined as the different potential between collector and emitter, so $V_{CE}$ can be expressed as below:

$$V_{CE} = V_C - V_E = V_C - 0 = V_C \tag{11}$$

And $V_C$ must be satisfied the condition below:

$$V_C = \frac{2}{3} \times V_{CC} \tag{12}$$

Due to the BFR92A transistor is the type NPN transistor.

Moreover, according to the BFR92A datasheet, the bias point of the transistor is as below:

$$V_C = 5V$$

$$I_C = I_E = 5mA$$

Therefore, the $V_{CC}$ should be 1.5 time larger than 5V of $V_C$. After calculating, the suitable value for supply voltage should be 8V.

Furthermore, as mentioned above, the BFR92A is an NPN transistor, so the emitter diode of the transistor is forward biased. It means that the forward base-emitter voltage drop $V_{BE}$ would be 0.7V. Then the value of base resistor $R_B$ is calculated as the equation below:

$$R_B = \frac{V_{CC} - V_{BE}}{I_B} \tag{13}$$

Where $I_B$ can be defined as:

$$I_B = \frac{I_C}{\beta} \tag{14}$$

With β is DC current gain of the transistor and the value of β is typically 100.

Therefore, according to equation 13 and 14, with the chosen supply voltage at 8V, $R_B$ can be calculated as below

$$R_B = \frac{8V - 0.7V}{\frac{5mA}{100}} = \frac{7.3V}{\frac{5\times10^{-3}}{100}A} = 14600\Omega$$

In the similar way, the collector resistor $R_C$ can be calculated

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{8V - 5V}{5mA} = 533\Omega \tag{15}$$

# 6 Frequency stability

The frequency stability is usually used to define the ability of the microwave oscillator to function at the fixed specific frequency over a time interval. The variation of frequency might be caused by the changes in the values of oscillator circuit such as circuit components, transistor parameters, supply voltages, stray-capacitances, output load or external conditions such as temperature variation, voltage variation, output load variation, and frequency aging. [15.]

In this project, to improve the resonant frequency stability of the circuit, a varactor diode was added into the RLC resonant circuit. A varactor diode is a voltage-dependent device. It means the output of the diode depends on their input voltage. In the other words, the applied reversed voltage through the diode causes the changes of the internal capacitance of the diode. Moreover, the capacitance of the varactor diode is inversely proportional to the reverse – bias voltage as the figure 14 below. It means an increase in reverse voltage would cause the decrease in the internal capacitance of the diode. [16.]

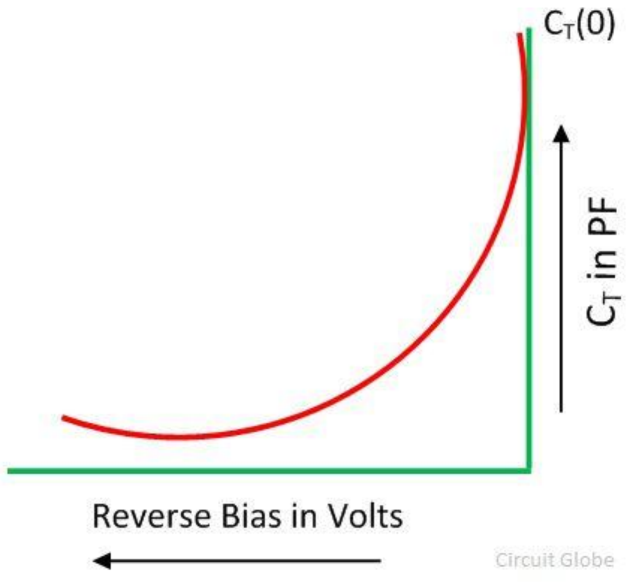

Figure 14: The relationship of capacitance and reversed voltage of varactor diode. Modified from Varactor Diode | Construction, Working, Characteristics, Applications [16].

In application, the varactor diode is usually used as the energy storage, so it can reduce the noise in the circuit. Therefore, in the project, the varactor diode was used in the resonant side of the oscillator to keep the central frequency stable.

The schematic of the resonant circuit with the varactor diode can be illustrated as the figure 15 below.

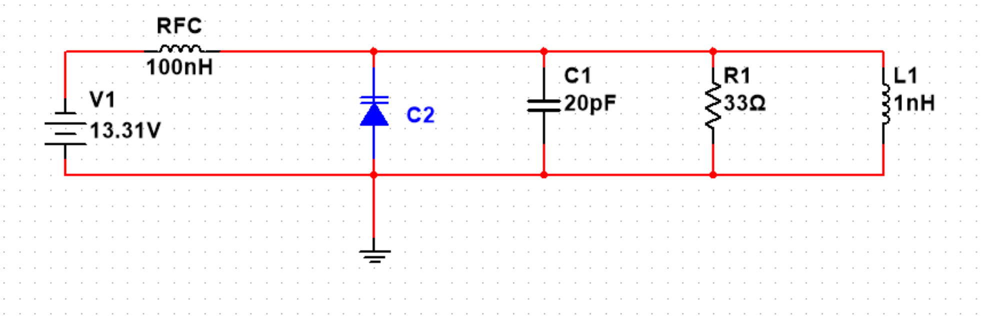

Figure 15: Resonant circuit with varactor diode

As the figure 15 above, there are four main components in the resonant circuit: resistor, capacitor and inductor as well as varactor diode. Besides that, the radio frequency choke RFC was added inside the circuit to block the AC current in the radio frequency range of the oscillator.

