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Design and Simulation of 1.5GHz Amplifier Utilizing the BFR92A and Transmission Lines

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ABSTRACT

The key factor of providing good performance for any electronic device is by eliminating unwanted reflections those lead to waste energy and, therefore, affect circuit stability. This is done by finding an approach to match both of the circuit's input and output to other in-between connected elements. Amplifiers fall within this category, in this paper, our target is to match the BFR92A transistor to 50ohms input and output loads to achieve 11dB gain at 1.5GHz with 100MHz of bandwidth that it can be used for RF low noise amplifiers.

In this research, different approaches were used to utilize and achieve our work requirements by, primarily, using Micro-Wave Office software (M.W.O) to calculate S-Parameters and simulate the amplifier performance. In the first design approach, intermediate line and quarter-wave plate have been used and the results are accurately discussed. Another way to design was by utilizing the stub lines to get preferred gain and bandwidth and, then, comparison has made between both approach's results to examine which is better to use.

Key words: S-Parameters, Transmission lines, Stub-lines, Mathematical representations, Design blocks.

تصميم ومحاكاة مضخم 1.5GHz بأستخدام BFR92A وخطوط النقل

الخلاصة

العامل الرئيسي في تقييم الأداء الجيد لأي جهاز إلكتروني هو من خلال القضاء على الانعكاسات غير المرغوب فيها تلك التي تؤدي إلى هدر الطاقة ، وبالتالي تؤثر على استقرار الدائرة. ويتم ذلك من خلال إيجاد تصميم لمطابقة كلا من مدخلات الدائرة والإخراج إلى البعض في الدوائرالفاصلة بين العناصر المتصلة. تقع المضخمات المستخدمة في الاتصالات ضمن هذه الفئة، في هذا البحث، هدفنا هو ايجاد توازن بين الترانزستور BFR92Aإلى حمل مدخلات واخراجات 50 اوم لتحقيق كسب 11 dB لتردد 1.5GHz مع توفير 100MHzكعرض نطاق ترددي المستخدمة في المضخمات الراديويه ذات النطاق الترددي العالي.

في هذا البحث استخدمت مناهج مختلفة لتحقيق متطلبات العمل المطلوبة وذلك بواسطة استخدام برنامج مكتبة التصميم المايكروية (MWO). أولا، تم استخدام خط النقل وصفيحة ربع موجة وتم مناقشة النتائج بصورة دقيقة في نهج التصميم الأول. بالاضافة الى استخدام طريقة أخرى للتصميم وذلك بأستخدام Stub-lines

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للحصول على كسب افضل لنفس عرض النطاق الترددي المذكور ومن ثم المقارنة بين الطريقتيين المستخدمتين من ناحية النتائج والرسوم فيما ايهما افضل.

INTRODUCTION

In term of modern electronic and electrical devices, different types of applications become widely used to facilitate and ease people's way of life. One of these ways is how to secure a high quality of wireless communications on everywhere. Hence, applications such as Bluetooth, WLAN and cellular communications pushed the wheel of technology to develop such elements to be used within wireless communication systems [1, 2].High frequency amplifier circuit is one of essential elements in designing the transmitter and/or the receiver of the wireless communication systems. The design of amplifier circuit operates by means of different approaches, in one hand, shielding, grounding and good layout design, which they are essential in HF circuit [3]. On the other hand, high frequency circuit tuning is also important but, unfortunately, difficultto be tunedwhenever the frequency becoming higher. However, tuning is still possible by using ferrite-core transformers and variable capacitors at frequency ranges from few Mega-Hertz (HF) to just lower than 1 Giga-Hertz (UHF) [3]. At more than 1 GHz, tuning the amplifier circuit becomes almost impossible due to the very small value of the capacitor is difficult to be tuned in term of lumped elements [4]. Therefore, there is a need to find a new way to design an amplifier circuit in more efficient and easy approach, and that is done by designing with verifying the scattering parameters (S-Parameters) of the transistor [3,5].

In this paper, the way of design 1.5GHz amplifier utilizing BFR92A (transistor Collector-base voltage (VCB): 20V, Collector current (IC): 25mA Power gain: 14dB @ 1 GHz, Noise figure: 2.1dB @ 1 GHz, Total power dissipation: 300mW, Package: SOT-12 plastic) to be used in applications of low noise amplifiers (LNA) used in receivers of microwaves systems has been carried out by withdrawing the way of using lumped elements because of its difficulty, and choose to design with transmission lines, which is more convenient way to work with. The paper organization falls in many sections. In the first section, mathematical expressions and suitable calculations and explanations of S-Parameters have been considered and made in order to calculate the stability factor (K) of the circuit. The second section will deal with circuit matching and optimization using both intermediate approach and quarter-wave plate method. Moreover, the design has been continued but, in this time, with stub-lines. To note that the smith chart was used to perform our goal to optimize the circuit and provide very useful display tool to visualize the results of different parameters by using Microwave Office (M.W.O). However, most of the calculation has been done by using MatLab as it is much faster and easier.

