Computer-Aided Design, Analysis and Optimization of HMIC SOP Broadband Balanced Amplifier

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Abstract: The purpose of this paper is to present a complete design and analysis of new HMIC 3.5-4.5 GHz broadband balanced amplifier modules using microstrip technology. Two different modules are designed and analyzed. Each module is implemented in a single substrate. The first module used Lange couplers as power splitters and combiners while the second used branch couplers. The components of the modules are designed using full-scale computer simulation program, performed by the author and named as MSDES, which takes fully into account all the discontinuities included in the microstrip lines; while the modules are analyzed and optimized using APLAC V7.61 software. A short and efficient CAD procedure for the broadband amplifier design is introduced. The first step is to design an initial narrowband high-gain microstrip amplifier at a center frequency equal to 4 GHz. The second step is to optimize the initial lengths and widths of the input and output microstrip-matching circuits to get the broadband amplifier over the range 3.5-4.5 GHz. The analyses of both narrow and broadband amplifiers are introduced in addition to the complete analysis of the designed 3.5-4.5 broadband balanced amplifier modules. The analysis of the designed balanced amplifier modules shows better efficiency and good performance. The complete AC schematic diagrams of the designed balanced amplifier modules are presented. These modules can be used in many applications including sensors, pulse Doppler communications, airborne radars, traffic control radars and satellite communications.

Key words: Computer-Aided Design and Analysis, Microstrip Technology, Microwave Devices and Systems.

1 Introduction

In general, the balanced amplifier structures are often used in high power applications [1, 2], because the output power can be doubled by combining the power from two paths [3-4]. In spite of compensation of more DC bias, the balanced amplifier has many advantages when compared with the single device amplifier. These advantages are: 1) improved input/output impedance matching, gain flatness, and phase linearity, 2) possible designing for amplifier to be simultaneously of minimum noise figure and good input match, 3) gain compression and intermodulation characteristics are good, 4) high stability for short and open circuits, 5) the amplifier gain can be controlled over wide ranges by DC bias with little effect on gain flatness or impedance matching, 7) if one amplifier fails, the balanced amplifier unit will still operate with reduced gain, 8) it is easy to cascade the balanced amplifier to another units, and 9) it usually has excellent input and output return losses.

Many researches had been done for the design of solid-state distributed amplifiers [3-7]. Recently the design of these amplifiers is performed using HEMT as an active element. The HEMT is usually implanted in a distributed passive network fabricated by microstrip line technology.

The HEMTs are widely used in microwave circuit design due to their excellent performances in the microwave range up to 18 GHz. In addition, with the good isolation between input and output, the HEMTs have high-gains, high powers, and low noise figures when compared with other solid-state devices operating in the same frequency range.

The designed microwave transistor amplifier is broadband balanced microstrip amplifier using ATF-54143 HEMT as active elements. The associated passive microwave circuits such as amplifier matching circuits and hybrid couplers are designed using microstrip line technology. Teflon substrate is used with the following parameters: relative permittivity (ε_r) = 2.2, dielectric thickness (H) = 0.7874 mm and conductor thickness (T) = 0.005 mm (skin depth–to-conductor thickness ratio ≅ 0.1).

2 Design and Analysis of Broadband Microstrip Amplifier

The design of broadband microstrip amplifier using ATF-54143 HEMT as an active element is performed using a full-scale computer simulation program developed by the author [8-11]. The program performs a complete analytical design of microstrip amplifiers and takes fully into account all discontinues in the microstrip circuit.

2.1 Design methodology

A short and efficient CAD procedure for the design of broadband microstrip amplifier is performed. It is based on the scattering-matrix parameters of the active element. The CAD procedure has mainly two steps. The first step is the design of an initial narrowband high-gain amplifier operating at a central frequency of 4 GHz.

The developed full-scale simulation program is used for stability consideration and analytical design of the input and output matching circuits [8-11].

The second step is to analyze and to optimize the initial design lengths and widths of the input and output matching circuits so as to get a broadband over a frequency range 3.5-4.5 GHz using the Aplac V7.61 software [12-13].

2.1.1 Design of a narrowband 4-GHz amplifier

In order that the amplifier delivers a maximum power to the load, it must be properly terminated at both input and output ports [14-21], hence the need of an input/output matching circuit arises. The scattering parameters of the used ATF-54143 HEMT at 4 GHz with V_{DS} = 4 V and I_{DS} = 60mA are: $S_{11} = 0.620\angle 137.4^0$, $S_{12} = 0.090\angle 18.7^0$, $S_{21} = 3.940\angle 30.9^0$, and $S22 = 0.070\angle -154.7^0$.

Figure 1 shows the general transistor amplifier circuit. First, the stability and simultaneous conjugate match for the source and load reflection coefficients of the used transistor at the frequency of 4 GHz are calculated through the calculation of K, Γ_{MS} and Γ_{ML} given by [22-24]:

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

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \tag{2}$$

$$\Gamma_{MS} = \frac{B_1 \pm \sqrt{B_1{}^2 + 4|C_1|^2}}{2C_1} \tag{3}$$

$$\Gamma_{ML} = \frac{B_2 \pm \sqrt{B_2{}^2 + 4|C_2|^2}}{2C_2} \tag{4}$$

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 \tag{5}$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 \tag{6}$$

$$C_1 = S_{11} - \Delta S_{22} \tag{7}$$

$$C_2 = S_{22} - \Delta S_{11} \tag{8}$$

Where: K is the stability factor, and Γ_{MS} (Γ_{ML}) is the source (load) reflection coefficient required for the simultaneous conjugate match.