Moreover, as the equation 9 above mentioned about the relationship of $R_{in}$ and $R_S$:

$$R_{in} = -3 \times R_S \quad (9)$$

Therefore, $R_S$ could be calculated as below when the value of Rin is optimally around -100Ω.

$$R_S = -\frac{1}{3} \times R_{in} = \frac{-(-100)}{3} = 33\Omega \quad (16)$$

Besides that, the value of inductor could be chosen at 1nH, so the suitable value for the radio frequency choke RFC should be 100 times greater than the value of inductor.

$$RFC = 100 \times L = 100 \times 1 = 100nH \quad (17)$$

With the chosen inductor above and the resonant frequency of 1GHz, the total capacitance of resonant circuit could be calculated as the following equation below.

$$f = \frac{1}{2\pi\sqrt{LC_T}} \tag{18}$$

$$C_T = \frac{1}{4\pi^2 \times f^2 \times L} = \frac{1}{4\pi^2 \times 10^{18} \times 10^{-9}} = 25 \times 10^{-12} = 25pF \tag{19}$$

Because the varactor diode functions as the capacitor to store the energy in the circuit, the total capacitance is the result of two serial capacitors.

$$C_T = C_1 + C_2 \tag{20}$$

From the equations 19 and 20, the values of capacitor and varactor diode could be chosen respectively as below:

$$\begin{cases} C_1 = 0.8 \times C_T = 20pF \\ C_2 = 0.2 \times C_T = 5pF \end{cases}$$

Based on the chosen value of varactor diode, the TOSHIBA variable capacitance diode 1SV285 was selected for the designed oscillator. According to the datasheet of the device, the capacitance of varactor diode could be calculated by the actual reversed voltage across the diode as the formula below.

$$C_2 = \frac{C \times k}{(V_b - V)^m} \tag{21}$$

Where C is the initial capacitance at zero-bias condition of varactor diode, $V_b$ is forward bias voltage, k is the constant and normally equal to 1 and the m is the material constant (the chosen varactor diode is made by silicon, so the m constant is 0.5)

Based on the datasheet of varactor diode, the values of C and $V_b$ are 6.5pF and 15V respectively. Therefore, with the equation 21, the necessary reversed voltage which is applied across the varactor diode can be calculated as below.

$$C_2 = \frac{C\times k}{(V_b - V)^m} \tag{21}$$

$$(V_b - V)^m = \frac{C\times k}{C_2} \tag{22}$$

$$V = V_b - \sqrt[m]{\frac{C\times k}{C_2}} = 15 - \sqrt{\frac{6.5\times 10^{-12}}{5\times 10^{-12}}} = 13.31V \tag{23}$$

## 7 Schematic and Simulations

In this project, all schematics, layouts and simulations for the oscillator circuit would be done with the NI AWR software. NI AWR software provides the simple but effective design environment with integrated high-frequency circuits as well as good simulation technologies to develop and complete the design for electronics devices before real manufacturing.

### 7.1 Stability Test

In RF design, the stability is one of the important factors. Therefore, before designing and implementing the oscillator circuit, it is essential to check the stable circle of the transistor.

In the oscillator design, it is expected for the transistor to be potentially unstable. Therefore, in stability circle, the unstable region should be as large as possible. To check the unstable of two-port transistor with NI AWR software, there are three simple steps. First, it is necessary to import the S parameter file of transistor (in the appendix 1) under Data file because all the stability checking would be done with the S parameters of the two-port transistor. Second, the next step is creating the new schematic which included only the transistor with two port as the input and output signal (as figure 14 below).

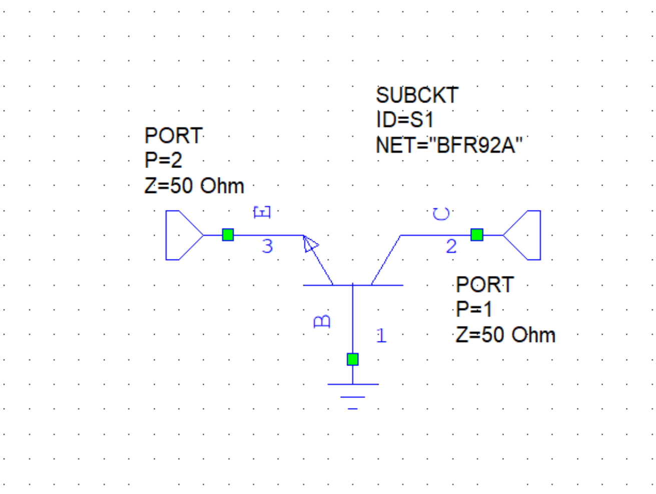

Figure 16: Transistor schematic for BFR92A

Finally, in the purpose of checking the output stability of the transistor, the final step is creating the new Smith Chart graph which would measure the output stability factor SCIR2 of the transistor from the output to the input (as figure 15 below).