Theory of Amplifier Design and Impedance Matching

Before of going deep on how to design the amplifier using transmission lines, it is very important to know what challenges could limit the goal of amplifier gain and bandwidth. One of these challenges is how to match circuit input to circuit output. This issue is known as impedance matching. Impedance matching is simply defined as elements inserted between the source and the load in order to achieve the goal of amplification, which is described by high power transfer from the circuit input, throughout the transistor and, finally, circuit load [1, 6]. The aspect of inserting circuit between the source and the load is to minimize voltage reflections results from mismatching issue (as the load can consider source to the transistor output as shown in the figure (1)) and, thereby, getting maximum power transfer, where it can be done be different methods as we will see later in this paper. In case of mismatching between source, load and transistor, reflected waves from the load may cause unwanted interference with the incoming waves travelling from source to load resulting in backward voltage standing waves. Consequently, this interference can affect maximum power transfer if both incoming and reflected signal were out of phase and that results to the phenomena of destructive interference. On the other hand, if both signals were in-phase, therefore, standing waves can appear, and, hence, the output of the amplifier will contain unwanted ripples [7].

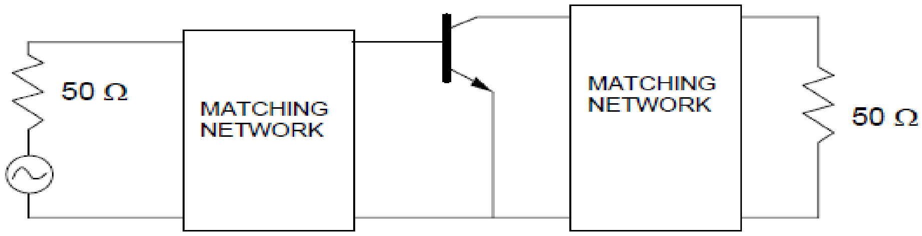

Figure (1): Impedance Matching

In form of S-Parameters, as shown in the figure (2), the reflected and transferred waves from the source and the load can be expressed by [8]:

$$S_{11} = \text{Reflected back from the input}$$
$$S_{21} = \text{Forward from the input to the output}$$
$$S_{12} = \text{Reverse from the output to the input}$$
$$S_{22} = \text{Reflected back from the output}$$

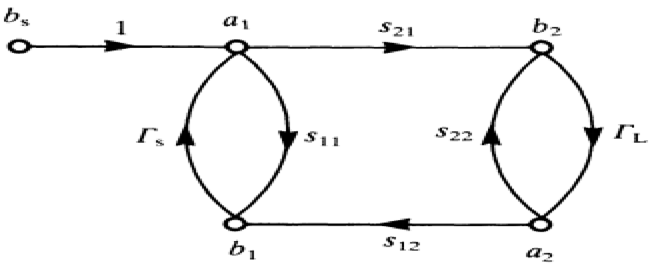

Figure (2): S-Parameters

From the above definition of the scattering parameters, it is obvious to see that S_{12} should be eliminated, in other words $S_{12} = 0$, to reduce reflected waves and enhance output gain $S_{21} > 0$.

Another point should be taken into account is the amplifier stability criteria (Stability Factor K). This factor should be greater than unity to prevent oscillation at desired frequency or any others[9].The stability factor is thus given by:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} \quad \dots(1)$$

Where;

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| \quad \ldots (2)$$

If the calculation of the above equation is greater than unity, or $K > 1$, then the device is unconditionally stable. To do that, ensure that the delta factor Δ is less than unity and/or $|S_{11}| < 1$ and $|S_{22}| < 1$ [7, 9].
Beyond to this discussion, it is meaningful to make calculations with special relations to do circuit matching. This issue is done by using transmission line. By connecting the transmission line to the source from one side and to the load impedance from the other side results in more complication in circuit design. This complication comes from the fact of voltage reflection that takes place in two opposite directions from source toward the load and load toward the source because of mismatching between them. Thus, the reflection coefficient is derived in [9, 10] and given by:

$$\Gamma_{out} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad \ldots (3)$$

$$\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad \ldots (4)$$

Where Z_L, Z_0 and Z_{in} are load, characteristic and input impedances respectively. For power consideration of transmission line, the input impedance must be chosen carefully and calculated using the following formula [11]:

$$Z_{in} = Z_0 \left(\frac{1 + \Gamma_{in}}{1 - \Gamma_{in}}\right) \quad \ldots (5)$$

Further to that, the reflection coefficient is changing as we move down to the transmission line. Therefore, after a distance of l, the new reflection coefficient is given by [11]:

$$\Gamma_{in} = \Gamma e^{-j\beta l} \quad \ldots (6)$$

And the length of transmission line is given by:

$$L = tan^{-1}\left(\frac{img(\Gamma)}{real(\Gamma)}\right) \quad \ldots (7)$$

Now, the first step is measuring the S-Parameters of the transistor to calculate the stability and delta factors ($K - Factor\ and\ \Delta - Factor$) by using equations (1) and (2) to determine whether the transistor is stable or not[12, 13].The design to do so is firstly drawn by connecting 50Ω ports to the input and the output of the BFR92A transistor by using Microwave Office Environment with frequency range of 1.3GHz to 1.7GHz as shown in figure (3).