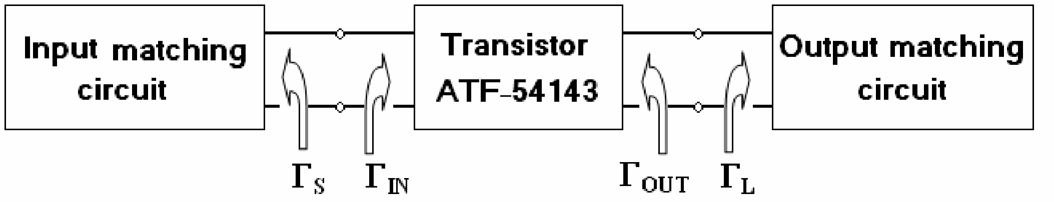

Fig. 1: The general transistor amplifier circuit

Using the developed full-scale computer simulation program, the following results are obtained:

1) The ATF-54143 HEMT is an unconditionally stable at the operating frequency of 4 GHz with K = 1.024, Δ_{MAG} = 0.3399, and $\Delta_{ANG} = 236.3^0$.

2) $\Gamma_{MS} = 0.883\angle -139.48^o$, and $\Gamma_{ML} = 0.725\angle 97.3^o$.

The input and output matching circuits are designed to transfer the calculated $Z_{MS}{}^*$ and $Z_{ML}{}^*$ to 50 Ω. The input and output matching circuits can be designed using two-section matching circuit (a series transmission line and an open/short single/balanced shunt stub). The analytical design procedure of the matching circuits is as follows:

1) Transform Γ_{ML} to $20 \pm jb$ mS using a series transmission line. The value of b is given by the relation:

$$b = \pm\sqrt{\frac{|\Gamma_L|^2(Y_o+G)^2-(Y_o-G)^2}{1-|\Gamma_L|^2}} \tag{9}$$

where G is the real part of the load admittance = 20 mS, b is the susceptance of the shunt stub, and Y_o is the characteristic admittance of the transmission line = 20 mS.

2) Transform $20 \pm jb$ mS to 20 mS using a single/balanced open/short stub.

The positive/negative sign was chosen for an open/short stub to keep the overall length below λg/4.

The lengths of a series transmission line, L_1, and a single open/short shunt stub, L_2, are calculated as follows: -

$$Y_x = 20 \pm jb \tag{10}$$

$$\Gamma_x = \frac{Y_o - Y_x}{Y_o + Y_x} = |\Gamma_x| \angle \Theta_{\Gamma_x} \tag{11}$$

$$L_1 = \frac{\Theta}{720} \lambda_g \tag{12}$$

where $\Theta = \Theta_{\Gamma_x} - \Theta_{\Gamma_c}$, λg is the guide wavelength $= \lambda_o / \sqrt{\varepsilon_{eff}}$, λo is the free space wavelength, and ε_{eff} is the effective permittivity.

For negative values of Θ, 360^o will be added. The length of a single open stub, L_2, is given by:

$$L_2 = \frac{1}{\beta} \tan^{-1} \frac{b}{Y_o} \tag{13}$$

For single short shunt stub, L_2 will be

$$L_2 = \frac{1}{\beta} \tan^{-1} \frac{Y_o}{jb} \tag{14}$$

where $\beta = 2\Pi / \lambda_g$

For balanced open/short shunt stub, the value of b will be replaced by b/2 and the equations [13] and [14] will be used to get the lengths of balanced open and short shunt stubs. As a result of the develop program, Table 1 shows the initial input and output matching circuits.

Table 1: Input and output matching circuits for a narrowband amplifier operating at 4 GHz

Length/width of microstrip line	Input matching circuit	Output matching circuit
Length of series line	L_0 = 22.2 mm	L_2 = 9.6 mm
Width of series line	W_0 = 2.408 mm	W_2 = 2.408 mm
Length of single shunt stub	L_1 = 2.2674 mm (short stub)	L_3 = 9.8498 mm (open stub)
Width of single shunt stub	W_1 2.408 mm	W_3 = 2.408 mm

The initial design of the 4-GHz high-gain narrowband amplifier is analyzed using the Aplac V7.61 software. The Aplac configuration and the AC schematic microstrip diagram of this amplifier are shown in Figure 2. Figure 3 and 4 show the S_{21}(dB), S_{11}(dB), S_{12}(dB) , and S_{22}(dB) versus frequency for the 4 GHz narrowband high-gain amplifier. The designed narrowband amplifier gives gain of 15 dB approximately with minimum return loss at the operating frequency of 4 GHz.