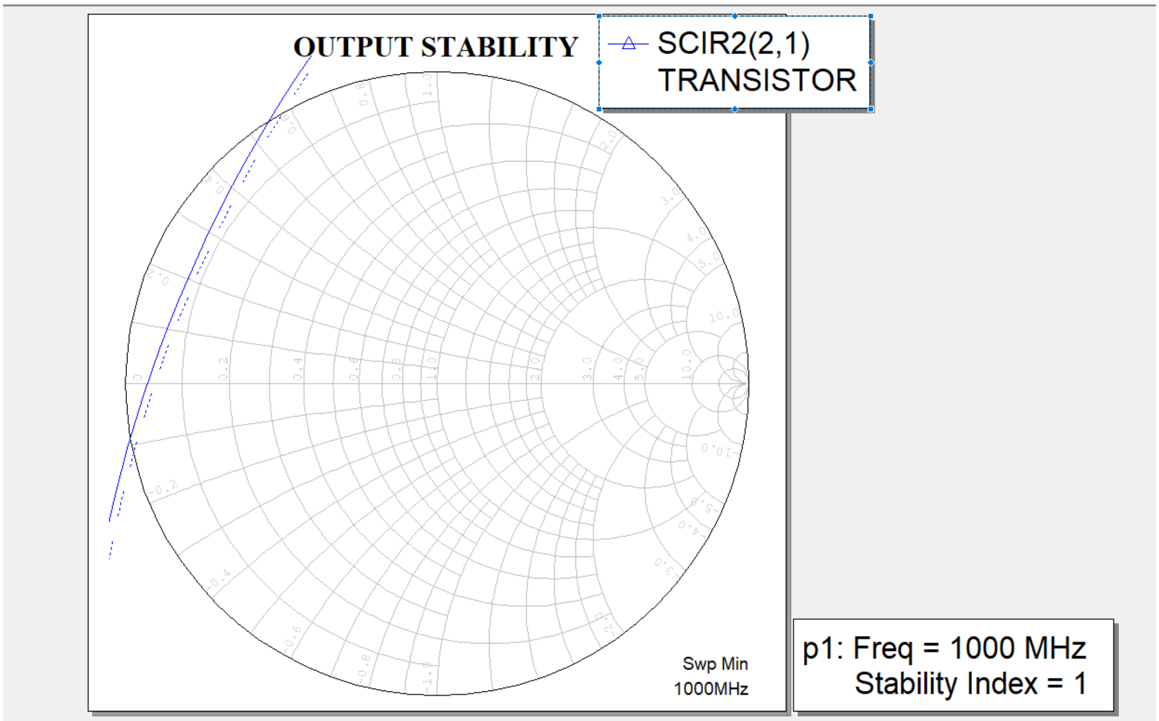

Figure 17: Output stability circle

The unstable region bounder was marked as the dot line in the figure 15. This region was expected as large as possible. In this case, the unstable region is good enough to create the oscillator based on that transistor. However, in other cases, if it is necessary, the additional inductor could be added between the base and DC ground to increase the area of the unstable region.

## 7.2 Schematics

To make it become easier to change or check the value of the whole circuit, it is essential to separate the whole circuit into two small schematics: transistor schematic with the all DC biasing elements and input tuning resonator circuit. Finally, to have the general look at the whole circuit, the third schematic was created in which all of parts of oscillator circuit can be put together.

### 7.2.1 Transistor Schematic

The transistor schematic presented the part of DC biasing circuit of the BFR92A as calculated. However, the DC supply voltage was changed into the DC ground because the DC supply voltage does not have any significance in the analysis if the larger RFCs are added into the circuit. In addition, if the DC supply voltage would still be kept inside the schematic, when the layout of the circuit was created, the nodes of DC supply voltage would be connected, and it might cause the unexpected mess inside the layout.

Therefore, the overall look of the schematic of transistor BFR92A in NI AWR as the figure 16 below:

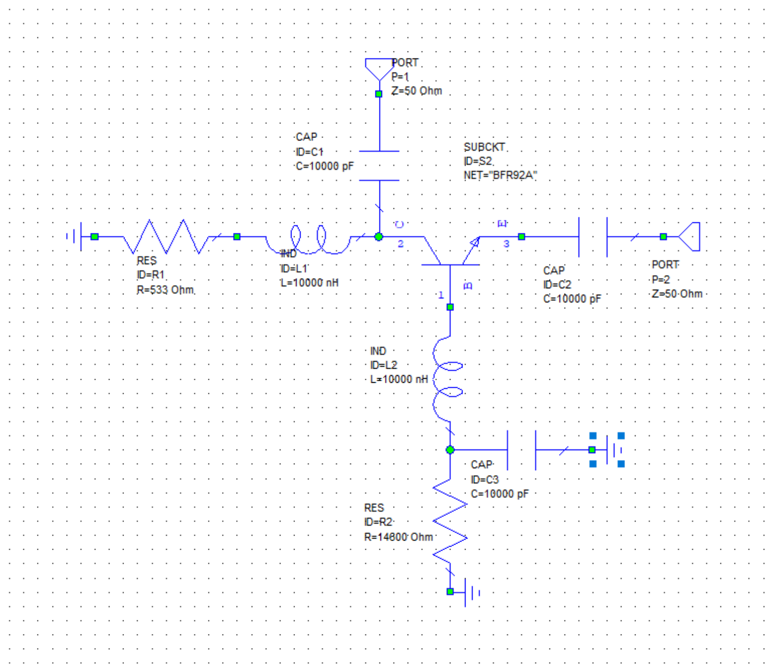

Figure 18: The schematic of transistor

Besides all calculated values of base and collector resistors (RB and RC), the 10nF blocking capacitors and 10mH RFC inductors were added to the circuit in the purpose of blocking all DC signals inside the circuit. Because if the DC signals leak out, it might cause the unexpected noise for the oscillation process of the oscillator.

### 7.2.2 Tuning Circuit Schematic

The schematic of tuning circuit basically presented a complex resistor ZFREQ which was connected to the input side of the transistor. In the other words, the ZFREQ circuit would function as the resonator circuits of the oscillator.

The schematic of resonator circuit has the simple look as the figure 17 below.

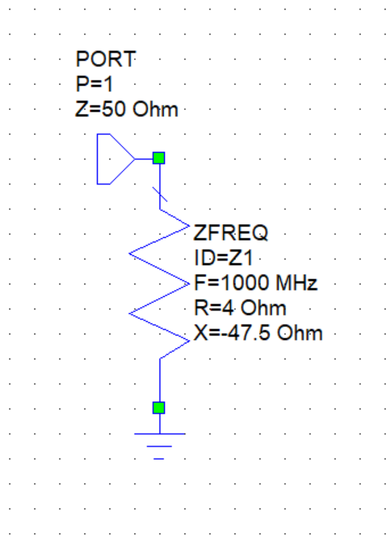

Figure 19: The schematic of resonator

### 7.2.3 Oscillator Schematic

Finally, when the schematics of transistor and the resonator were done as mentioned above, the sub-circuit of both schematics were automatically created under the Sub circuits tab of Elements panel. Then, the new schematic was created and named with “The whole circuit” in which all the sub-circuits of the oscillator would be put together and connected to the port.

As you can see in the figure 18 below, the additional lumped element was added to the output side of two-port transistor. That inductor worked as output matching circuit between the transistor and the output load. The chosen value for that inductor will be explained later in the next part of this paper.