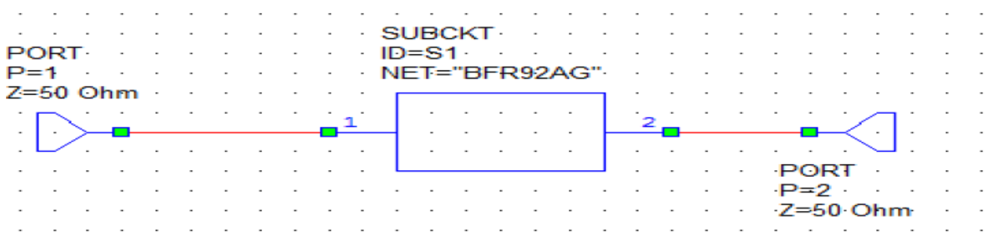

Figure (3): Schematic of measurement circuit.

Further, the Smith chart, as shown in figure (4), has been plotted to visualize the stability criteria and to measure the S-Parameters of BFR92A transistor. The S-Parameters are included in Table (1).

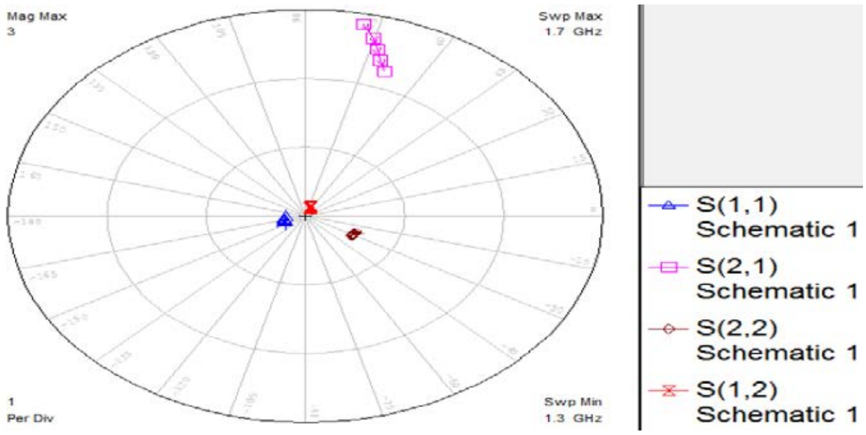

Figure (4): Smith Chart

Table (1)Scattering Parameters

S-Parameters	Real Part	Imaginary Part
S_{11}	0.2155	-0.06361
S_{12}	0.0464	0.131
S_{21}	0.7189	2.42
S_{22}	0.4739	-0.2773

By using the above S-Parameters in Table (1), we can find the delta and stability factors. Once we used Equation (2), the delta factor is found to be:

$$\Delta = S_{11}S_{22} - S_{12}S_{21} = 0.1645 - j0.1767$$
$$|\Delta| = |0.1645 - j0.1767| = 0.2414$$

The Stability factor is found to be:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} = 1.0106$$

Form the above abbreviations, it is clear to conclude that the transistor is unconditionally stable as the stability factor is greater than unity. Another factor must be carefully considered is S_{12} which has a value of greater than zero and this means that there is a negative feedback (reflected waves from the output load towards the input) affects the input signal. The optimum design with high transfer power to the output is by setting $S_{12} = 0$.

Therefore, and from the above calculations and considerations, the design will be complicated and matching between input and output must be simultaneously designed. The optimum design is reached by considering $S_{12} = 0$, design the matching circuit separately and, finally, utilize M.W.O optimization to optimize our design for S_{12} that we already have.

The Design Approuches (Simulation And Results)

Design with Intermediate Line

Prior to the optimization, the first design has been connected as shown in figure (5). The simulation curves of S-Parameters magnitudes and Smith chart are shown in figures (6) and (7).The purpose of this approach is mainly to eliminate the imaginary parts of reflection coefficients S_{11}, S_{22} of the design. Using equations (6) and (7), the lengths of each transmission line on BFR92A transistor sides have been found as shown in Table (2). The second section of the design is quarter wave plate of length $\lambda/4 = 2.77mm$, impedance $Z_0 = \sqrt{Z_{in}Z_l}$ and load impedance found by using same formula of equation (5).