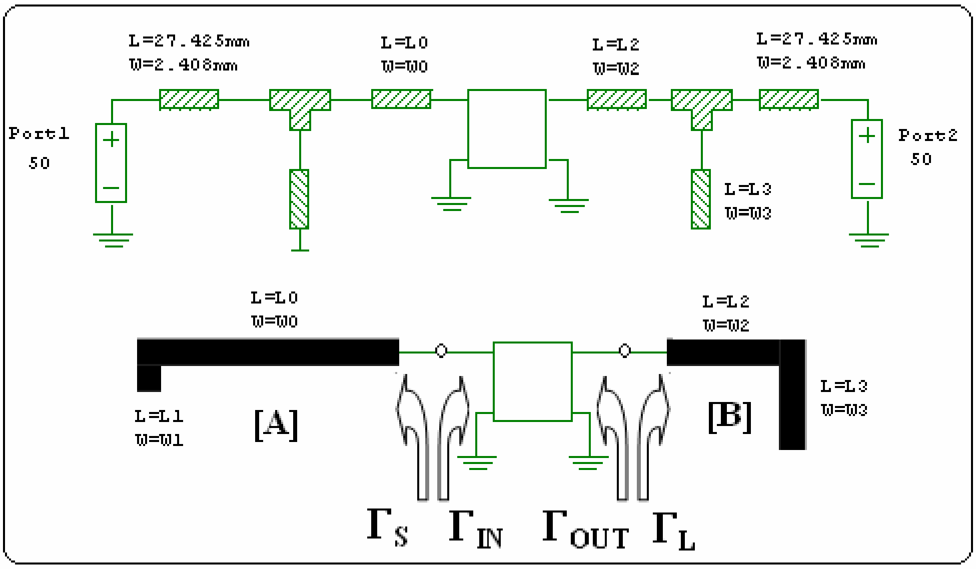

Fig. 2: The Aplac configuration and the AC schematic microstrip diagram of the 4 GHz narrowband high-gain amplifier: (A) Input matching circuit using short/single, and (B) Output matching circuit using open/single stub.

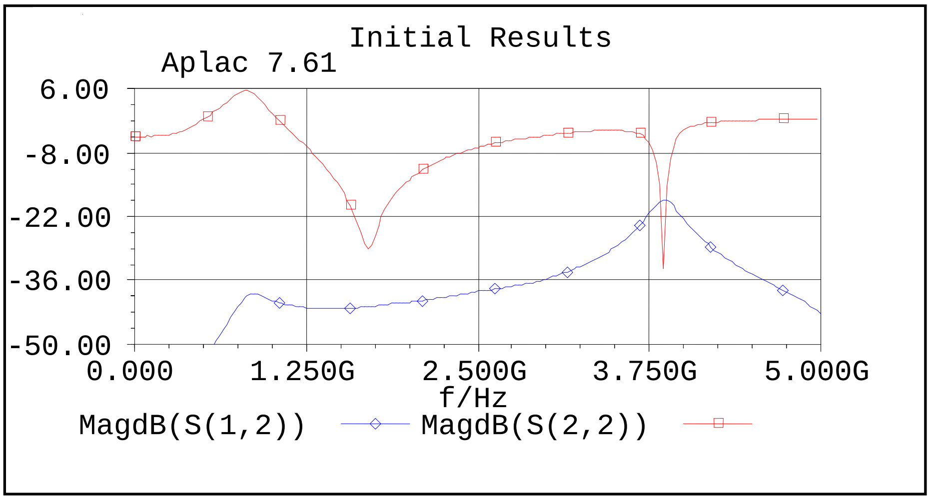

Fig. 3: The S_{12}(dB), and S_{22}(dB) versus frequency (GHz) for the narrowband high-gain amplifier operated at 4 GHz.

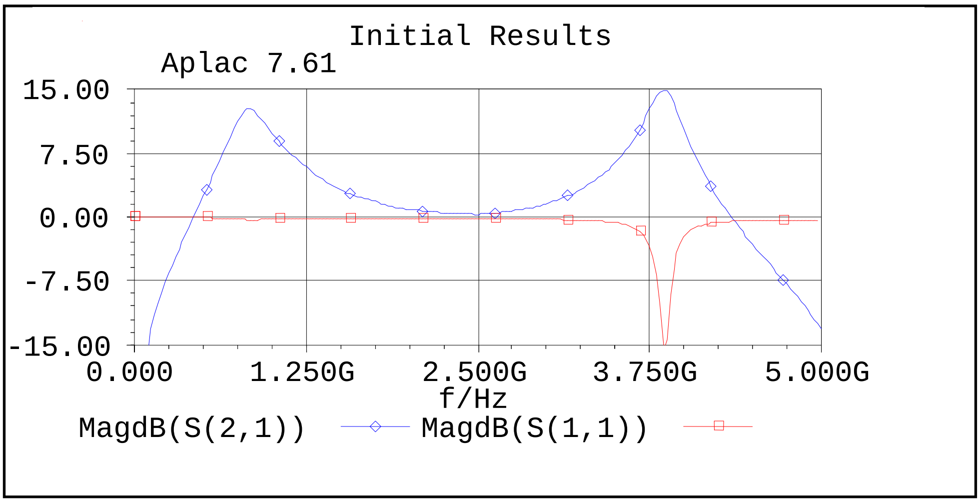

Fig. 4: The S_{21}(dB), and S_{11}(dB) versus frequency (GHz) for the narrowband high-gain amplifier operated at 4 GHz.

2.1.2 *Design of broadband 3.5-4.5 GHz amplifier*

MSDES program is used for narrowband amplifier design with maximum gain while the design of broadband amplifier is performed by an optimization process using Aplac V7.61 software. The main purpose of the optimization is to modify a set of preselected variables in such a way that optimum design, in a sense defined by the user, is achieved. Aplac includes ten different optimization methods, gradient, conjugate gradient, minmax, Nelder-Mead, random, exhaustive search, simulated annealing, genetic optimization, tuning (manual optimization), and gravity center. The genetic optimization process is used to adjust the circuits parameters (lengths/widths of microstrip input and output matching circuits given in table 1) to achieve a flat gain over the range 3.5-4.5 GHz.

As a result of the optimization process, the final lengths/widths of the input and output matching circuits for 3.5-4.5 GHz broadband amplifier are given in Table 2.

