Modelling and Simulation of Microwave Amplifier for Enhanced Gain Stability

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Abstract **- This paper presents the modelling and simulation of microwave amplifiers for enhanced power gain stability with the objectives of showing how scattering parameters (s-parameter) could be used; and also to show how the data so generated could be used in calculating the Rollett stability K, which states that a microwave amplifier is stable if K is greater than unity. This was made possible by simulating the behaviours of two commercial microwave amplifiers (A03184ia and M86576v5) using a set of software called PUFF; a microwave simulation program with a high level of accuracy for calculating scattering parameters of an amplifier. However, the result obtained after several tests, experimentations and simulations such as resistive loading test, input and output reflection coefficient improvement test gave a perfect match; a situation where all the scattering parameters meet at the centre of the smith chart with a Rollett stability factor K of 6.635 which signifies that the microwave amplifier stability enhancement has been achieved.**

Keywords – Scattering **Parameter, PUFF, Reflection Coefficient, Rollett Factor, Amplifier.**

I. INTRODUCTION

The use of simulation software in electronic engineering design is a common practice in recent times. A simulator can provide a significant reduction in time and cost of the implementation of any electronic system. Provided adequate models are available for system elements, simulators can accurately predict the response of a system allowing the engineer to tune the design to obtain the desired response before fabrication. In order to be able to predict the response of a system, the simulator must have accurate models of all the elements that compose it. Therefore, the generation of accurate simulation models plays an important role in modern electronic design . A microwave amplifier is a device for enhancing the output power signal of a microwave device, usually by increasing the amplitude or height of the wave that directly relates to its power level. This is accomplished by channelling additional input power to the microwave device so that its microwave radiation carries more energy .

II. RELATED WORKS

In his paper [1] examined the stability behaviour of a microwave amplifier using Volterra Series approach which is one of the earliest often studied methods of modelling microwave amplifier. It presents an advantage over power series methods that it is capable of modelling systems with memory. Volterra Series describe non-linear systems using a multidimensional convolution operation with the general form presented in equation 1

$$W(t) = \int_{-\infty}^{\infty} h_1(\tau_1)S(t-\tau_1)d\tau_1 + \int_{-\infty}^{\infty}\int h_2(\tau_1,\tau_2).S(t-\tau_1).S(t-\tau_2)d\tau_1 d\tau_2 + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_3(\tau_1\tau_2\tau_3).S(t-\tau_1).S(t-\tau_2).S(t-\tau_3)d\tau_1 d\tau_2 d\tau_3 + \ldots\ldots \quad \text{--(1)}$$

The different functions h_n $\tau_1,\tau_2,\tau_3 \ldots\ldots \tau_n)$ are called nth-order kernels and they represent the non-linear impulse response of the system. Something that can be inferred from equation 1 is that it is represented as a series of infinite terms that when converted to discrete time so as to be handled by a computer will need to be truncated, thus loosing accuracy. Therefore, at some point a compromise between accuracy and complexity will be required; this represents one of the main limitations of the Volterra Series. As the device presents a more non-linear behaviour, the total number of kernels needed to keep the truncation error under an acceptable level will increase significantly. In general, Volterra Series analyses are only practical with weakly non-linear devices. Although some efforts have been made in order to simplify their complexity extracting and simulating Volterra Series models can be a tedious process.

[2] In his work introduced and developed a simple approach for estimating and designing a microwave amplifier for a perfect stability condition. In his approach the amplifier is approximated by a very simple equivalent model consisting of the intrinsic voltage controlled current source (generator) and the parasitic output parallel capacitor and series inductor. The weakly non-linear effects are ignored and the trans-conductance is considered to be linear until the voltage across it and/or the current supplied by it clips strongly when voltage pinch off and/or current saturation is reached. Under these assumptions, Cripps developed linear mathematical expressions, which tie together the load-line and the voltage and current limits across the intrinsic generator with the external load and the output power delivered to this load. He showed how to present the relation between the intrinsic load-line and the external impedance on a Smith Chart as constant output power (load-pull) contours.

