Single-Stage Amplifiers Simulation
for Microwave Applications Using S-Parameters

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ABSTRACT

A single-stage amplifier circuits containing transistor as BJT or FET transistor were designed for the microwave application using S-parameters, and developed as a lumped circuit then converted to its equivalent microstrip distributed circuits on different substrates such as Alumina (ε_r=9.8) and Beryllia (ε_r=6.3). The output results as power gain G_p, noise figure NF, and stability factor K were obtained. These results were compared with other published worked included circuits having the same conditions. The comparison shows that in case of the feedback applied to the circuit the G_p achieved about (~1.5) dB for BJT circuits along (0.6-1) GHz and noise figure increased about double, where for FET circuit the increasing in G_p about (7) dB along (2) GHz, and noise figure was less than BJT circuit. The physical characteristics are discussed with respect to substrate and show that the substrate with high permittivity was helpful to reach the higher operating frequency and good power gain values.

Keywords: single stage, amplifier, field effect, bipolar transistor, microstrip**,** microwave

INTRODUCTION

The development of microwave solid state circuits is directly dependent upon the availability of suitable active devices. Active devices are required as gain blocks in circuit application and to allow a circuit to increase RF energy at a desired frequency. At low frequency, a lumped component used with transistors and diodes as needed, that is, R, L, and C. When the components become about $\lambda/8$ long, about 500 MHz to 1 GHz, we may add transmission line components in addition to lumped components. When the free-space wavelength becomes less than 1mm, the designers are usually forced to use distributed transmission line elements where possible. Other forms of transmission are also used due to the limitations of TEM transmission lines, such as waveguides, surface modes, slotline, coplanar waveguide, inverted microstripline, and suspended microstripline (Vendelin *et al.*, 2005). For microwave circuit applications the microwave bipolar transistor BJT, and FET are the two most important and commonly used active elements. The easer method for amplifier circuit design must be guided by a device's measured scattering parameters (S-parameters) to determine the circuit-element values needed to surround an active device or devices in an amplifier design. S-parameters are based upon the concept of incident (a_i) and exiting (b_i) waves in the amplifier circuit. Recently, the cascade and cascaded circuit topologies were implied to achieve higher gain and low noise-figure. The feedback in the microwave amplifier circuits showed that the applying of the negative feedback caused an increase in bandwidth but with degradation in gain. (Abdul *et al.*, 2020). A single stage amplifier achieved high gain and low noise due to the noise optimization used inductive drain feedback, (Othman *et al.*, 2013). Simulation of single stage LNA was performed especially for multi-standard wireless system with two different frequencies using combines of a notch filter with inductive degenerated, (Azman *et al.*, 2015). The most important part of the design relies upon extensive use of RF/microwave software programs. Such as general simulator/optimizer Microwave Office (Abrie, 2009), (Ivan, 2002).

In this work, an FET and BJT devices were designed and simulated for microwave applications using S-parameters. Characteristics such as the gain and noise figure were determined for each design. Each model has been compared with previous practical examples published with the same conditions.

Structure and Design Characteristics

1. At microwave frequency, however voltage and currents have little meaning and amplitudes are better way to describe microwave fields. In the network shown in Fig. 1, (**a**) and (**b**) represents the wave amplitude of the incident wave and the resultant wave, (Fuller, 1990).
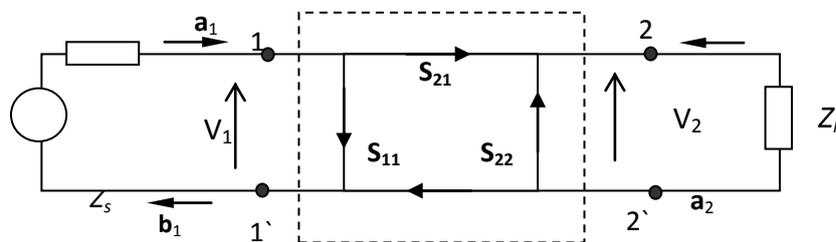

Fig. 1: The equivalent two port circuit

They are related by the scattering parameters:

$$b_1 = S_{11} a_1 + S_{12} a_2 \quad \text{and} \quad b_2 = S_{21} a_1 + S_{22} a_2 \quad \text{..............................} (1)$$

Suppose port 1 as the input and port 2 as output of the network. If the two ports are terminated in their characteristic impedance (Z_o) the physical meaning of scattering parameter can be explained as, $\Gamma = b/a$. So from equation (1), we can write the S-parameters as:

$S_{11}=b_1/a_1$, is the input reflection coefficient, for $a_2=0$
$S_{12}=b_1/a_2$, is reveres transfer coefficient, for $a_1=0$
$S_{21}=b_2/a_1$, is the forward transfer coefficient.
and, $S_{22}=b_2/a_2$, is the output reflection coefficient, for $a_1=0$

2. When designing an amplifier, many characteristics should be considered such as:
Power Gain (G_p): The ratio of the power delivered to the load, to the actual power supplied into a circuit is fined as the G_p and given by (Weber, 2001):

$$G_P = \frac{1}{\left(1-|S_{11}|^2\right)}|S_{21}|^2 \frac{1}{\left(1-|S_{22}|^2\right)} \quad ....(2)$$

Stability (K): A stability amplifier condition is where there are no unwanted oscillations anywhere, [Davis and Agarwal, 2001]. This condition lead to the following requirement, (Bahl, and Bahartia, 1988);

$$K = \frac{1+|S_{11}S_{22}-S_{12}S_{21}|^2 -|S_{11}|^2 -|S_{22}|^2}{2|S_{12}||S_{21}|} > 1 \quad ....(3)$$

When simultaneously matching a two-port, the maximum transducer gain G_{max} is, (Trinogga *et al*., 1991):

$$G_a = \left|\frac{S_{21}}{S_{12}}\right|(K \pm \sqrt{K^2 -1}) \quad ....(4)$$

here, if K >1, the sign is usually (- negative sign).
The maximum stable gain (G_{max}), is obtained by substituting K=1 then:

$$G_{max} = \left|\frac{S_{21}}{S_{12}}\right| \quad ....(5)$$

Noise Figure (NF): The actual noise figure, of any linear two-port network can be expressed by their noise temperature, [Laio, 1985]:

$$NF = \frac{GK(T_o + T_e)B}{GKT_o B} = 1 + \frac{T_e}{T_o}, \quad ....(6)$$

These parameters are described in this work and calculated independently by (Microwave Office). Software.