Table 2 Input and output matching circuits for the 3.5-4.5 GHz broadband amplifier

Length/width of microstrip line	Input matching circuit	Output matching circuit
Length of series line	L_0 = 17.47501mm	L_2 = 12.73877 mm
Width of series line	W_0 = 2.408 mm	W_2 = 2.408 mm
Length of single shunt stub	L_1 = .1128813 mm (short stub)	L_3 = 21.3179 mm (open stub)
Width of single shunt stub	W_1 = 0.373695186 mm	W_3 = 2.07102 mm

Figures 5 and 6 show the S_{21}(dB), S_{11}(dB), S_{12}(dB) , and S_{22}(dB) versus frequency (GHz) for 3.5-4.5 GHz broadband amplifier. The designed broadband amplifier gives gain of 12 dB approximately over the range 3.5-4.5 GHz with minimum return loss.

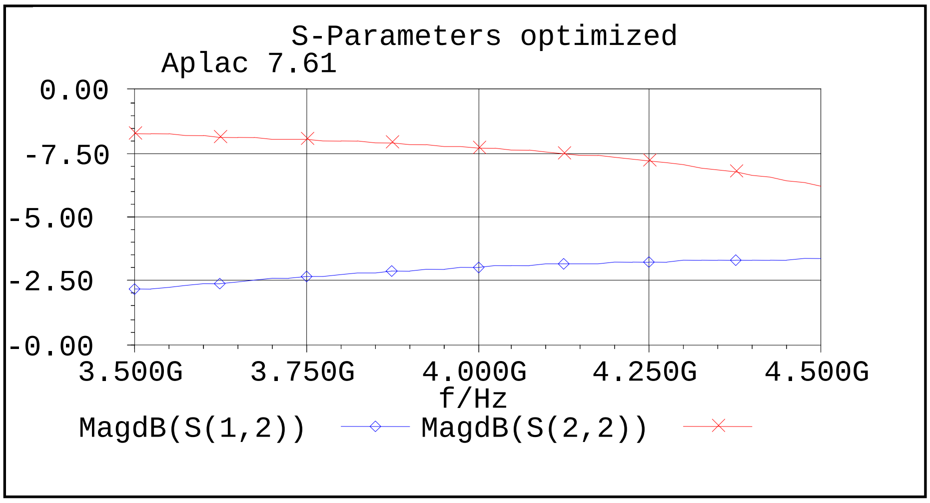

Fig. 5: The S_{12}(dB), and S_{22}(dB) versus frequency (GHz) for the 3.5-4.5 GHz broadband amplifier.

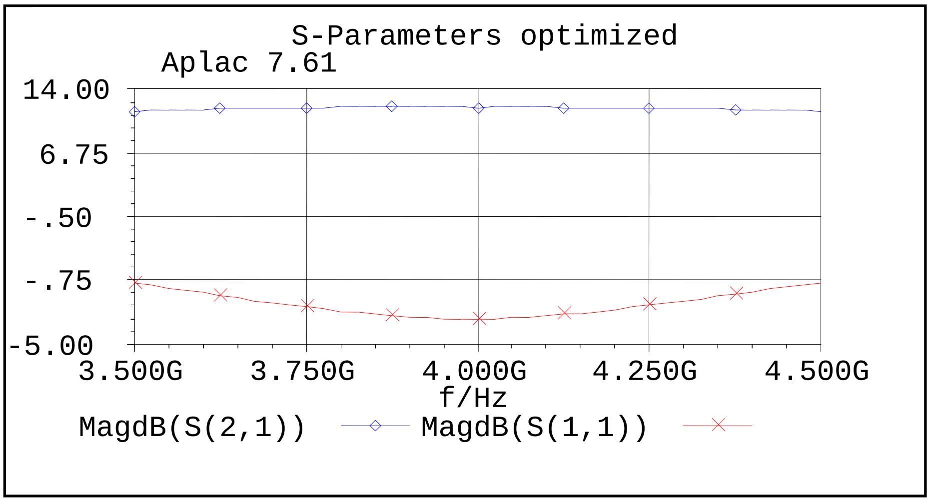

Fig. 6: The S_{21}(dB), and S_{11}(dB) versus frequency (GHz) for the 3.5-4.5 GHz broadband amplifier.

3 Design of Lange and Branch Couplers

The balanced amplifier has two amplifying devices that are run in quadrature [16, 16, 22, and 23]. That is, they are operating 90^0 apart in phase. A quadrature coupler or splitter on the input phase-shifts the two signals 90^0 at the amplifier inputs, then a second quadrature coupler on the output "un-phase shifts" the signals at the amplifier outputs so they combine in phase. The balanced amplifier with coupled-line hybrid as quadrature coupler of the input and output stages has mainly two problems. The first one is that the required even and odd mode characteristic impedances of the coupler are beyond the manufacturing capability, even on high permittivity substrate, because the required spacing between the lines is too small. The second problem is that the two outputs emerge on opposite sides of the isolated ports, so a symmetrical circuit layout is difficult to achieve.

Lange or branch coupler can be used to overcome these two problems [16-17]. The developed full-scale computer simulation program developed by the author is used to design the Lange hybrid operated at a central frequency of 4 GHz with four coupled lines and coupling factor = 3 dB. As a result of the developed program, the parameters of the Lange hybrid are: strip separation (S) = 0.1418 mm, Strip width (W) = 1.456 mm, even mode impedance (Z_{oe}) = 176.4 Ω, odd mode impedance (Z_{oo}) = 52.5384 Ω, even mode W/H ratio = 1.158, odd mode W/H ratio = 7.293, and coupled line length (L) = 14.095 mm. Figure 7 shows the Aplac configuration of 4 GHz Lange coupler. Figure 8 shows the optimized S_{21}(dB), S_{31}(dB), and S_{41}(dB) versus frequency (GHz) for the Lange coupler operated at 4 GHz. Figure 9 shows the optimized phase difference between coupled and directed ports of the Lange coupler.