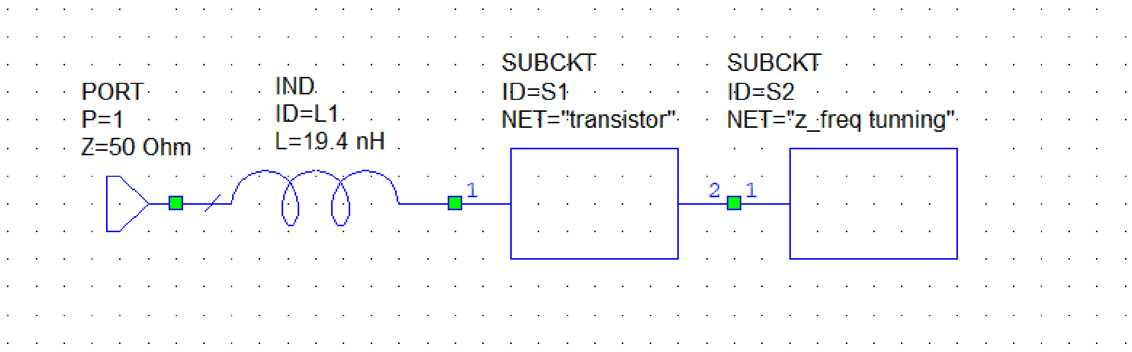

**Figure 20: The schematic of oscillator**

## 7.3 Simulations

When all schematics were created in correct way, there are two main graphs which should be used to check the function of the oscillator. The first one was output stability circle. In output stability circle, there are two measurements covered: the output stability factor SCIR2 of the transistor schematic and the input reflection coefficient S11 of the resonator schematic. The reason why two measurements should be check is that it is important for input reflection coefficient S11 of the resonator should be in the unstable region of the output stability of transistor to make the whole circuit function as the microwave oscillator instead of amplifier.  As the figure 19 below, the values of input reflection coefficient S11 was presented as the pink small square and it was in the unstable region of transistor as the expectation of designer.

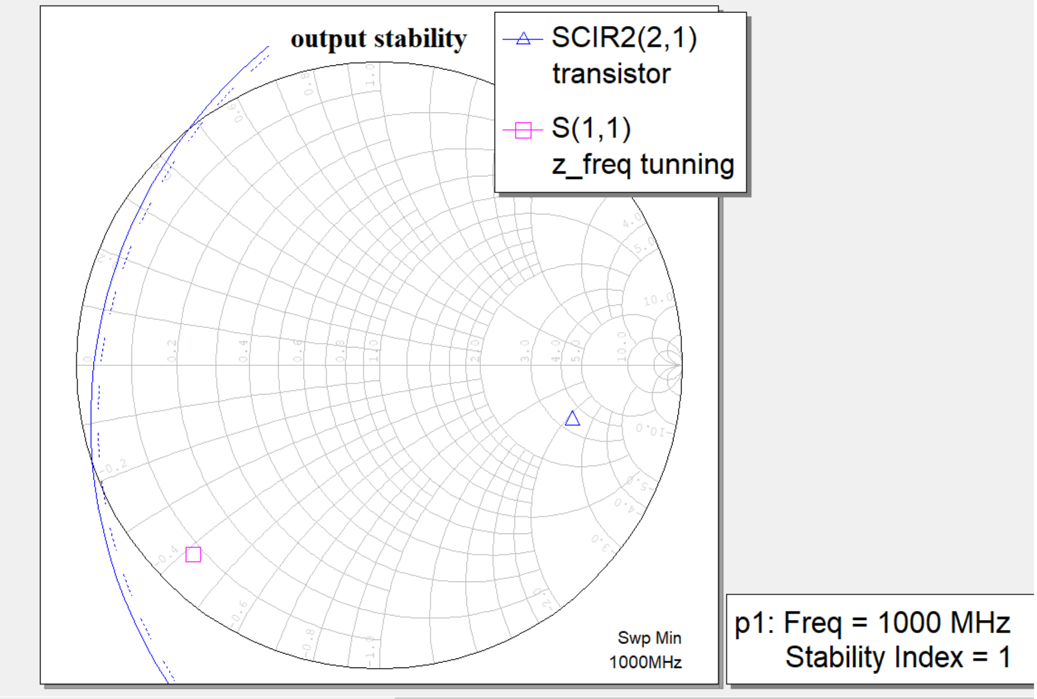

Figure 21: Output stability and S11 parameter of resonator

Besides the output stability circle, there was another graph which must be used to simulated or measured the value of impedance parameter Z11 of the whole circuit to find the most suitable value for impedance Z11.

As mentioned in the section 2.2.3, basically, the value of $Z_{in}$ and $X_{in}$ must be satisfied the equations 8 and 9 below:

$$X_{in} = -X_S \tag{8}$$

$$R_{in} = -3 \times R_S \tag{9}$$

The value of $R_{in}$ should be chosen wisely and carefully so the oscillations will not cease until it reaches the steady condition. Additionally, the optimal value for Rin is usually around -100Ω.

Therefore, in this simulation, the tuning tool of NI AWR was used for the value of resonator ($R_S$ and $X_S$ in the formula above) to choose the optimal value for Rin in this circuit.

First, the tuning tool was applied for ZFREQ values in both real and imaginary parts. Then the new rectangular graph was created with two measurement. The first one was presenting the real part of Z11 parameter of the whole circuit (Rin in the formula) and the second one was presenting the imaginary part of Z11. Because the input impedance parameter depends on the source or resonator impedance, whenever the value of the resonator impedance changes, the input impedance also changes.

The tuning process happened until the value of the real part of Z11 down to -100 or more, then back to output stability to check whether the input reflection coefficient S11 of resonator was still in the unstable region, then the circuit would work perfectly as the oscillator.

The figure 20 below shows the result of the Z parameter graph after the tuning process.