Table(2)Intermediate section characteristics

	Γ	Length of the intermediate section (mm)	Z_0 (Ω)	Electrical Length (EL) in (Degrees)
Input	-0.2247	29	39.7827	90
Output	0.5465	25.4	92.3304	90

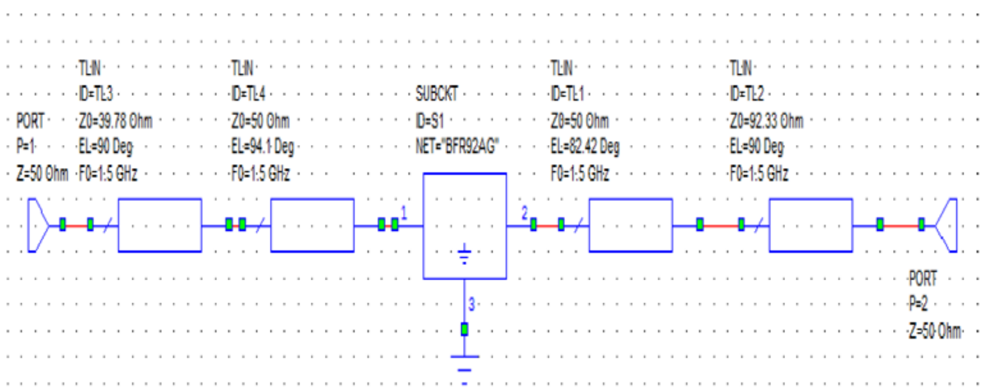

Figure (5): Intermediate Line Circuit Design

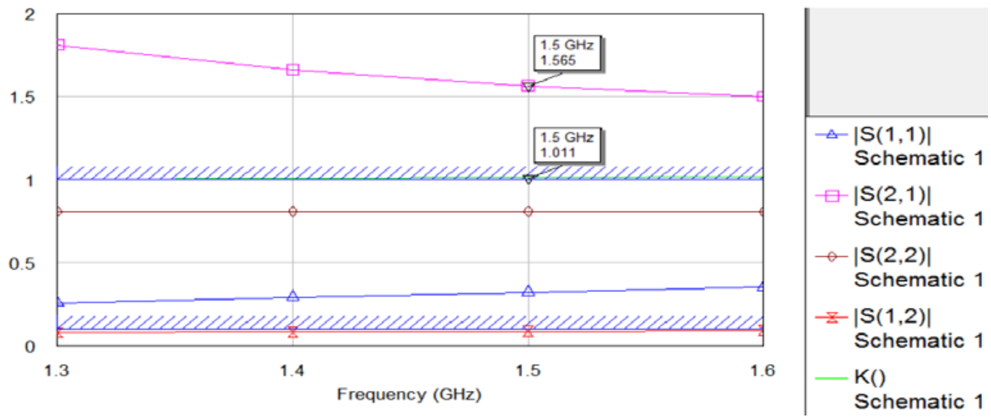

Figure (6): Magnitudes of S-Parameters

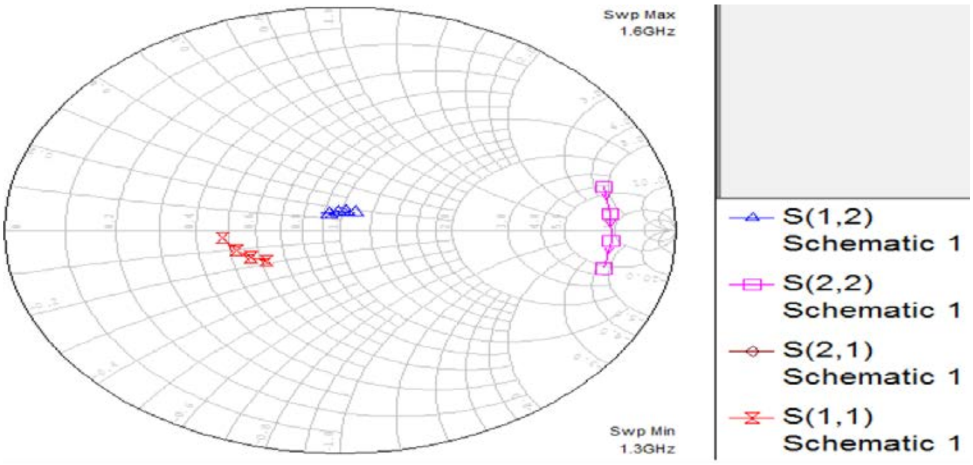

Figure (7): Smith Chart

It is clear from figure (7) that we are so far from getting the gain and the match, however, with running the optimization method with focusing of being $S_{11} < 0.3$, $S_{22} < 0.3$ weight 1, and $S_{21} > 11$ dB with weight 2. Hence, the new characteristics of intermediate section become as in Table (3) and the design is shown in figure (8). Further, Figures (9) and (10) represent the new S-parameters magnitudes and Smith chart respectively. The electrical length of the quarter wave is changed to be for the input $EL = 76.97$ Degrees and for the output $EL = 97.67$ Degrees.