3.   Amplifier Design
Using S-parameters usually completes microwave amplifier designs, since this is the most accurate two-port description of the transistor. The S-parameters of microwave transistor can be measured by using network analyzer system. At any frequency, every designer have to ensure that the input and output matching networks for the amplifiers are matched to 50 ohms load at the input and output terminal [Pozar,2000], and has the following parameters: S_{11}, S_{22}, and S_{21}, with significant magnitude general topology of the single-stage amplifier consists of three stages: the input matching circuit (M1), the amplifier itself and the output matching circuit (M2) (Jung-Jang *et al*., 2001), (Lu *et al*., 2010);
  i. an input lossless matching network M1,
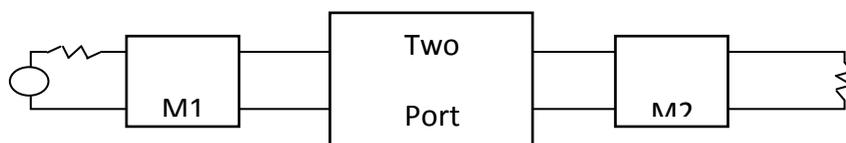 **ii.** an output lossless matching network M2.

Fig. 2: The two-port network

If the stability factor K>1, the above two networks can be found to give the maximum available gain given expressed by eq. (5). If the stability factors K =< unity, the amplifier could be terminated in matching structure which causes oscillation, that is G_a is infinite (Vendelin, 1982). Thus, the stabile design will require some input and output mismatch impractical. There are at least two treatments, (i) adding resistive matching element or, (ii) adding feedback to make K >=1.

The design of single-stage amplifier would usually have the following specification, which must be calculated: Gain, (G) flatness±(1.5) dB, bandwidth (f_2-f_1), and center frequency (f_o), noise figure (NF). Usually, short-circuit stubs are placed near the transistor to allow dc biasing. The following steps can be tabulating for the design of a one-stage amplifier:

i.   Select transistor based upon S-parameters, noise figure and linear output power.

ii.   Calculate K and G_a or G_{max} versus frequency.

iii.   For K >1, select the topologies that match the input and output at the upper band edge f_2. This will give G_{max}, and $S_{11} \approx S_{22} \approx 0$, ideally, for the initial design. Next, the topology may be varied to flatten gain versus frequency at the expense of S_{11} and S_{22}.

iv.   After finding initial M1 and M2, make adjustments in topology until the specifications for gain, VSWR are satisfied.

v.   Design dc bias circuit. Lay out the elements of the complete circuit and check realizably.

4.   Distribution Circuit:

Microwave circuit techniques included printed circuit board (PCB) MIC, and MMIC technologies. The circuit designer uses packaged devices roughly are centimeter in size for PCB circuit (Weber, 2001). Microwave circuit commits of several passive components called resistor, capacitors, and inductors. Then elements are placed in space of substrate. Transmission lines are composed of these elements, but they are distributed over origin rather than being identified with a point in space. In addition to their components, controlled current and voltage sources are used to describe the performance of active elements such as transistor. The substrate is assumed to be perfect conductor and have constant potential everywhere on it. Transmission lines are used to model distributed parameter circuits and its elements such as capacitors and inductors (Weber, 2001). After choosing the values and elements of the designed circuit, it is suitable to do optimization on the results of output the circuit and reaching to the best results.

Next, the design will be converted into distributed circuit, so the resistances are converted to its values as a microstrip line with dimensions W, L which equal; (Bahl, 1979):

$$W = Z_o \frac{h}{Z_c \sqrt{\varepsilon_e}}, \qquad \text{...(7)}$$

where, Z_o, is the air characteristic impedance (376.6Ω) and, h, is the substrata high, and Z_c is the lumped resistance or characteristic impedance of the microstrip. And, the length of element which equivalent to resistance is equal,

$$L = \frac{c}{2f_o\sqrt{\varepsilon_e}} - 2\Delta\ell \qquad \text{.. (8)}$$

where, f_o the center frequency, c=3 ×10^8 and $\Delta\ell$ the effective length, and can calculated by:

$$\Delta\ell = 0.412h\left(\frac{\varepsilon_e + 0.3}{\varepsilon_e - 0.258}\right)\left(\frac{(w/h)+0.264}{(w/h)+0.8}\right) \text{...................(9)}$$

The effective primitively evaluate from eq. (10) if, w/h≥1, or from eq. (11) if, w/h≤1, (Emad, 1991):

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{-1/2} \qquad \text{.................................. (10)}$$

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\left(1+\frac{2h}{w}\right)^{-1/2} + 0.04\left(1-\frac{w}{h}\right)^2\right] \qquad \text{…………...............} (11)$$

One equation for the inductance of a strip of metal having a length ℓ (mils) and width w (mils) is, (Rohde, 2000):

$$L = (5.08\times10^{-3})\ell[\ln(\frac{\ell}{w}) + 1.193(\frac{w}{\ell})] \qquad \text{.....................................}(12)$$

Where; L is in nH, and the unit (mils $\cong$ 1/39 mm).
The capacitor formed by the metal strip over the ground plane is given by:

$$C = q\varepsilon_o\varepsilon_r(\frac{w\ell}{h}) \qquad \text{......................................}(13)$$

Where; C in farads, $\varepsilon_o = 8.86\times10^{-12}$ (F/cm) is the permittivity of free space, and ε_r is the dielectric constant of the substrate. A "fringe factor" q, is included to account for necessary fringing (estimated to be here 10%).