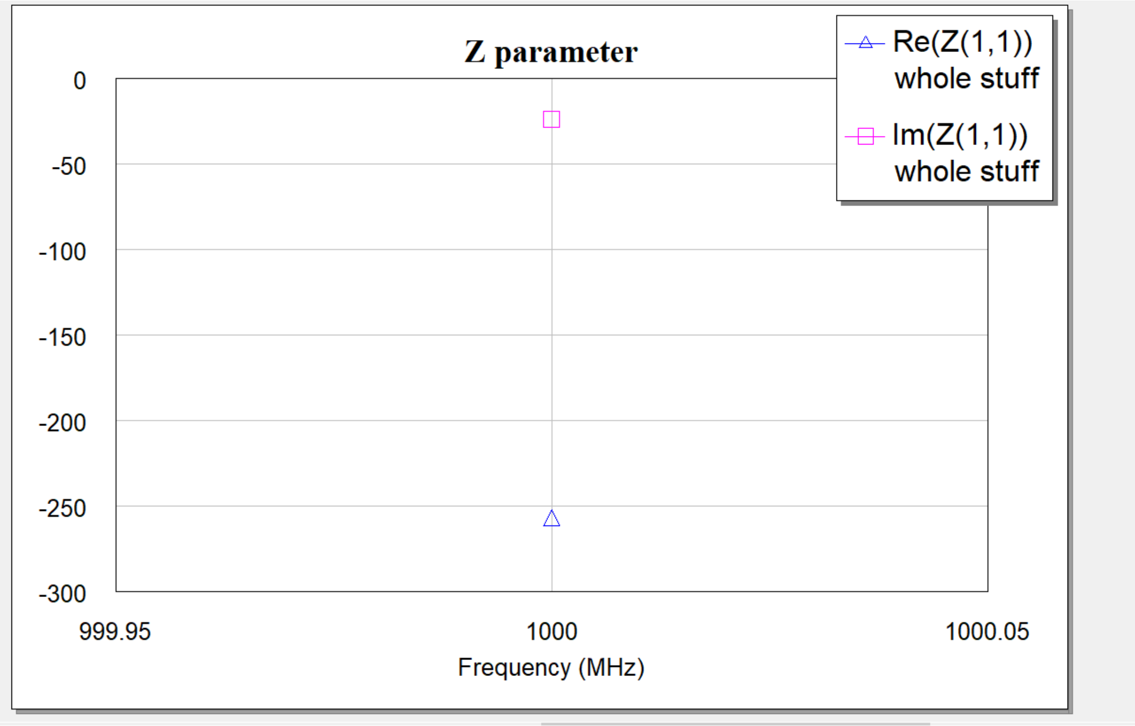

Figure 22: Z11 parameter of the oscillator after tuning ZFREQ

However, it is essential to compensate the imaginary part of Z11 of the whole circuit so in the future, only the real part of Z11 will make the effect on the function of the oscillator. Therefore, to compensate the imaginary part of Z11, the lumped inductor would be added as the output circuit from the output side of the two-port transistor. The figure 21 below shows the Z parameter graph after adding the suitable value of the lumped inductor.

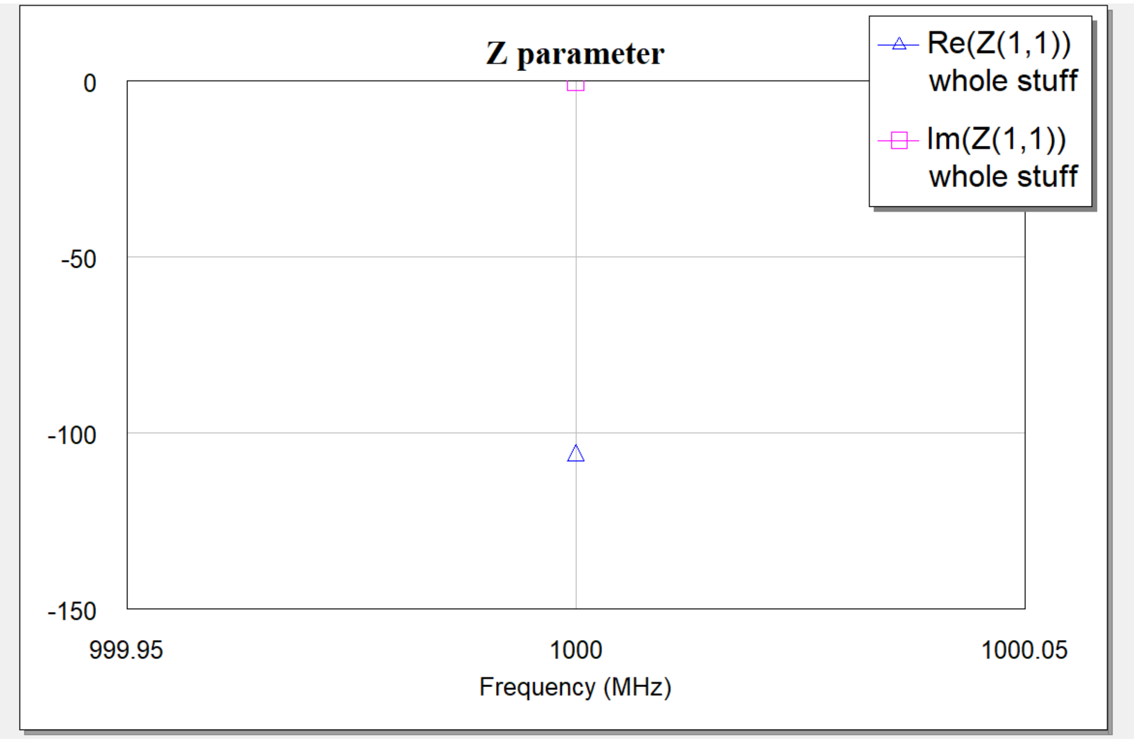

Figure 23: Z11 parameter of the oscillator after adding the inductor

The values of the resonator ZFREQ and the inductor to get the suitable value as the figure 21 above respectively as:

$$\begin{cases} R(ZFREQ) = 4\Omega \\ X(ZFREQ) = -47.5\Omega \\ L = 19.4nH \end{cases}$$

## 8 Layout Design

After all simulations were done and gave the expected value, the layout was designed for printing circuit board.

For this project, the substrate FR-4 was used as the conducted lines between components. In creating layout for the circuit, there are two main steps which must be completed.

The first step is adding physical layouts for all the components. Basically, NI AWR already prepares some basic package data for component layout. In this project, SOT343 and chip component package were imported.

For all lumped components in the circuit, the physical layout of 0603 in chip component package was applied for resistors and capacitors, while 0805 layout was used for inductors. Besides that, according to the transistor datasheet, BFR92A is a surface mount transistor with the layout of SOT23. Therefore, in NI AWR, under the package of SOT343, the layout of SOT23 was chosen to be the physical layout for the transistor.