Table (3) Intermediate section characteristics after optimization

	Γ	**Length of the intermediate section (mm)**	Z_0 **(Ω)**	**Electrical Length (EL) in (Degrees)**
Input	-0.2247	29	25.18	90
Output	0.5465	25.4	74.82	90

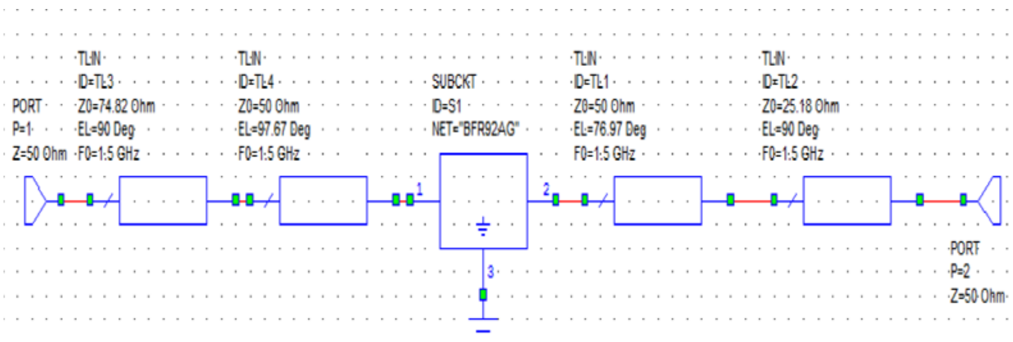

Figure (8): Intermediate Line Optimized Circuit

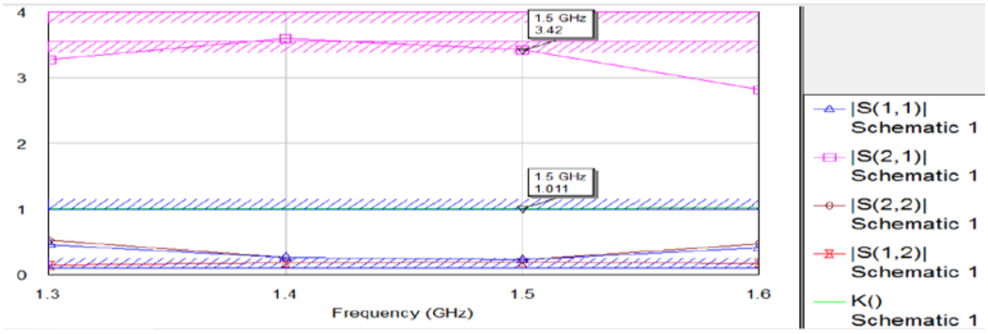

Figure (9): Magnitudes of S-Parameters after Optimization

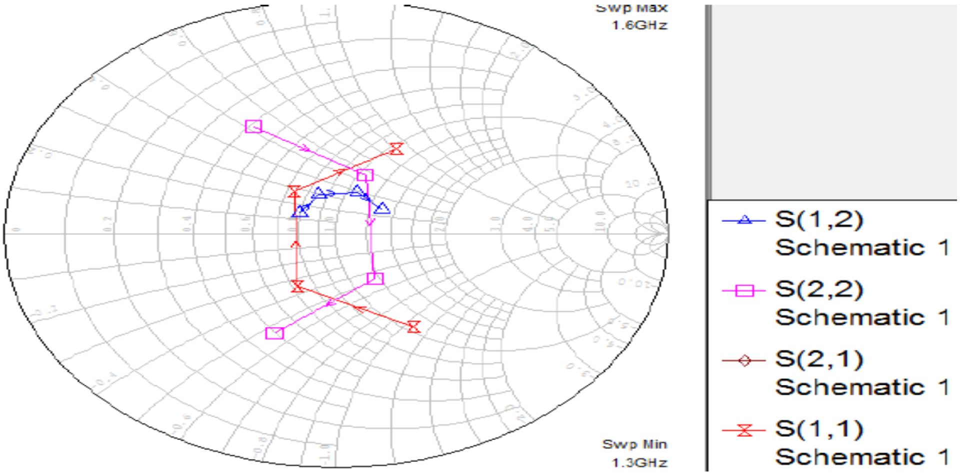

Figure (10): Smith Chart after Optimization

As a result of the optimization process, the matching has been done with gain equal to 10.68dB; however, the bandwidth is only half (about 45MHz) on what is required. Thereby, the amplifier has been designed with new approach by using stub line.

Design with Stub Lines

This design is to eliminate the imaginary parts of reflection coefficients $S_{11}S_{22}$ were given in Table (1). Currently, the design configurations carried out by using stub lines as shown in figure (11) with measured S-parameters and Smith chart shown in figures (12) and (13) respectively. Note that the reflection coefficients are negatives; as a result, admittances are positives. In order to cancel the imaginary parts, we have to work with short stub lines have characteristics of $Z_0 = 50\Omega,\ \varepsilon_r = 3.2, input\ EL = 85.05, output\ EL = 75.96$. Furthermore, the second section of the design is quarter waves, which input impedance, output impedance and the length have been calculated using MATLAB and Tabulated in Table (4).