5. Circuit Material: Any microstrip circuit or structure is made of two parts. The dielectric substrate and metallic conductor on the substrate's face, (Gardiol, 1988).
i. The dielectric material of the microstrip is chosen with a homogeneous distribution for its high h, dielectric constant has to be, ($2<\varepsilon_r<12$). And the tangent losses ($\tan\delta$) must be very small (<0.001).
ii. Microstrip metallic deposited on the semiconductor substrate. The metal layers must exhibit the following characteristics: low resistivity (small ohmic losses), sufficient thickness, at least three times the skin depth, the layer must be quite thin (t~0.001mm) and may also be used to realize resistors.

On synthetic substrates all good conductors such as gold, copper, silver, and aluminum are adequate and present a good adhesion. Gold is often selected for the outer layer, due to its very good resistance to oxidation and aging.

6. Analyzing the Circuit
The circuit must be analyzed to display the output results and shown by graphs. First the stabilization must be optimized so;
i. If the stability graph shows the stability factor K to be less than 1, typically it is necessary to add input and output networks to the transistor device to stabilize it over an extended frequency range.
ii. It will be necessary to edit the element parameter values as we construct the output stability network.
iii. All microstrip elements must have a substrate parameter element in the schematic.
iv. The next step is to finish the output stability network. Place and edit elements in the schematic to look like the Fig. (3).

The work is supported by "Microwave Office 2000" package, which is a completely new suite of RF/microwave design tools. The entire design solution is constructed using advanced object-oriented programming methods that result in impressive performance, reliability and ease of use. Microwave Office 2000 was developed by "Applied Wave Research Inc." to provide the user interface for setting up circuits for linear, non-linear, EM analysis, and physical layout.
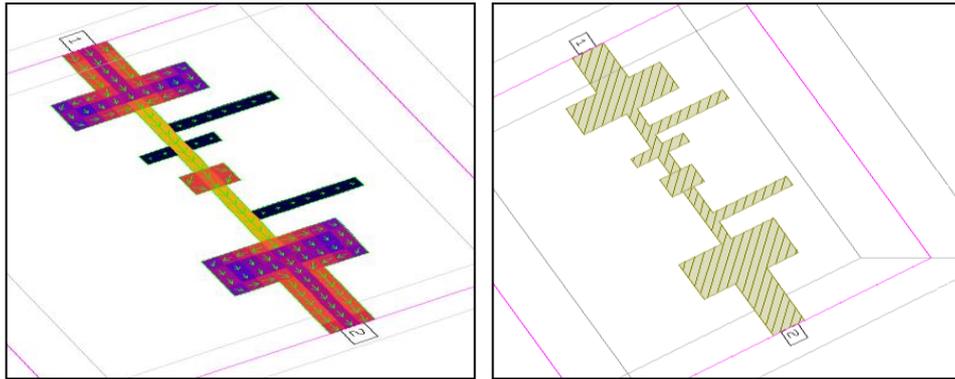
Fig. 3: Shows the Distributed Layout Design and the Distributed Field

RESULTS AND DISCUSSION

The results were obtained by using the following procedures:

a)   Specifying the operating frequency rang that we can find S_{11} or S_{22} in the lowest value. In our work we have depended on (S_{11}) the input reflection coefficient with units (dB).

b)   The stability factor must be equal or larger than unity, (k ≥ 1) at this range.

c)   Measuring of the value (S_{21}) or power gain with units (dB) at the lumped design working area which we could find S_{11}, the lowest value and the litter which is next to it. So, the reflection of the signal does not appear and must not change the gain or S_{21} more than (3dB) from the lowest frequency to the highest frequency limits of signal operating area.

d)   After that it has computed transforming lumped circuit into distributed circuit with changing the elements, like the resistance and some parts of transmission line into form of microstrip line. At the same time the program showed that the output layout for the general figure for microstrip circuit.

e)   After that the power gain can be measured and it is named here (gain) with units (dB) in this distributed circuit to distinguish on the previous lumped circuit.

f)   Measuring the noise, if it founds in the form of noise figure (NF) with units (dB), although we are using (LNA) but sometime the transistor showed some noise.

In order to reach to the best values, it is depending on the ability of optimize circuit, which is founded by the software (Microwave office) which is used.

BJT Circuit:

This design is for single-stage BJT. It is a simple amplifier using the transistor (A010011), which is working as signal amplification. Alumina substrate was used with dielectric constant (ε_r=9.8) of thickness h=1mm.