The Cripps Approach became very popular because of its simplicity and the satisfactory results it provides in many cases. The simple three-element equivalent model can easily be extracted when a full linear equivalent circuit is fitted to the *S-parameters* of the particular transistor. This approach is, however, often not general enough.

Some of its limitations are that it does not allow for feedback or transistor losses. Cripps pointed out that it is a simple task to implement the equations presented in his work into a linear simulator to simulate the power performance in the same manner that most simulators compute noise figure. He also pointed out that, with a slightly more innovative approach, the effect of the feedback could also be taken in account but Cripps' work was able to achieve a stability constant of 0.89879 which by implication is less than unity[3][4].

[5] In his paper modelled a microwave amplifier using a Vector Network Analyzer (VNA) which was manufactured by Hewlett Packard in the late 80s. VNAs provided a quick and accurate way to characterize electrical networks by providing a whole set of network parameters (e.g. impedance-Z, admittance-Y). The features that made the VNA an essential measurement tool include: the ability to obtain both the magnitude and phase of the network parameters, and the use of vector corrections to de-embed errors due to cables and other imperfections from the measurements. However there are some limitations of Vector Network Analyzer and these are:

- Conventional network analyzers use their own internal RF Source, which generates a single tone continuous wave. Therefore, multi-tone tests (e.g. inter-modulation distortion) cannot usually be performed.
- The purpose of a VNA is to obtain S-Parameters, which are ratios of the input and output voltages incident to and reflected from the device under test. Therefore, absolute power levels cannot be directly measured with VNAs. When this is required, an external power detector will be needed.
- The VNAs receivers are tuned to a predetermined frequency and will capture signals within a limited (IF) bandwidth. The frequency at which the receiver is tuned is usually set equal to the frequency of the RF source. This circumstance impedes VNAs from obtaining harmonics that the device under test may generate. Some VNAs include a frequency offset mode that allows them to measure amplitude at frequency other than the generated for the RF; however this mode does not allow for obtaining phase, unless a special phase calibrator is available.
- VNAs measure phase by using a phase detector that will produce a voltage signal proportional to the difference in phase between the two signals being ratioed. The basic operation of a phase detector requires phase lock between the two signals and, as a consequence, it imposes that both signals need to be at the same frequency. A VNA will therefore be unable to obtain phase information of harmonics or any other frequency component other than the fundamental input.

The data so generated by Gonzales[6]was able to give a stability factor of 0.999998 when computed using the Rollett stability condition, though, it was approximated to one but this value is not so good because as the frequency increases, the amplifier becomes more unstable [7][8].

III. DESIGN METHODOLOGY

The methodology of the proposed modelling and simulation of microwave amplifier for enhanced gain stability is divided into three stages namely: resistive loading, input reflection coefficient improvement, and output reflection coefficient improvement.

3.1Resistive Loading

One of the methods developed in this work to predict improvements in stability and degradation of noise figure is the use of resistive loading. Designing an effective microwave amplifier requires a high-performance transistor, but most suitable devices are potentially unstable at microwave frequencies, leading to oscillation. Fortunately, resistive loading at the input or output of the active device can prevent oscillation at the frequency of interest for all passive source and load terminations. In this work a single stability parameter, k, to characterize amplifier stability and prove that the condition k > 1 is necessary and sufficient for unconditional amplifier stability. In the figure below, the first and last two-ports in the cascaded network represent one element, either a series or parallel resistor connection, while the centre two-port represents the transistor with transmission parameters computed from its scattering parameters.