After adding physical layouts for all components, the second step is creating the microstrip lines between components.

Then the whole schematic of the circuit can be presented as figures below:

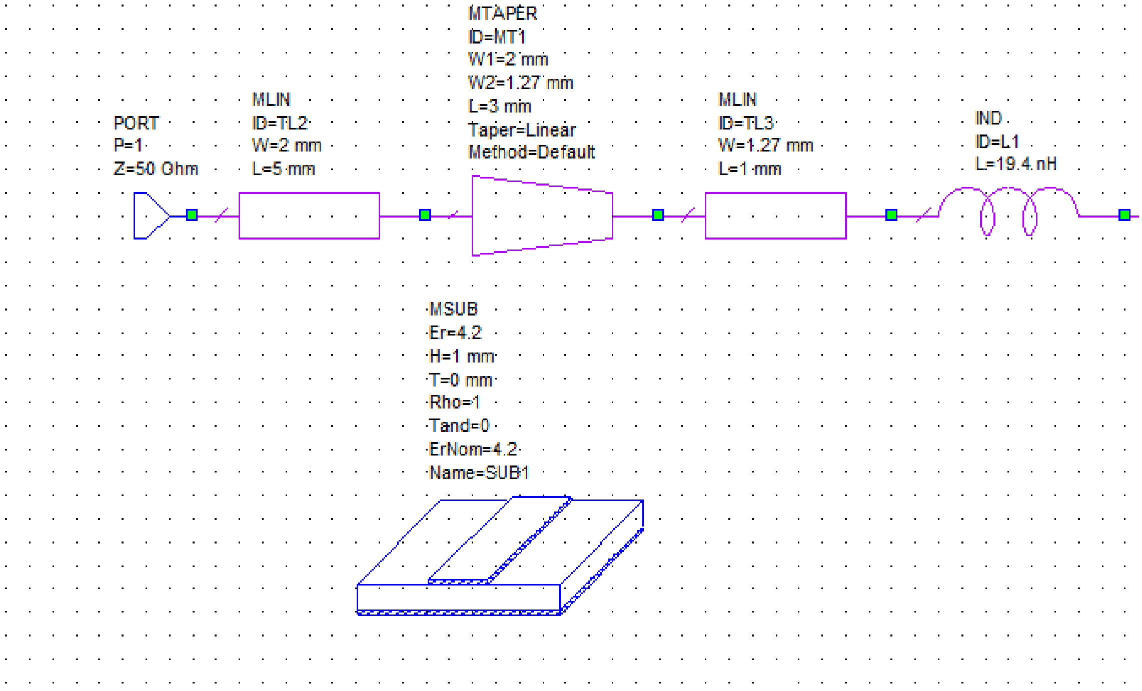

Figure 24: The whole circuit schematic with added microstrips (part 1)

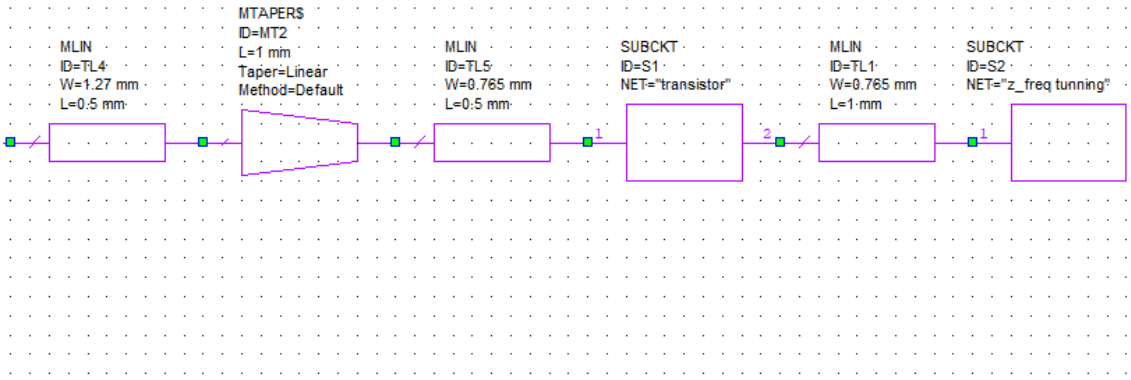

Figure 25: The whole circuit schematic with added microstrips (part 2)

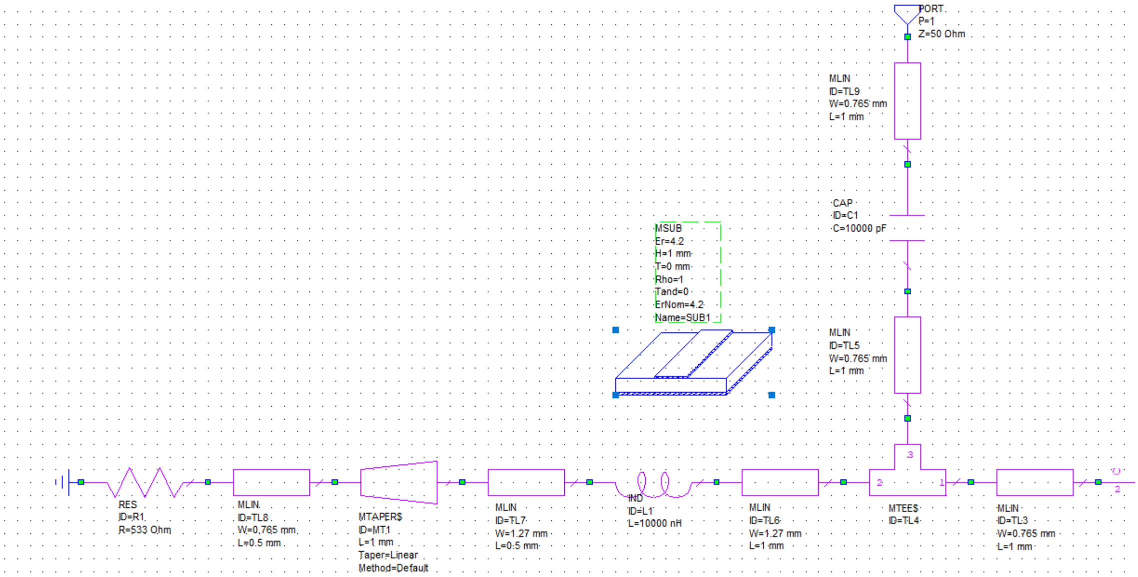

Figure 26: The transistor schematic with added microstrips (from collector of transistor)