The feedback was arranged with fewer models surrounding the transistor of the previous design. The matching was indicated at (0.56GHz) as in Fig. (4).
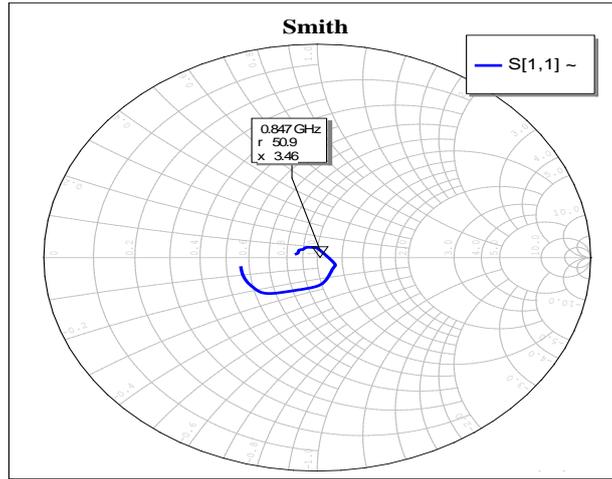
Fig. 4: Smith chart denoted matching for BJT **circuit**

Fig. (5) for S-parameters also shows that circuit could work safely up to (1GHz). S-parameters also shows that S_{21} increased up to (~13.6dB) at (1GHz) and it is denoted more than that at 0.6 GHz. Fig. (6) shows the gain of distributed circuit was (13.7dB). This G_p was about (3.3dB) less than the G_{max} that possible to obtain. The stability of this amplifier is shown in the Fig. (6) below. Stability factor was (K>1) along the operating frequency. But there is (5.5dB) in noise figure at that frequency, see Fig. (8).
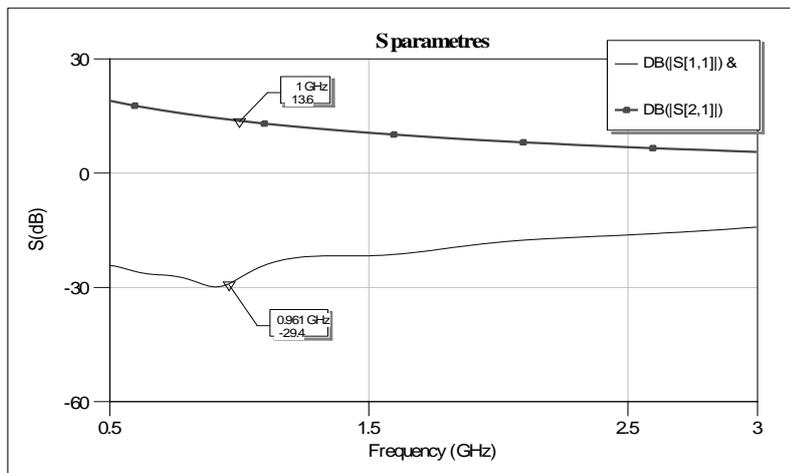
Fig. 5: S-parameters single BJT-stage lumped BJT **circuit**
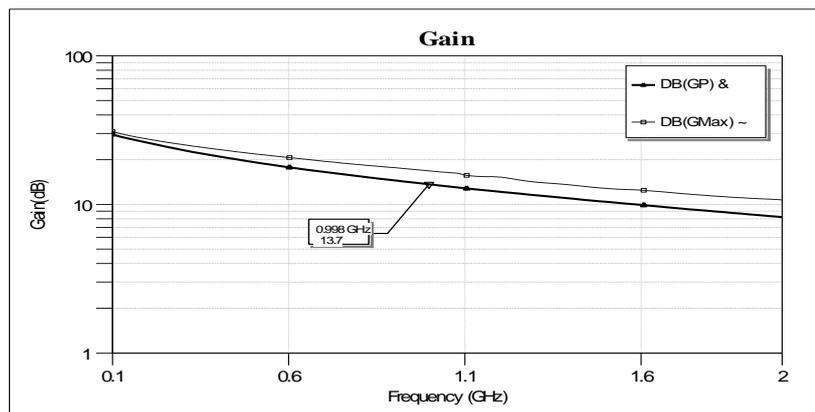
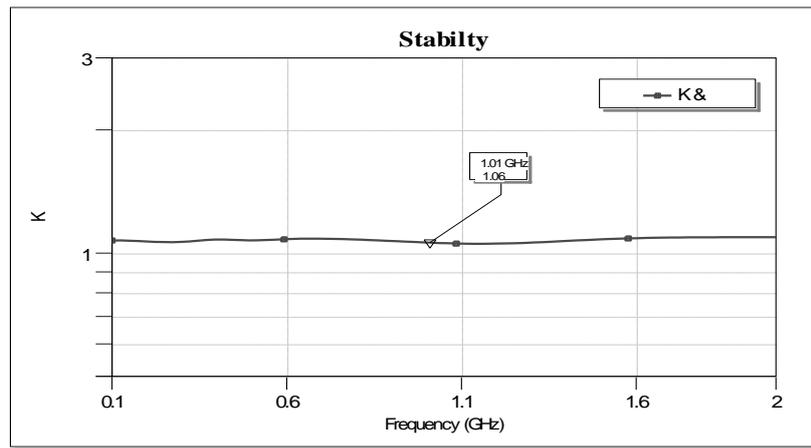**Fig. 6: The linear power gain for distributed** BJT **circuit**

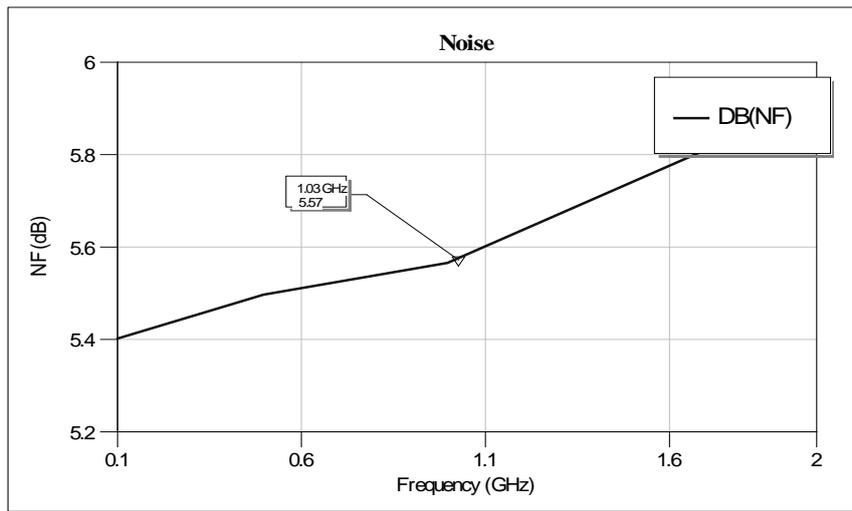**Fig. 7: The stability factor K>1 of BJT circuit**