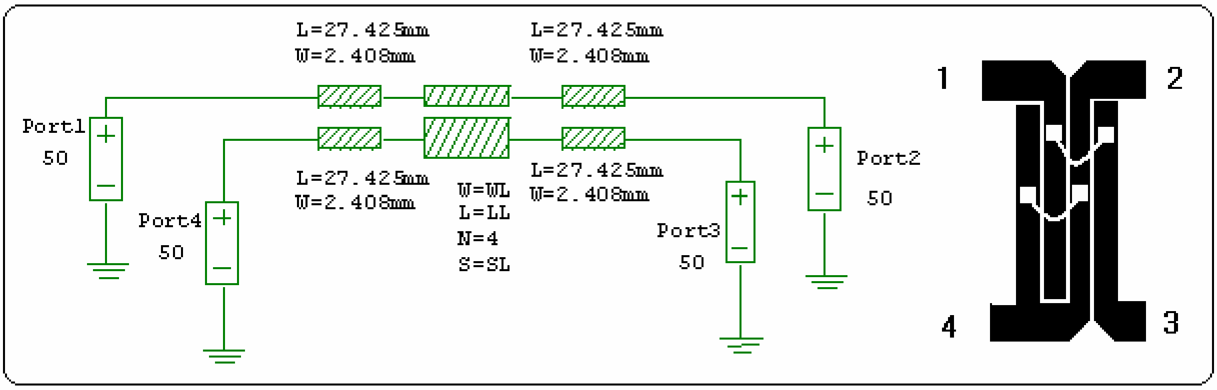

Fig. 7: The Aplac configuration of the designed Lange coupler operated at 4 GHz: (1) Input port, (2) Coupled port, (3) Directed port, and (4) Isolated port

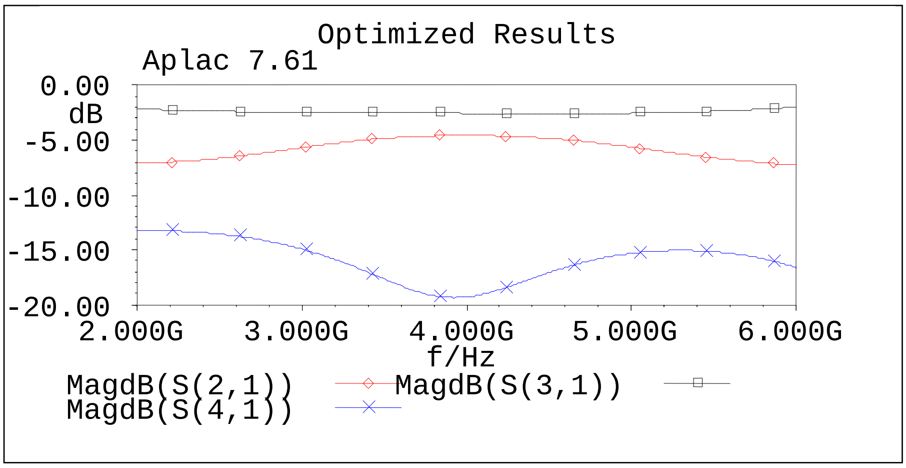

Fig. 8: The optimized S_{21}(dB) ,S_{31}(dB), and S_{41}(dB) versus frequency for Lange coupler operated at 4 GHz.

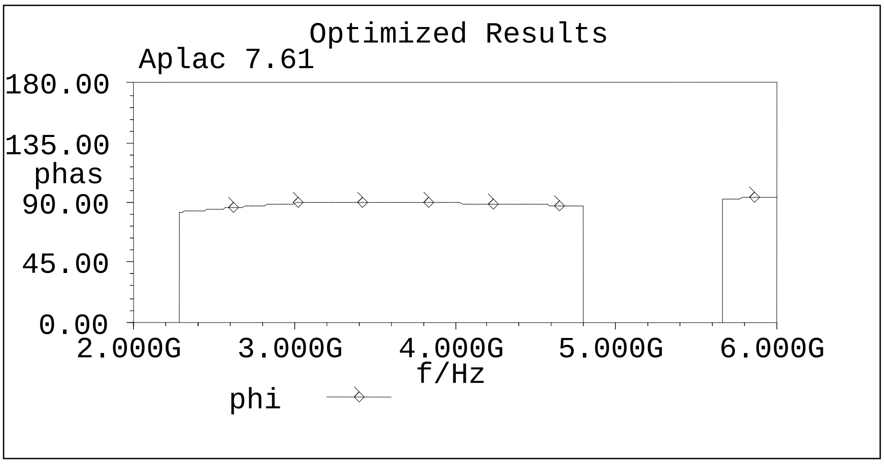

Fig. 9: The optimized phase difference between coupled and directed ports of Lange coupler

The developed full-scale computer simulation program is used also to design the branch hybrid operated at central frequency of 4 GHz [18, 19]. The designed parameters of the branch coupler are: width of series line (W_1) = 3.9417 mm, length of series line (L_1) = 13.5123 mm, impedance of series line = 35.3 Ω, width of branch line (W_2) = 2.416 mm, length of series line (L_2) = 13.71 mm, and impedance of series line = 50 Ω. Figure 10 shows the Aplac configuration of 4 GHz branch coupler. Figure 11 shows the optimized $|S_{21}|$, $|S_{31}|$, and $|S_{41}|$ versus frequency (GHz) for the branch coupler operated at 4 GHz. Figure 12 shows the optimized phase difference between coupled and directed ports of the branch coupler.