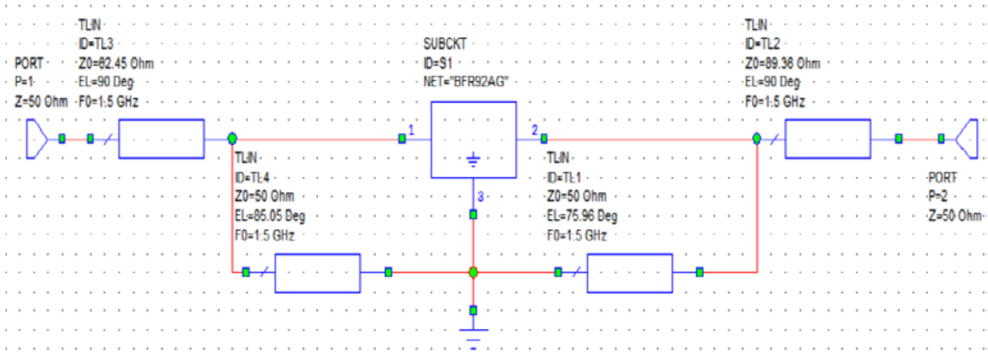

Figure (11): Amplifier Design with Stub Lines

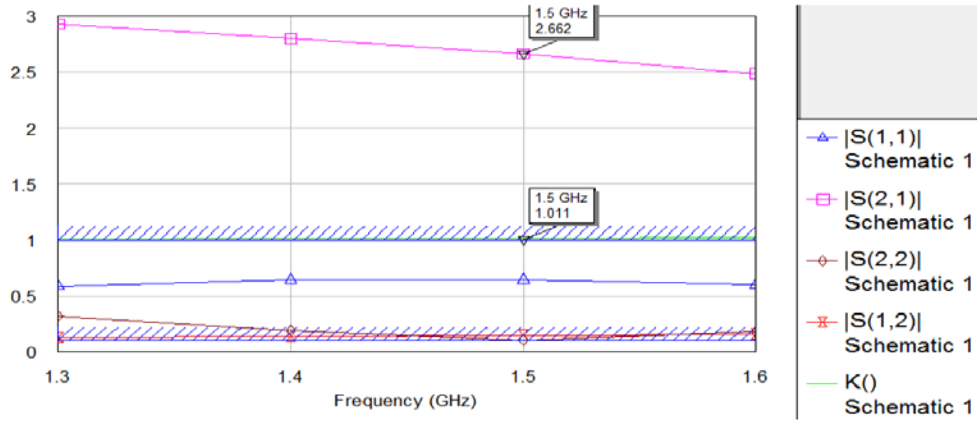

Figure (12): Magnitudes of S-Parameters using Stub Line

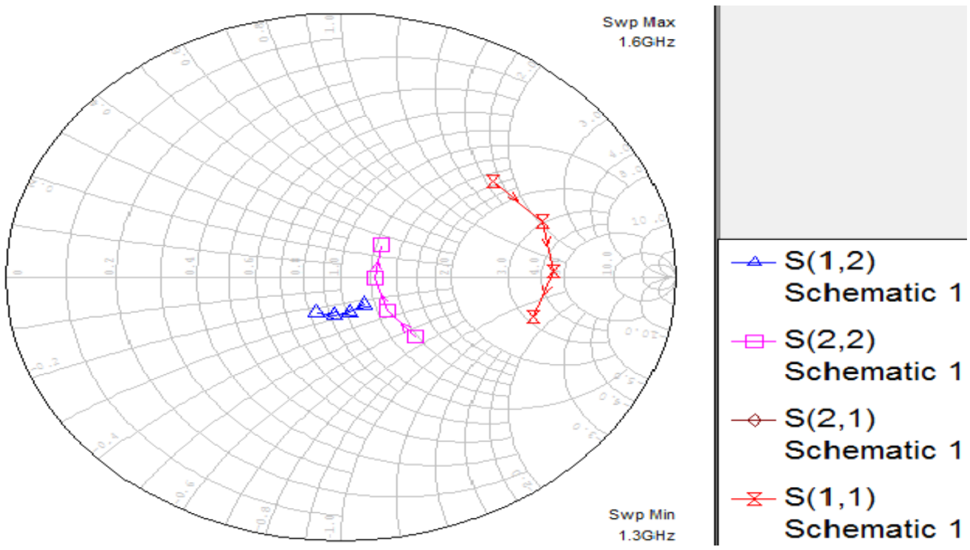

Figure (13): Smith Chart of Design using Stub Line

Table (4) Quarter Wave section characteristics

	Length of the quarter wave section (mm)	Z_0 **(Ω)**	**Electrical Length (EL) in (Degrees)**
Input	26.2	62.4552	90
Output	23.4	89.3649	90

The gain is low with only 8.2dB compared to the first design with intermediate line, as well as the bandwidth is lower than 50 MHz, therefore, with running optimization process with the same procedure of intermediate design, we get both the matching and bandwidth as shown in figures (14) and (15). And the new parameters after optimization process are given in Table (5). Note that Z_0 and EL (electrical length) on stub stage are up for optimization process with frequency range between 1.4GHz to 1.6GHz.