Fig. 8: Noise-Figure of BJT circuit

All these results are summarized in (Table 1) and compared with those given reference Rohde, which has the same conditions, (Rohde, 2000). The lumped circuit for Rohde and distributed circuits for this work are shown in Fig. (9) and (10).
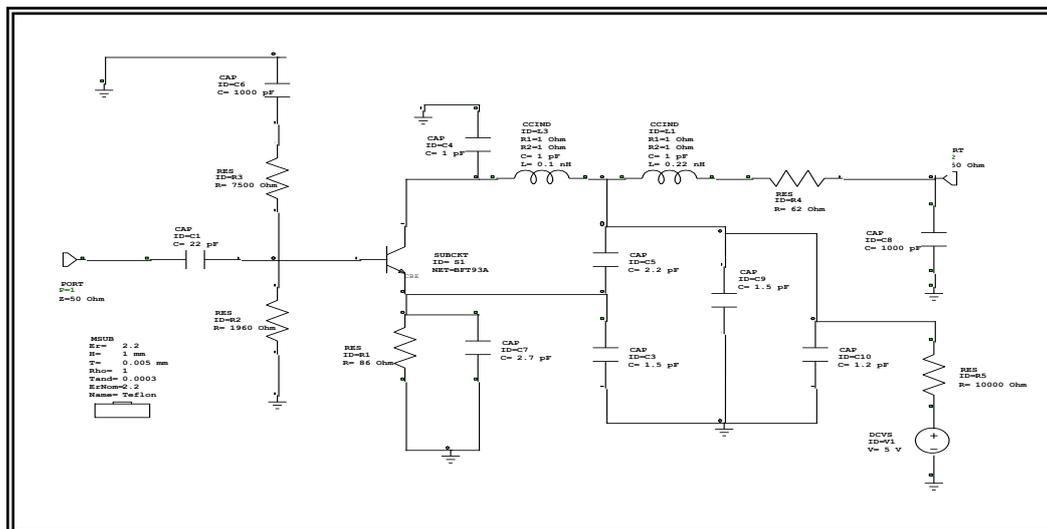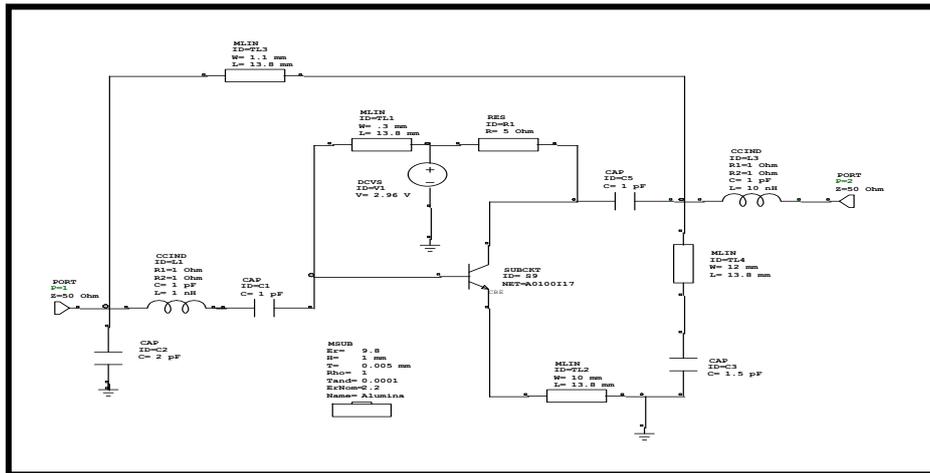

Fig. 9: The Lumped BJT circuit

Fig. 10: The distributed circuit for BJT

Table 1: Summary of results of BJT circuit and Rohde ref

The circuits	S_{21}(dB) For lumped Circuit	Gain (dB) For distributed Circuit	NF(dB)
This work	13.6 @ 1GHz	13.7 @ 1GHz	5.5
Ref. Rohde	12.3 @ 1GHz	12 @ 1GHZ	2.3

In this work the design gives the gain and S_{21} about (1.3dB) and (1.7dB) respectively more than ref. design, for both lumped and distributed circuits. We expect that an improvement is due to the feedback, which added some voltage that reduced the expected voltage distortion in this circuit. These increased the input current to the transistor so the output level increased, and may be a phase shift occurs as the output signal adding by feedback. In addition this substrate has thermal conductivity (0.37W/cm.K) which is in middle level but for low frequency it was caused a noise occurs much more than previous reference circuit.

FET Circuit:
A FET type (HMC5008A) was used on the dielectric substrata Beryllia (ε_r=6.3) with thickness h=1.5mm. The results were compared as in the (Table 2) with those achieved from Anvari, which has the same conditions, (Anvari *et al.*, 1986).