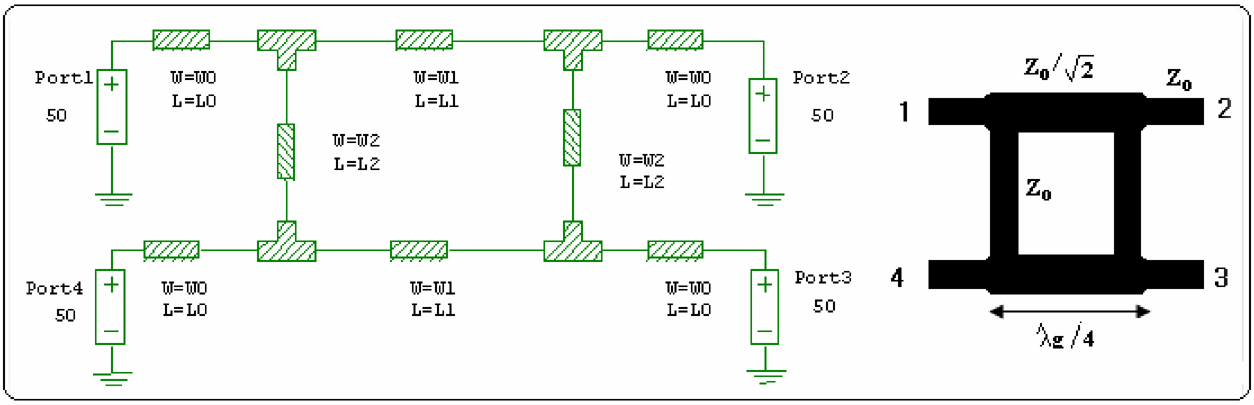

Fig. 10: The Aplac configuration of the designed branch coupler operating at 4 GHz: (1) Input port, (2) Coupled port, (3) Directed port and (4) Isolated port.

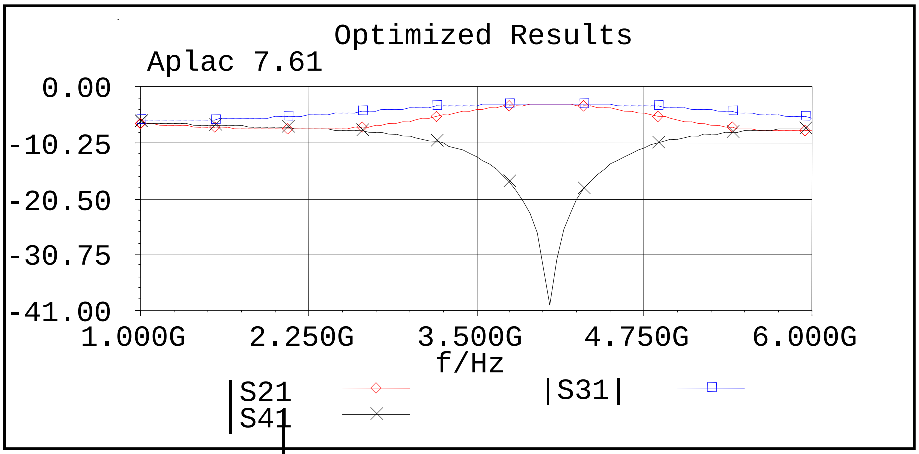

Fig. 11: The optimized $|S_{21}|$, $|S_{31}|$, and $|S_{41}|$ versus frequency (GHz) for branch coupler operated at 4 GHz.

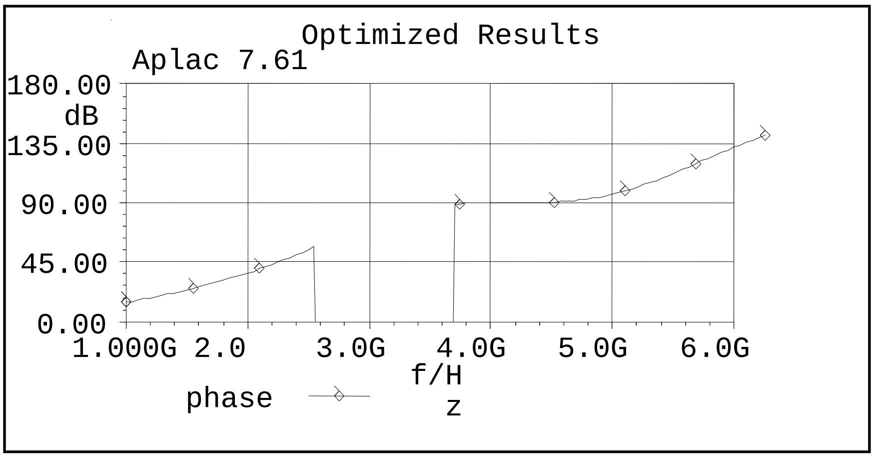

Fig. 12: The optimized phase difference between coupled and directed ports of branch coupler.

4 Broadband Balanced Amplifier Modules

Figure 13 and 14 show the Aplac complete configuration and the AC schematic diagram for the 3.5-4.5 GHz broadband balanced amplifier using Lange coupler. The complete circuit of the broadband balanced amplifier is analyzed and optimized using the Aplac V7.61 software. The final input matching circuit parameters are:

- Length (L_0) and width (W_0) of the series line are 17.875mm and 2.408 respectively.
- Length (L_1) and width (W_1) of the short/single stub are 6.438mm and 1.011 mm, respectively.