The stability of an overall network of this type can be found by cascading the transmission parameters, converting from transmission to scattering parameters, and then applying the stability condition to determine the value of k for the overall configuration. Eight different input/output combinations are available for investigation with this technique depending upon whether resistors are connected in series or parallel to one or both of the active device's ports

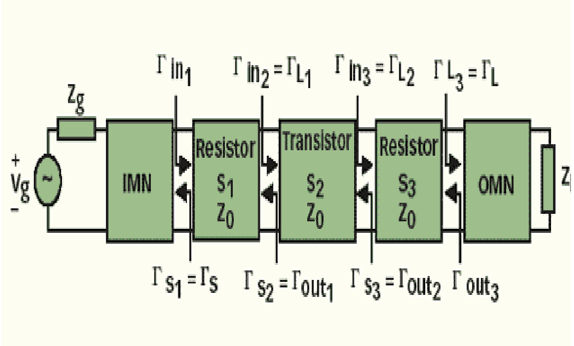


Fig. 1 cascade of two-port network

Resistive loading was implemented in the following ways; in case one as shown in fig. 2, the microwave amplifier was simulated without any resistor connected, its K-factor data generated are as shown on table 1 below. In the second case as shown in fig. 3, a resistance of 90 Ω was experimented by connecting it in series with the amplifier, its data is as shown on the table 1. Case three as shown in fig. 4, has a parallel resistance of 670Ω to the amplifier input, case four as shown in fig. 5, has a series resistance of 400 Ω connected to the amplifier output. Case five, as shown in fig 6, was experimented with a parallel resistance of 18 Ω connected to the output of the amplifier, while case six, as shown in fig. 7 has a parallel resistance of 1450 Ω and a series resistance of 116 Ω both connected to the input and output ports of the amplifier respectively. Case seven, as shown in fig. 8, has a resistance of 150 Ω and a parallel resistance of 10 Ω connected to the input and output ports of the amplifier respectively, case eight, as shown in fig. 9, has a parallel input resistance of 5285 Ω and a parallel output resistance of 50 Ω connected to the amplifier and finally, case nine as shown in fig.10, has series resistance of 28 Ω and also a series resistance of 480 Ω connected to the input and output ports of the amplifier respectively, all these resistor values were experimented and simulated with Puff as a simulating tool and the various data generated are shown in table 1

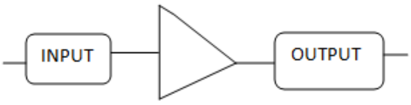


Fig. 2 Case One; without any resistor loading

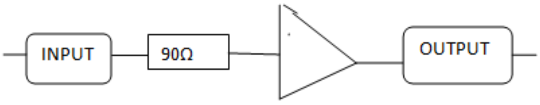


Fig. 3 Case two; amplifier with a 90Ω series input resistor

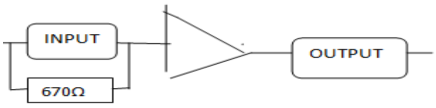


Fig. 4 Case three; amplifier with a 670 Ω parallel input resistor

Fig. 5 Case four; amplifier with a 400 Ω series resistor

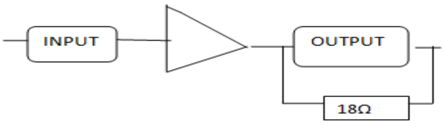


Fig. 6 Case five; amplifier with an 18 Ω parallel resistor

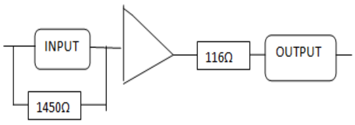


Fig. 7 Case six; amplifier with 1450 Ω input parallel and 116 series output resistors

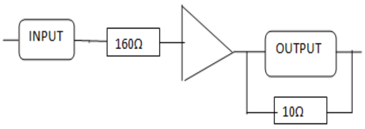


Fig. 8 Case seven; amplifier with 160 Ω series input and 10 Ω parallel output Resistors

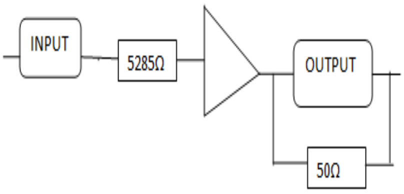


Fig. 9 Case eight; amplifier with 5285 Ω series input and 50 Ω parallel output resistors

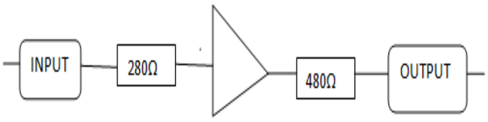


Fig. 10 Case nine; amplifier with 280 Ω series input and 480 Ω series output resistors

Table 1 shows k as a function of frequency from 0.10 to 30 GHz, for the nine cases in the table: with no, one, and two stabilization resistors. Networks containing two resistors introduce an additional degree of freedom from instability.