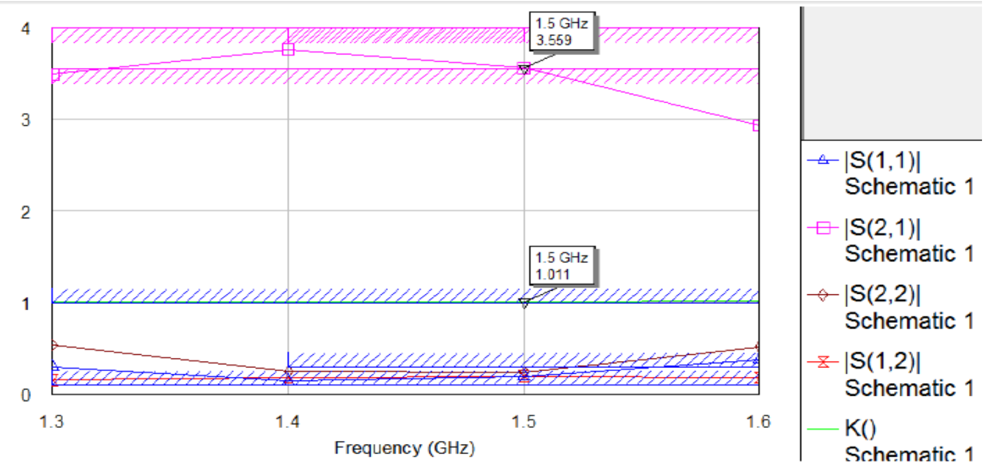

Figure (14): Magnitudes of S-Parameters using Stub Line (Optimized)

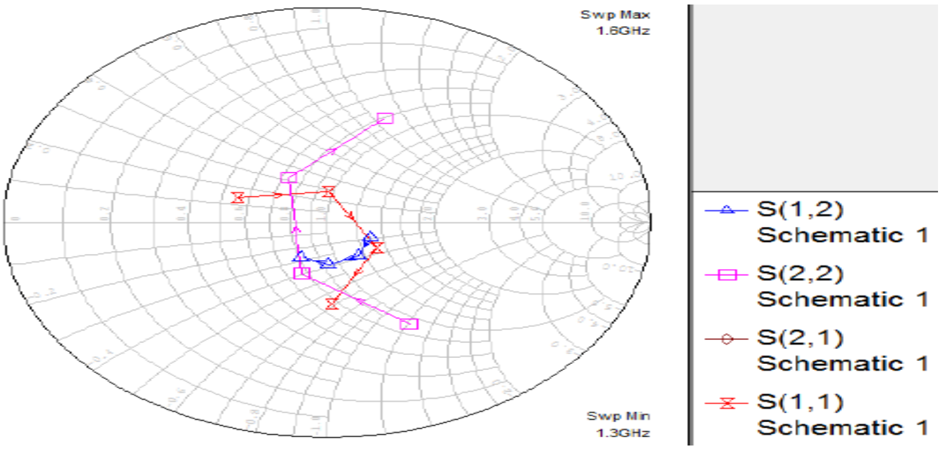

Figure (15): Stub line method's Smith Chart

Table (5) Characteristics after Optimization Process

	Quarter Wave Length (mm)	Z_0 (Ω)	Electrical Length (EL) in (Degrees)
Input	26.2	29.8	90
Output	23.4	107.5	90

By this stage of simulation and design process, we are now in getting both of the desired gain of 11.02dB (means maximum power transfer has been achieved by matching the input port to Transistor and Output port to the output BFR92A Transistor with almost no negative reflections towards the source, see figure (15) and bandwidth of 70MHz is also desired. The requirements have been improved compared to the intermediate line method.

Testing Design with MICROSTRIP Substrate

The final stage of our design is to insert MICROSTRIP substrate with characteristic values calculated and tabulated in Table (6) by using TXline tools of the M.W.O software shown in figure (16). Stub's length and quarter wave with is also given in Table (7). More to that, an optimization process is processed to earn the best results of the design with using MICROSTRIP substrate in figure (17). After optimization, the goal of designing an amplifier using BFR92A Transistor using transmission lines to achieve 11dB of gain and 100MHz has been recorded in figure (18).

Table(6)Microstrip Parameters

MICROSTRIP Parameters	Values
Dielectric Constant (ε_r)	3.25
Conductivity (σ)	1
Height (H)	787 µm
Thickness (T)	17.5 µm
Loss Tangent ($Tand$)	0.0009