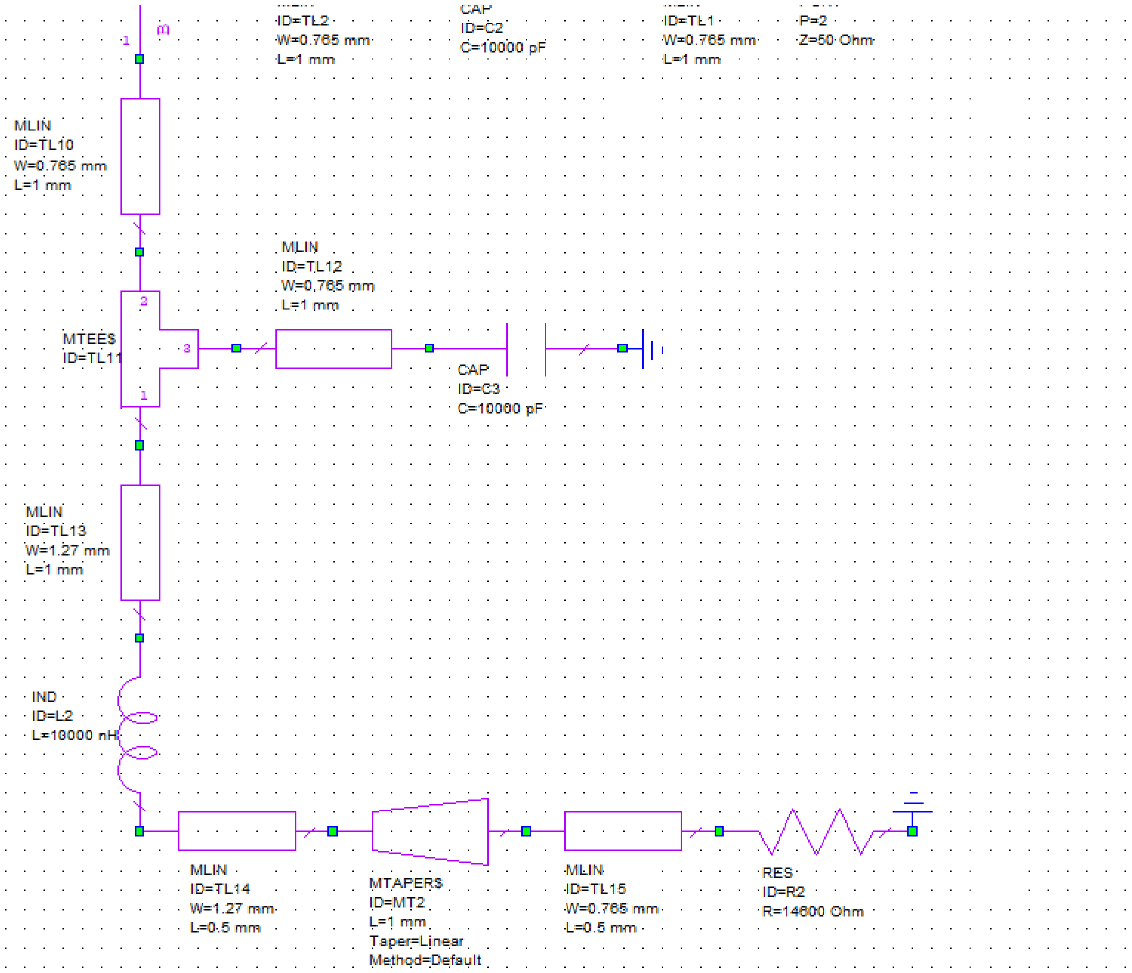

Figure 27: The transistor schematic with added microstrips (from base of transistor)

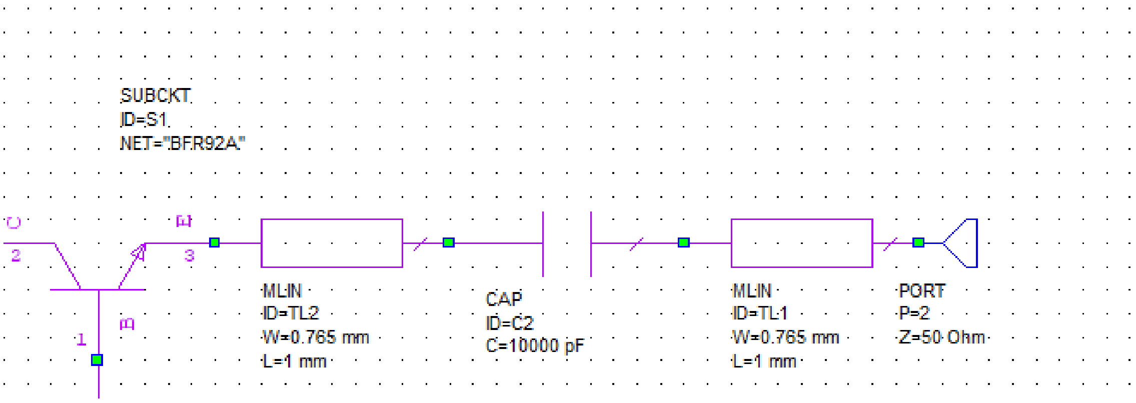

Figure 28: The transistor schematic with added microstrips (from emitter of transistor)