Table 1 K--factor as a function of frequency from 0.10 to 30 GHz, for the nine case

Curve	**Series resistance (Ω) at input**	**Parallel resistance (Ω) at input**	**Series resistance (Ω) at output**	**Parallel resistance (Ω) at output**	**Computed value of K**
1	-	-	-	-	0.17054
2	90	-	-	-	1.118064
3	-	670	-	-	1.130005
4	-	-	400	-	1.190016
5	-	--	-	18	1.950032
6	-	1450	116	-	1.20545
7	150	-	-	10	1.40675
8	-	5285	-	50	1.45674
9	280	-	480	-	1.50062

3.2 Input Reflection Coefficient (S_{11}) Improvement

Improving the input reflection coefficient S_{11} of the amplifier can improve its stability to a great extend; this is made possible with a small compensation capacitor which is connected from the input port of the amplifier to ground. Also it was discovered that the value of S_{22} will vary a little bit if S_{11} is changed by the addition of the capacitor. Several values of capacitors, inductors and resistors where experimented as shown in table 3 below, but in order to achieve a perfect match, So some changes of the parts connected from the output to ground were necessary thus, at the output a series connection of 82Ω, 1.5pF and 4.7nH is now added. See table 2.

Table 2 S_{11} Improvement Data

S/N	Capacitor	Resistors (Ω)	Inductor	S_{11} Values
1	10uf	10	20nH	-0.834dB<154.7°
2	10pf	50	10nH	-0.87dB<-154.6°
3	2pf	80	5nH	-19.35dB<-101.2°
4	1.5pf	82	4.7nH	-34.48dB<127.4°

3.3 Output Reflection Coefficient (S_{22}) Improvement

In order to improve the output reflection coefficient of an amplifier, we experimented by connecting inductor and resistor in series from the output port of the amplifier to ground. Several values of inductors and resistors were experimented until a connection of a 68Ω resistor and a 2.7nH inductor were used which gave a better result as shown in the table 3.

Table 3 S_{22} Improvement Data

S/N	Resistor (Ω)	Inductor (nH)	S_{22} Values
1	20	10	-7.35<32.8°
2	56	3.5	-23.89dB<103.9°
3	68	2.7	-41.18dB<-146.8°

The resistance and / or the inductance were changed in small steps and the result simulated at every step, the goal is to ensure that the S_{22} curve runs exactly through the centre of the Smith chart at 2GHz.

IV. RESULTS AND DISCUSSIONS

Considering table 1, a typical search algorithm for obtaining resistor values consists of a pair of nested loops, initial resistance values are incremented or decremented, depending on whether the resistor in question is connected in series or in parallel. If the pair of resistors results in an unconditionally stable amplifier, i.e., the stability factor k, is greater than unity for every frequency examined, the routine reports the resistance values along with the frequency where the minimum value of k occurs and plots the results as a function of frequency. For this work, a search algorithm was designed to identify resistor combinations that stabilize the amplifier at all frequencies while providing a stability factor as close to unity at a frequency of 2 GHz as possible. For this particular amplifier, it proves possible to adjust the minima of k for the parallel resistance input/series resistance output and parallel resistance input/parallel resistance output to approximately 10 GHz.