The Fig. (11) for Smith's chart shows matching of this circuit arrived at the frequency 7.5GHz.
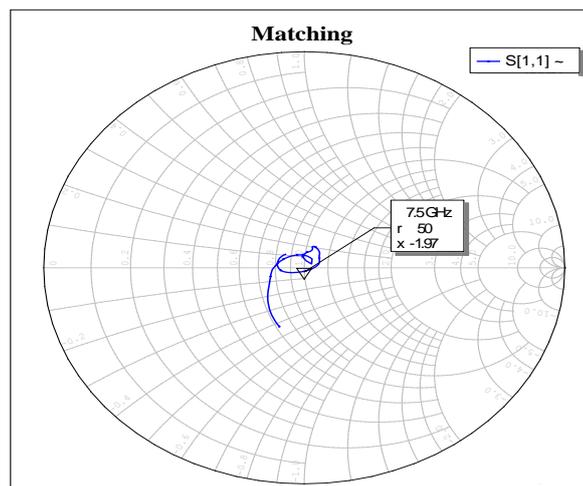

Fig. 11: Smith chart shows the matching at 7.5GHz for FET circuit

Fig. (12) gives the high value of S_{21} (15.4dB) at the lowest value for S_{11} in the frequency 7.5GHz too. This value is fixed along 2GHz frequency width, where far of this range. We expect reflection amplitude was observed as the level of S_{11} rises. The gain of distributed circuit was (15.5dB) as shown in Fig. (13). This value fixed and extended along operating frequency between (6.0-8) GHz. Here we pointed the power gain (P_G) coincide with maximum gain (G_{max}) level.
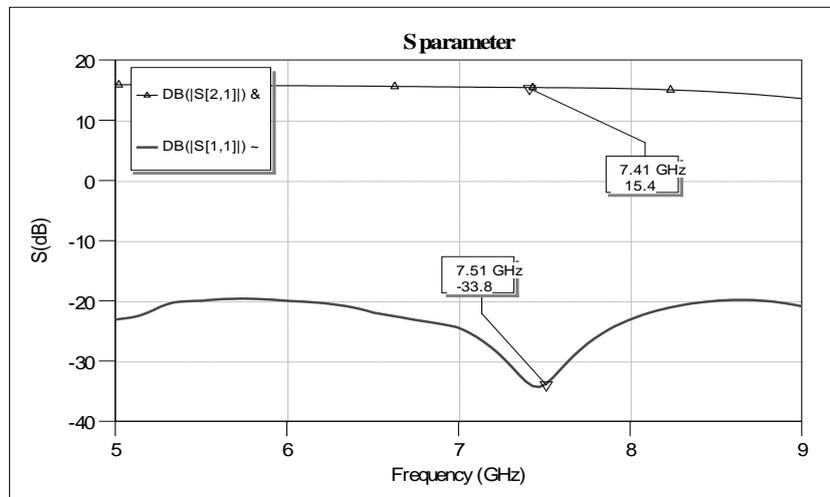

Fig. 12: The S-parameters indicate for FET **circuit**
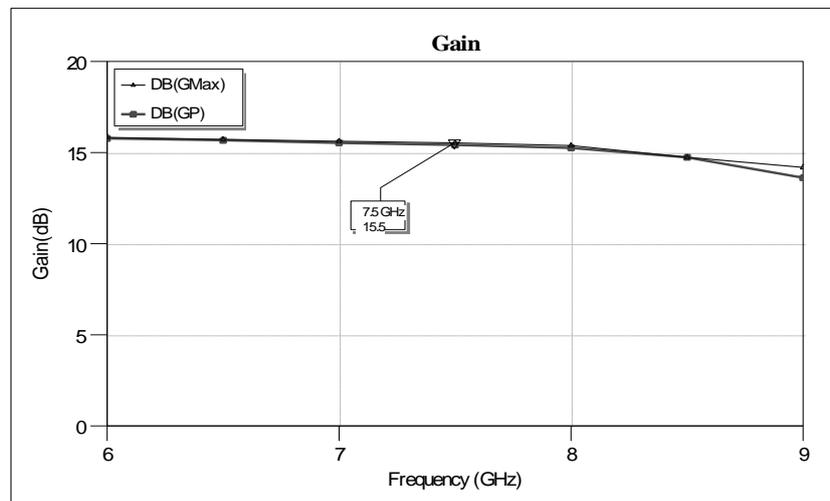