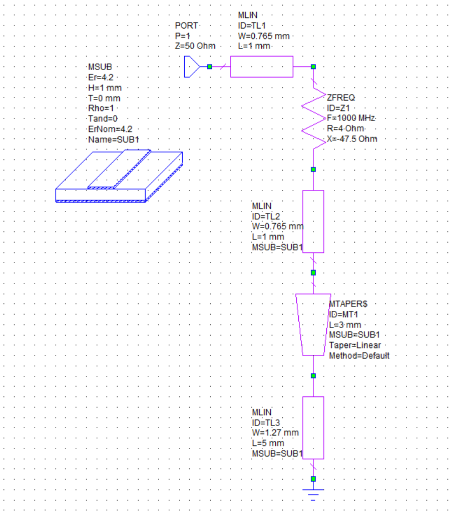

Figure 29: The ZFREQ tuning schematic with added microstrips

Then with all the schematic of the oscillator circuit are shown in the figures above, in NI AWR, it could be translated into the printable layout as below:

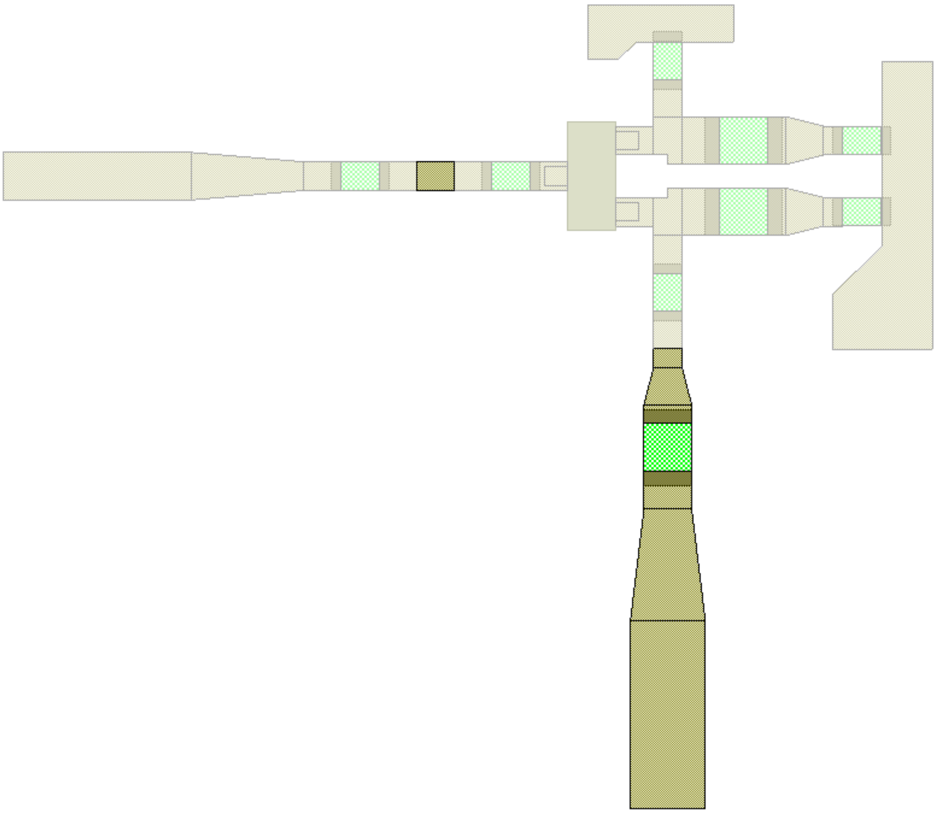

Figure 30: The final layout of the oscillator circuit

After snipping all components together, it is important to simulate one more time about output stability circle as well as Z parameter of the circuit. It might be different because of the effect of microstrip lines. But in this case, all the values kept in remain after adding the microstrip lines.

## 9 Conclusion

As the simulated result from NI AWR, the design oscillator circuit could function in the correct way. However, in practice, there are many aspects which can make the bad effect on the result of the oscillator such as milling process, soldering and noise. Therefore, at the final stage of the project, the oscillator can be able to work in application based on the good result in NI AWR. Through the project, the student can learn how to design a simulating oscillator by NI AWR as well as gain the deep knowledge about oscillator and RF design in general. This project can be used as the theoretical document for other who can to study more about oscillator design.

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## Appendix 1: S parameter of BFR92A

```
!{BFR92A, Si-NPN RF-Transistor in package SOT 23}
! {Vce = 5V, I c = 5mA}
# GHZ S MA R 50
!f      S11             S21             S12             S22
0       0.7     0       23      180     0.0     90      0.97    0
0.04    0.669   -16.6   23.024  164.2   0.008   79.9    0.97    -8.2
0.1     0.593   -39.2   19.631  145.4   0.02    72.1    0.873   -17.5
0.2     0.449   -67.6   14.753  125.9   0.033   68.7    0.716   -24.7
0.3     0.356   -86.7   11.181  113.9   0.043   66.2    0.62    -26.8
0.4     0.313   -99.2   8.899   106.3   0.052   68      0.562   -27.2
0.5     0.275   -113.9  7.512   99.9    0.06    67.4    0.531   -26.9
0.6     0.243   -120.1  6.336   95.7    0.07    69.7    0.512   -26.9
0.7     0.219   -127    5.513   92.2    0.078   71.3    0.499   -26.9
0.8     0.213   -139.5  4.868   88.8    0.089   72.4    0.494   -27
0.9     0.194   -144.7  4.319   85.8    0.089   72.5    0.488   -27.2
1.0     0.182   -156.2  3.953   82.4    0.106   73.1    0.479   -27.4
1.2     0.190   -163.4  3.339   77.5    0.125   73.5    0.472   -28.3
1.4     0.193   -175.5  2.945   72.4    0.144   73.3    0.465   -30.1
1.6     0.185   -179    2.626   69.3    0.163   73.6    0.466   -31.4
1.8     0.163   163.1   2.316   65      0.181   73.3    0.465   -32.8
2.0     0.179   156     2.174   61.7    0.2     72.6    0.462   -34
2.2     0.21    142.6   1.977   57.6    0.219   72.5    0.443   -35.4
2.4     0.216   144.8   1.857   54.6    0.24    71.1    0.429   -38.9
2.6     0.23    143.8   1.762   52.1    0.258   70.5    0.424   -42.4
2.8     0.213   136.1   1.657   49.3    0.279   70      0.427   -44.9
3.0     0.24    127.1   1.571   45.5    0.299   68.6    0.419   -46
```