From tables 2 and 3 that the PUFF simulation display as seen in the figures below validates the design analysis of microwave amplifiers (MGA 86576 and A03184) being more stable when biased with resistors, capacitors and inductors. It is also important to note that the value of the inductor should not exceed 5.11nH in order to avoid self oscillation of the amplifier. The result of the various input reflection coefficient improvement tests are shown below:

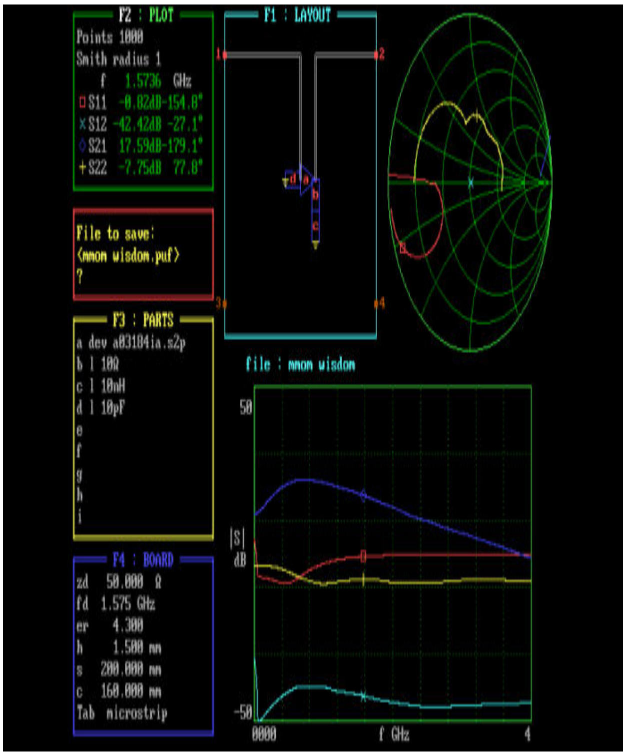

```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5736  GHz
□S11  -0.82dB-154.8°
×S12 -42.42dB -27.1°
◇S21  17.59dB-179.1°
+S22  -7.75dB  77.8°

File to save:
<mmon wisdom.puf>
?

F3 : PARTS
a dev a03184ia.s2p
b l 10Ω
c l 10nH
d l 10pF
e
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er     4.300
h      1.500 mm
s    200.000 mm
c    160.000 mm
Tab  microstrip
```

Fig 11 PUFF Simulation when biased with 10Ω, 10nH and 10pF

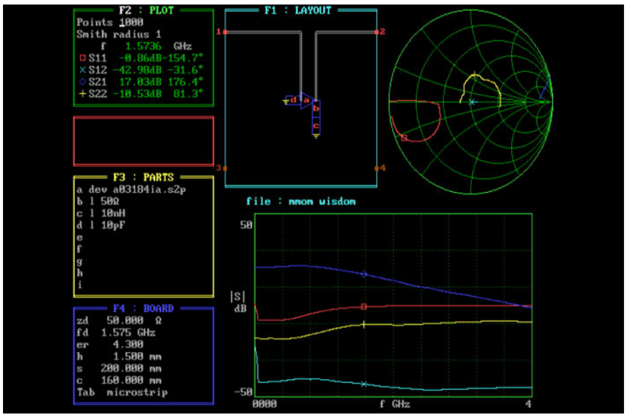

```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5736  GHz
□S11  -0.86dB-154.7°
×S12 -42.98dB -31.6°
◇S21  17.03dB 176.4°
+S22 -10.53dB  81.3°

F3 : PARTS
a dev a03184ia.s2p
b l 50Ω
c l 10nH
d l 10pF
e
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er     4.300
h      1.500 mm
s    200.000 mm
c    160.000 mm
Tab  microstrip
```