The final output matching circuit parameters are:

- Length (L_2) and width (W_2) of the series line are 17.84 mm and 2.408 mm, respectively.
- Length (L_3) and width (W_3) of the short/single stub are 1.585 mm and 8.075 mm, respectively.

Figures 15 and 16 show the optimized scattering parameters of the broadband balanced amplifier using Lange coupler.

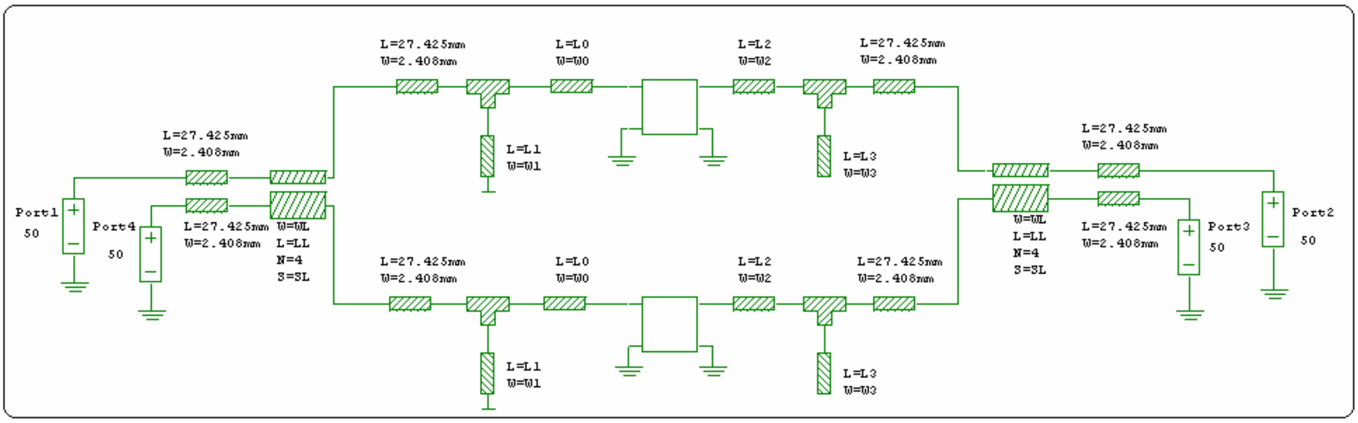

Fig. 13: The Aplac configuration of the 3.5-4.5 broadband balanced amplifier using Lange coupler.

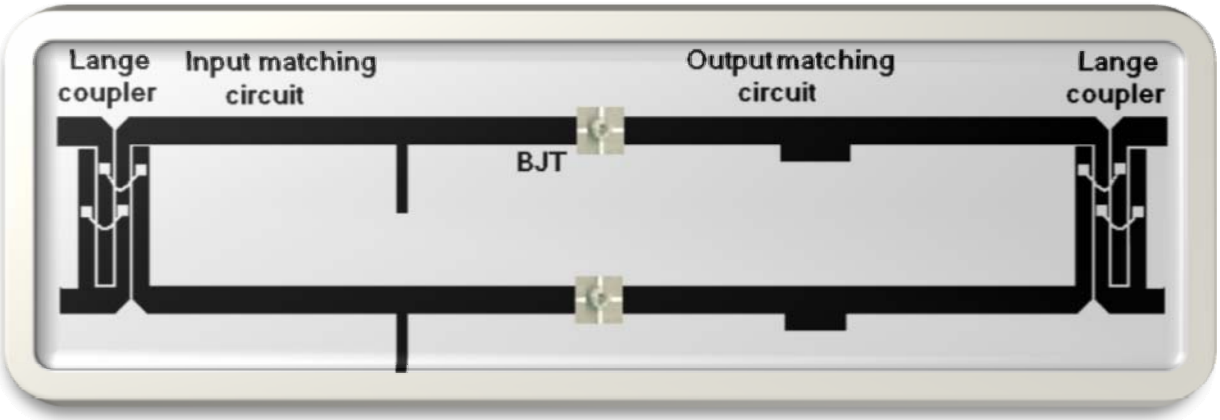

Fig. 14: The AC schematic diagram of the 3.5-4.5 broadband balanced amplifier using Lange coupler.

Figure 17 and 18 show the Aplac complete configuration and the AC schematic diagrams for the 3.5-4.5 GHz balanced amplifier using branch coupler. The complete circuit of the broadband amplifier is analyzed and optimized using the Aplac V7.61 software.

The final input matching circuit parameters are:

- Length (L_0) and width (W_0) of the series line are 23.508 mm and 2.408 mm, respectively.
- Length (L_1) and width (W_1) of the short/single stub are 39.510 mm and 7.497 mm, respectively.

The final output matching circuit parameters are:

- Length (L_2) and width (W_2) of the series line are 12.505mm and 2.408 respectively.
- Length (L_3) and width (W_3) of the short/single stub are 28.237 mm and 4.298 mm, respectively.

Figure 19 and 20 show the optimized scattering parameters of the broadband balanced amplifier using branch coupler.

For stability verification of the broadband case, the optimization process is used to insure the stability of the broadband design with specific goals; in addition with the design methodology achieves the proper matching terminations at the input and output of the amplifier.