Fig.13: The power gain for the distributed FET circuit

But the stability factor was observed higher, more than one as shown in Fig. (14). The noise figure (NF) was equal to 3 dB as in the Fig. (15), but it indicated (1.5dB) only in the reference.
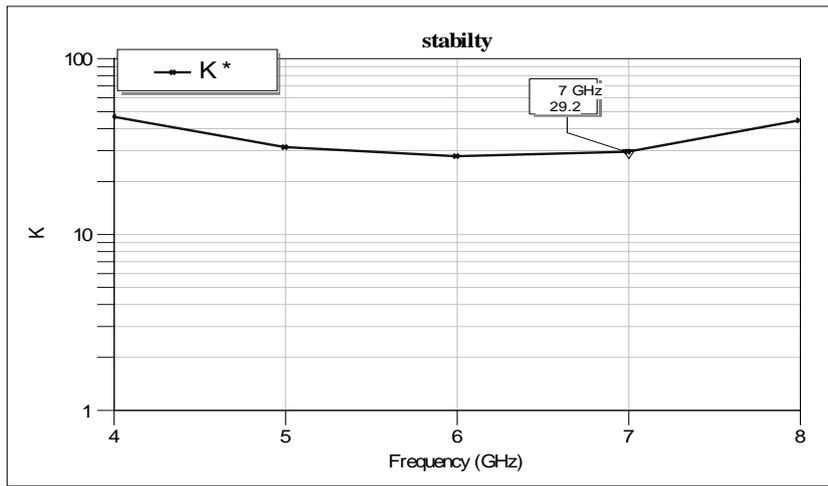
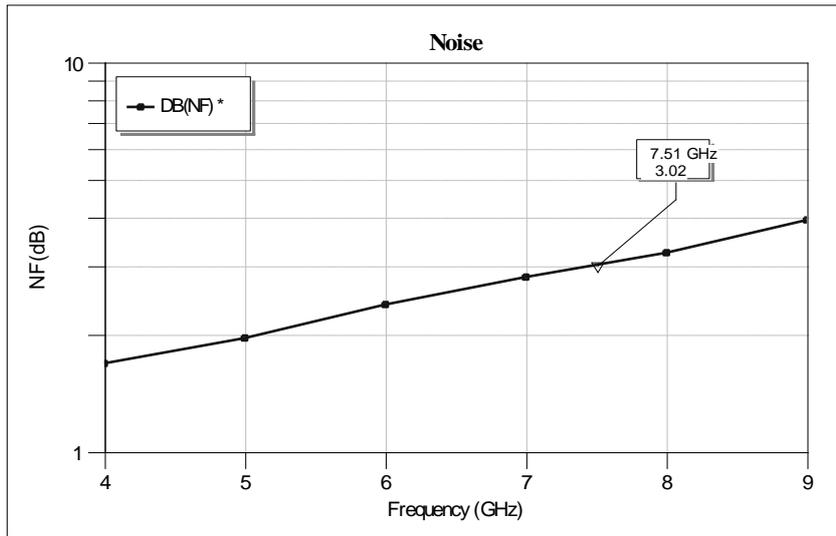**Fig. 14: The stability factor K>1 along operating frequency for** FET **circuit**

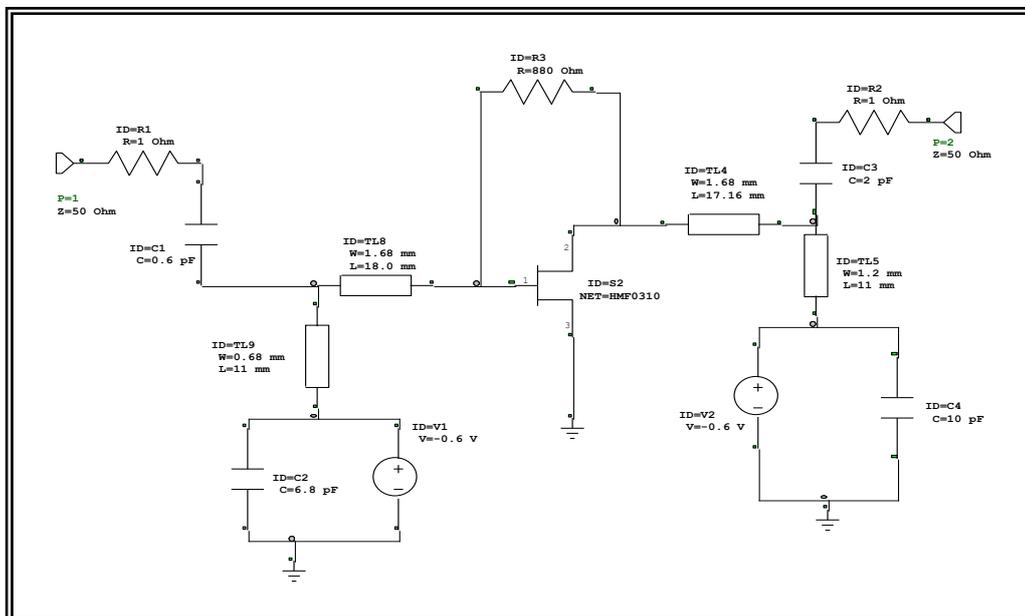**Fig. 15: The Noise-Figure NF at matching frequency of FET circuit**

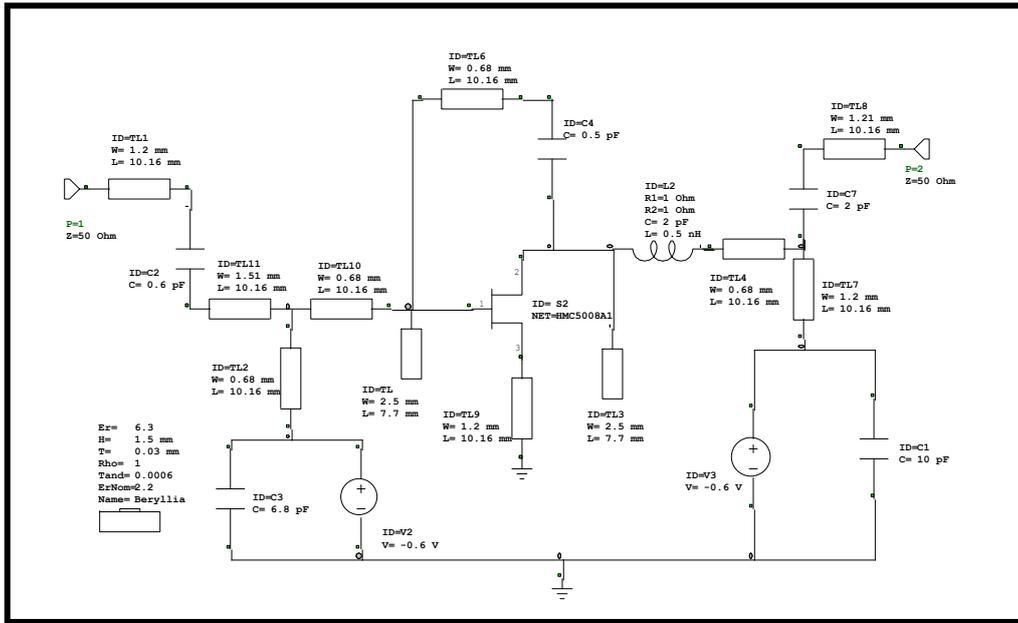**Fig. 16: The distributed circuit of Reference Anvari**