Fig 12 PUFF Simulation when biased with 50Ω, 10nH and 10pF

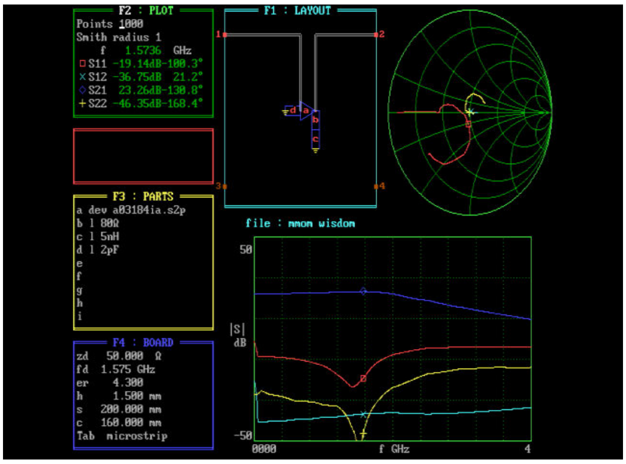
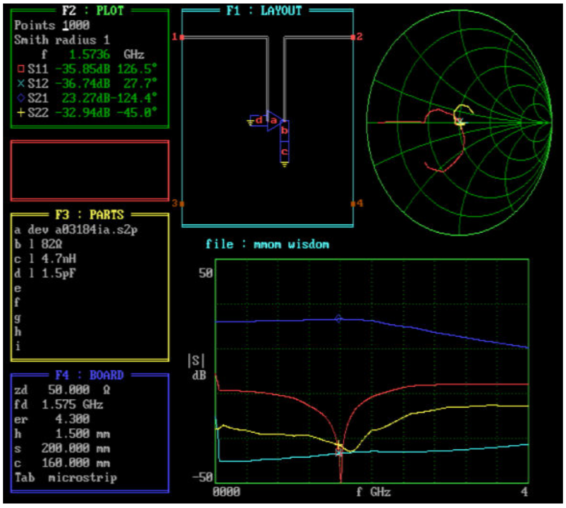

```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5736  GHz
□S11 -19.14dB-100.3°
×S12 -36.75dB  21.2°
◇S21  23.26dB-130.8°
+S22 -46.35dB-168.4°

F3 : PARTS
a dev a03184ia.s2p
b l 80Ω
c l 5nH
d l 2pF
e
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er     4.300
h      1.500 mm
s    200.000 mm
c    160.000 mm
Tab  microstrip
```

Fig 13PUFF Simulation when biased with 80Ω, 5nH and 2pF

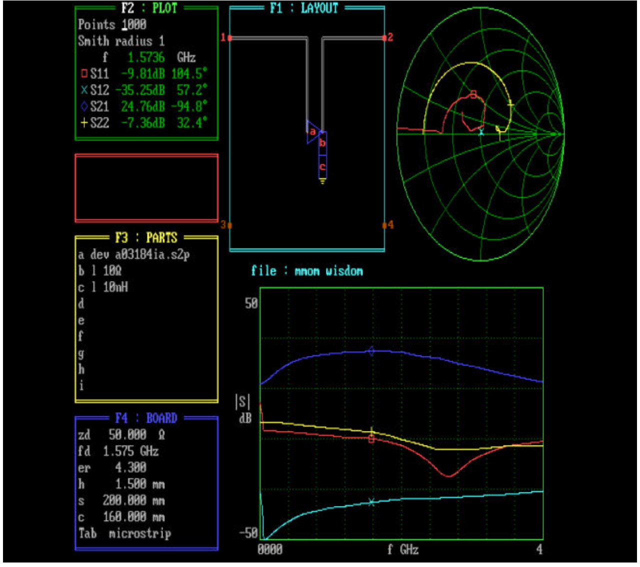


```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5736  GHz
□S11 -35.85dB 126.5°
×S12 -36.74dB  27.7°
◇S21  23.27dB-124.4°
+S22 -32.94dB -45.0°

F3 : PARTS
a dev a03184ia.s2p
b l 82Ω
c l 4.7nH
d l 1.5pF
e
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er    4.300
h     1.500 mm
s   200.000 mm
c   160.000 mm
Tab  microstrip
```

Fig 14 PUFF Simulation for S11 improvement using 82Ω, 4.7nH and 1.5pF

From the above figures, a better value of the input reflection coefficient (S_{11}) was obtained when the output port of the amplifier is grounded with a series combination of resistor and inductor values of 82Ω and 4.7nH respectively while the input of the amplifier is grounded with a 1.5pF capacitor, this resulted in an input reflection coefficient (S_{11}) value of -35.85dB< 126.5° as shown in Fig. 14 above.

Improving the output reflection coefficient (S_{22}) of a microwave amplifier will definitely improve its stability this is done by grounding the output of the amplifier with a series combination of a resistor and an inductor. The test was carried out using a resistance and an inductance of 10Ω and 10nH respectively connected to the output port of the microwave amplifier, this yielded an output reflection coefficient value of -7.36dB<32.4° as can be seen on the fig.15 below.