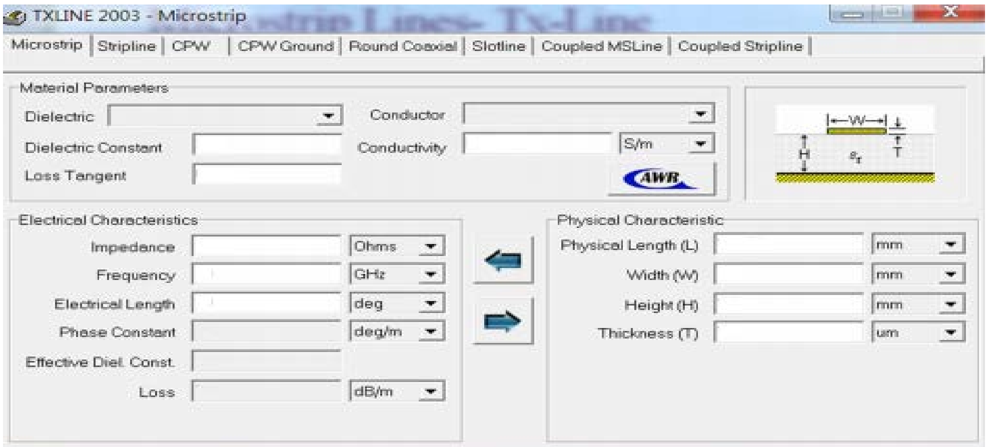

Figure (16): TXLINE ToolBox for MICROSTRIP Substrate

Table(7)Stub Lines Characteristics

	Input Quarter Wave	Input Stub	Output Quarter Wave	Output Stub
Length	35605.7 µm	17167.6 µm	3771 µm	30716.5 µm
Width	4943.37 µm	2425.45 µm	595.101 µm	2425.45 µm

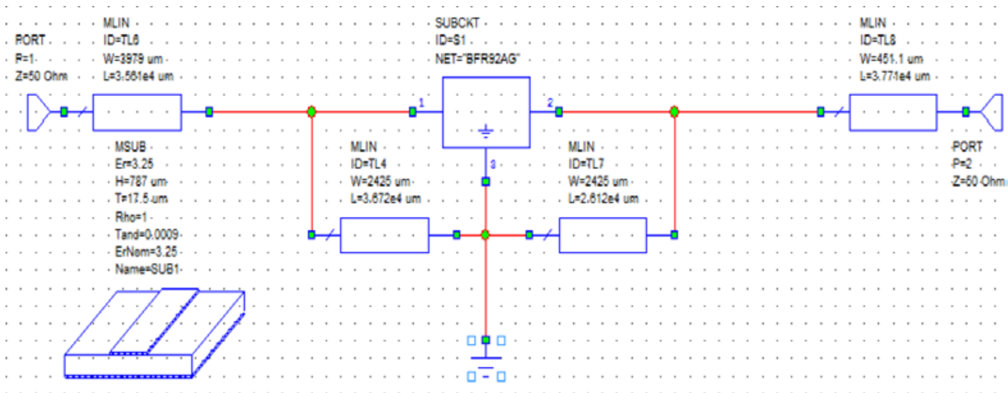

Figure (17): Final Design Stage with Microstrip Substrate

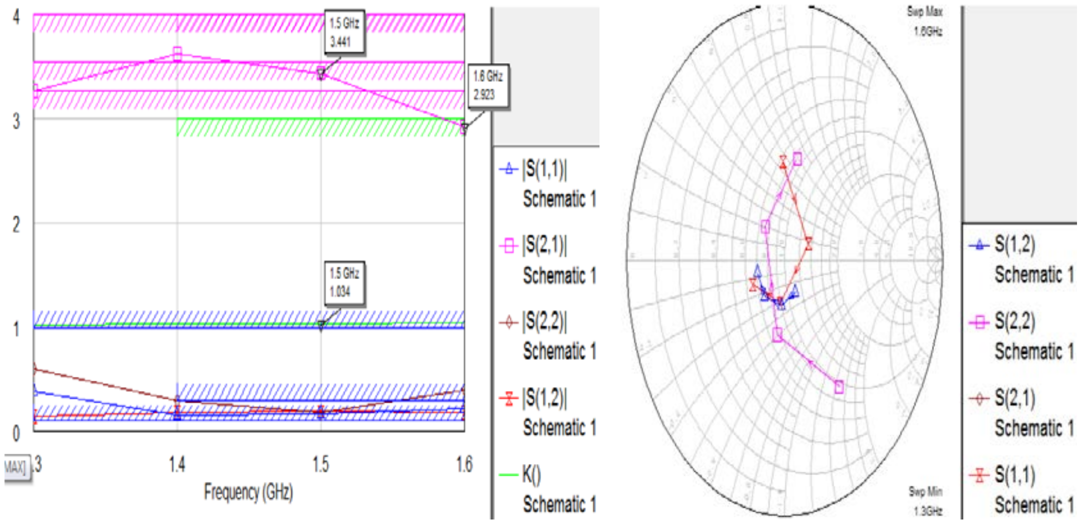

Figure (18): Final Design Magnitudes Curves and Smith Chart

CONCLUSION

In conclusion, the design with intermediate line and in term of bandwidth and circuit simplicity, has very limited bandwidth but simple design because it shows no interference with D.C. biasing. In the second approach, by using stub

line, and in term of bandwidth, it has doubled and achieved the desired gain with 11dB at 1.5GHz. However, the short circuiting (D.C. bias) the base and collector of the BFR92A transistor to the emitter. This needs to be solved with the use of coupled capacitors. In this case, this shows much more difficulty but higher performance.

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