Fig. 17: The Distributed Circuit

Table 2: Comparison of results for FET circuit and those from ref. Anvari

The circuits	S_{21}(dB) For lumped Circuit	Gain (dB) For distributed Circuit	NF(dB)
This work	15.4 @ 7.5 GHz	15.5 @ 7.5GHz	3
Ref. Anvari,	8 @ 6-7 GHz	8.4 @ 6-8GHz	1.5

In this design a short transmission line with a feedback on transistor has been successfully used for input and output matching network and to increase the linear gain. This achievement gives a good result (~7dB) in both gain and S_{21} values. But this design appears a double value of noise Fig. (3dB), along operating frequency range of 2GHz. By using Beryllia (BeO) with permittivity (6.3) lower than alumina (9.8) the increasing of power gain at higher frequency was caused a noise figure increased, at high frequency. (BeO) presents a very large thermal conductivity that makes its use particularly interesting for high power applications. The design shows little shift in operating frequency this may be due to the discontinuity for new added microstrip components of this circuit. The results obtained from the modified circuits are tabulated in (Table 3).

Table 3: The summary results for both BJT and FET circuits

Characteristics	BJT Permitivity $\varepsilon_r \sim (9.8)$	FET Permitivity $\varepsilon_r \sim (6.3)$
F_o (GHz)	0.5 - 1	7.5
ΔF (GHz)	0.5 - 1	1.5 – 2
G_p (dB)	13.6	15.5
NF (dB)	Higher	Lower
K	> 1	>1

*F_o: operating frequency. ΔF: operating frequency range. G_p: power gain NF: noise figure.   K: stability factor

The linear power gain of BJT with high permittivity was good as well as for FETs. The noise figure of FETs is lower than BJTs. The stability was more than one for both circuits. The substrate materials, which have high permittivity and low thermal conductivity, remove the produced heat slowly and noise figure may rise in BJTs more than FETs. Here it is possible to say that BJT and FET amplifiers could be improved by using:

(**1**)   The feedback concept such as the lossless-feedback which may be used in BJT or FET amplifier design. This could be arranged surrounding the transistor. In some way the feedback acts as a directional coupler that can increase the output signal with respect to input signal. If there is no out of phase one could get a lower noise figure with higher linear gain.

(**2**)   The substrate and its dielectric losses which have an important role in the performance of the designed circuit such as: (i) BJT circuits with substrate of high permittivity, work at low frequency up to 1GHz and output gain could be high, but this may lead to increase noise figure value. Thermal conductivity has little effects here. (ii) FET circuits the high permittivity substrate was work at higher frequency and output gain could be high also, but in this case the noise figure value lower than BJT. It was found that the operating frequency was more than of BJT.

CONCLUSIONS

In this work we have used special known substrate and transistor. The acceptable circuits produced the optimized results for the linear power gain, noise figure, and stability factor.

Both the BJT and FET were used in the designed circuits, with same dielectric substrate. The package software helped to find the accepted and the best circuits that give good output results as power gain, the noise figure and stability factor. From the results we conclude:

i.   The BJT circuits using substrate with high permittivity (ε_r=9.8), were worked at low frequency up to 1GHz, and the operating frequency was narrow. The output gain found to be within (~13.6), the noise figure was high up to ~5dB.

ii.   In FET circuits using substrate of permittivity (ε_r=6.3), the operating frequency worked up to 7.5GHz. The power gain obtained was within (15.5dB). The noise figure was relatively less than BJT.

iii.   The feedback concept has an important role also in this work. It acts as a directional coupler and increases amplitude of the output signal with respect to input signal. The magnification due to this feedback may raise the noise figure as the linear gain increases.

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محاكاة لمضخمات أحادية المرحلة لتطبيقات الميكروويف باستخدام معلمات التشتت S

الملخص

صممت دوائر جديدة باستخدام ترانزستورات مايكروويف للأنواع BJT و FET باستخدام معلمات S. ونظمت كدوائر مجمعة lumped circuit ثم حولت الى مكافئاتها من الدوائر الشريطية الموزعة microstrip distributed circuits على قواعد أساس substrate materials ذات النفاذية عالية (Alumina, ε_r=9.8) و(Beryllia ε_r=6.3). قورنت نتائج التصاميم مع نتائج دوائر أخرى لها من الظروف نفسها اختبرت سابقا. بينت النتائج ان استخدام التغذية العكسية في تصميم دائرة BJT أعطت زيادة في التحصيل 1.5 dB تقريبا عن القيمة المرجع على مدى ضيق من الترددات بينGHz (0.6-1) ولكن رفعت قيمة الضوضاء الى الضعف، فيما أنجزت الدائرة مع FET تحصيلا بزيادة 7 dB عن تصميم المرجع على مدى أوسع يصل 2 GHz، مع انخفاضا في قيمة الضوضاء عن السابقة. نوقشت الخصائص الفيزيائية بالنسبة لمادة الأساس وتطبيقات الموجات المايكروية واستنتج ان مواد ذات النفاذية العالية تساعد في رفع التردد العامل وتعطي تحصيلا جيدا ولكن يلاحظ ارتفاعا في مستوى NF لدوائر BJT اعلى منها لدوائر FET. وكان أداء FET أفضل من أداء BJT لبعض التطبيقات المؤشرة.

الكلمات الدالة: ترانزستورات المايكرويف، معاملات التشتت، ترانزستورات تأثير المجال، ترانزستورات ثنائية القطب.