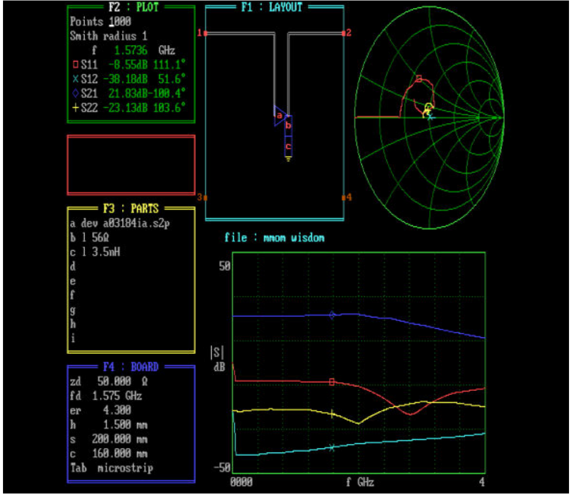


```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5736  GHz
□S11  -9.81dB 104.5°
×S12 -35.25dB  57.2°
◇S21  24.76dB -94.8°
+S22  -7.36dB  32.4°

F3 : PARTS
a dev a03184ia.s2p
b l 10Ω
c l 10nH
d
e
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er    4.300
h     1.500 mm
s   200.000 mm
c   160.000 mm
Tab  microstrip
```

Fig 15 PUFF Simulation for S_{22} improvement using 10Ω

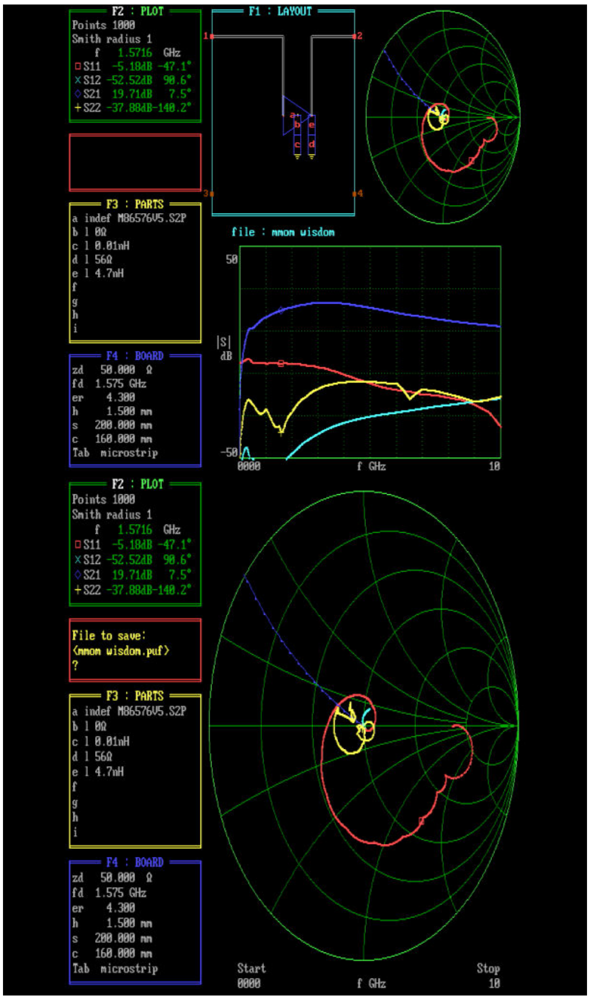
In order to improve the value of the output reflection coefficient the more, other values of resistor and inductor were used. A series connection of 56 Ω resistor and a 3.5nH inductor were experimented and the result shows an improvement of the output reflection coefficient (S_{22}) of -23.13dB< 103.6° as shown below in Fig 16.

A final test for output reflection coefficient improvement using a series combination of 56 resistor and a 4.7nH inductor resulted in a perfect match; a situation in which all the scattering parameters (S_{11},S_{12},S_{21},S_{22}) meet at the centre of the smith chart with an S_{22} value of -37.88dB <-140.2° as shown on fig. 17 below.



```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5736  GHz
□S11  -8.55dB 111.1°
×S12 -38.18dB  51.6°
◇S21  21.83dB-100.4°
+S22 -23.13dB 103.6°

F3 : PARTS
a dev a03184ia.s2p
b l 56Ω
c l 3.5nH
d
e
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er    4.300
h     1.500 mm
s   200.000 mm
c   160.000 mm
Tab  microstrip
```

Fig 16 PUFF Simulation for S_{22} improvement using 56Ω and 3.5nH



```
F2 : PLOT
Points 1000
Smith radius 1
   f   1.5716  GHz
□S11  -5.18dB -47.1°
×S12 -52.52dB  90.6°
◇S21  19.71dB   7.5°
+S22 -37.88dB-140.2°

F3 : PARTS
a indef M86576V5.S2P
b l 0Ω
c l 0.01nH
d l 56Ω
e l 4.7nH
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er    4.300
h     1.500 mm
s   200.000 mm
c   160.000 mm
Tab  microstrip

F2 : PLOT
Points 1000
Smith radius 1
   f   1.5716  GHz
□S11  -5.18dB -47.1°
×S12 -52.52dB  90.6°
◇S21  19.71dB   7.5°
+S22 -37.88dB-140.2°

File to save:
<mmom wisdom.puf>
?

F3 : PARTS
a indef M86576V5.S2P
b l 0Ω
c l 0.01nH
d l 56Ω
e l 4.7nH
f
g
h
i

F4 : BOARD
zd   50.000  Ω
fd  1.575 GHz
er    4.300
h     1.500 mm
s   200.000 mm
c   160.000 mm
Tab  microstrip
```

Fig 17 PUFF Simulation for a perfect match stability condition

Considering fig. 17, it could be seen that a perfect match stability condition was established when all the scattering parameters (S_{11}, S_{12}, S_{21} and S_{22}) met at the centre of the smith chart. Thus, computing the stability condition with Rollett factor K as given in equation 2 we have:

$$K = \frac{1 + |D_S|^2 - |S_{11}|^2 - |S_{22}|^2}{2[(|S_{12}|^2)(|S_{21}|^2)]}$$

Where, Ds = $S_{11}S_{22}$-$S_{12}S_{21}$

S_{11} = -5.18dB<-47.1 or 0.550<-47.1, S_{12} =-52.52<90.6 or 0.00237<90.6

S_{21} =19.71<7.5 or 9.672<7.5, S_{22} = -37.88<-140.2 or 0.01276<-140.2

Computing Ds, we have:

Ds =[(0.550<-47.1)(0.01276<120.2)-(0.00237<90.6)(9.672<7.5)]

Ds = 0.007018<172.7 – 0.022923<98.1

Ds = 0.02212<99.7

Substituting the magnitude of Ds into the above stability equation we have,

$$K = \frac{1 + |0.02212|^2 - |0.550|^2 - |0.01276|^2}{2[(0.00237)(9.672)]}$$

$$K = \frac{1 + 0.0004193 - 0.3025 - 0.0001628}{0.105121}$$

$$K = \frac{0.697756}{0.105121}$$

$$K = 6.635$$

From the above computation for stability factor, it is clear that the value of K is greater than unity which implies that the microwave amplifier is now stable.

V. CONCLUSION

The modelling and simulation of microwave amplifier for enhanced gain stability has been presented. The discussion above provides a lucid understanding of the procedure for amplifier modelling and simulation, however, the techniques discussed here are exclusively applicable only to microwave amplifier because of following reasons; scattering parameters are frequency dependent and gain is higher at low frequency than at higher frequency. It is important to recall that for an amplifier to be stable, the Rollet's stability factor K must be greater than unity, thus, all efforts must be geared towards maintaining this stability condition. From the above computation for stability factor, it is clear that the value of K is greater than unity which implies that the microwave amplifier is now stable.

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