Figures 21 and 22 show the values of stability factor (K), input reflection coefficient (gamIn) and output matching coefficient (gamOut) for the broadband balanced amplifier using Lange and branch couplers. It is noticed that the values of K > 1, |gamin| < 1 and |gamOut| < 1 over the range 3.5-4.5 GHz. These results verify the stability for the broadband case.

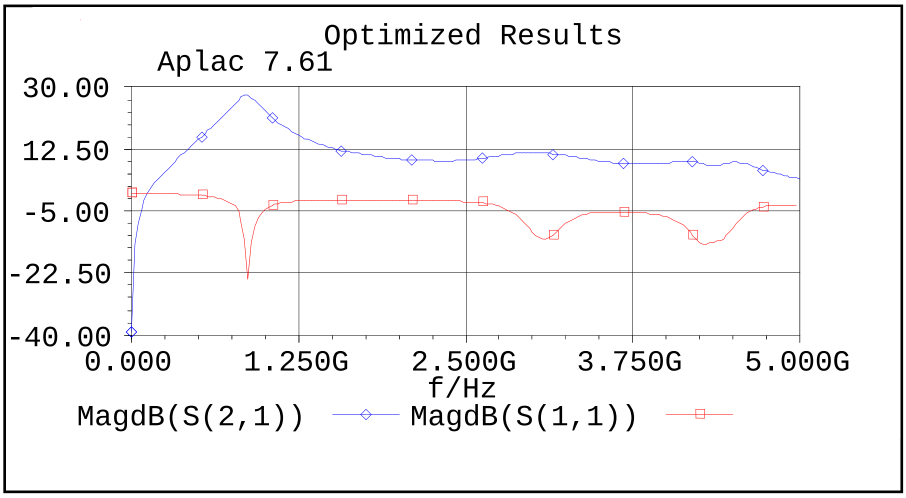

Fig. 15: The optimized S_{21} (dB), and S_{11} (dB) versus frequency (GHz) for the 3.5-4.5 broadband balanced amplifier using Lange coupler.

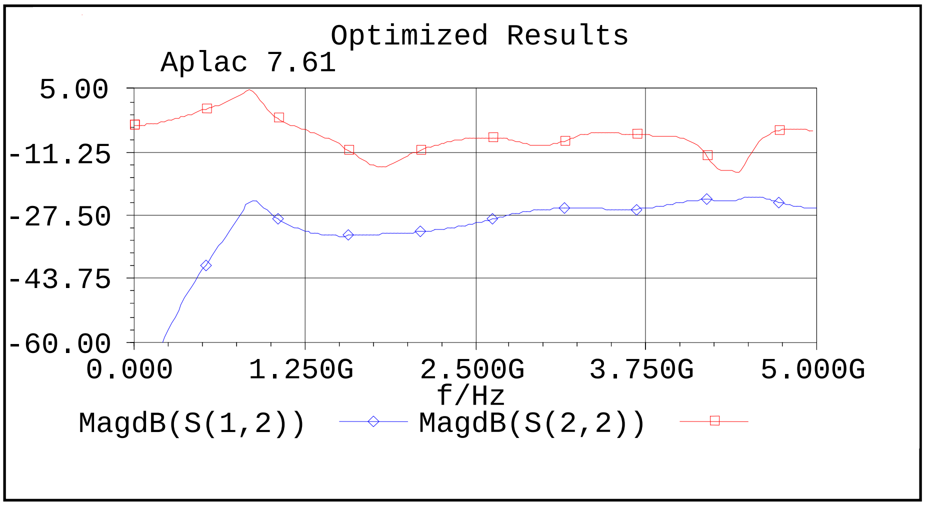

Fig. 16: The optimized S_{12}(dB), and S_{22}(dB) versus frequency (GHz) for the 3.5-4.5 broadband balanced amplifier using Lange coupler.

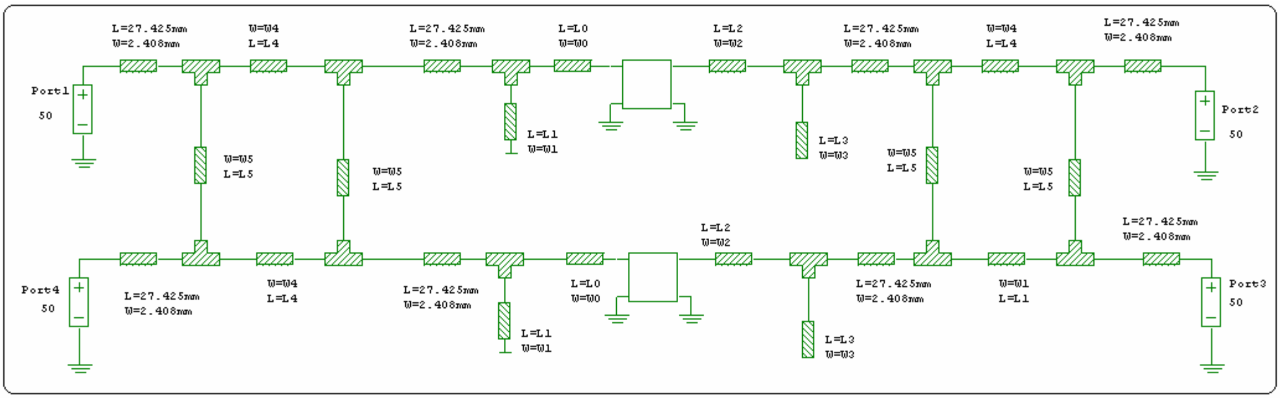

Fig. 17: The Aplac configuration of the 3.5-4.5 broadband balanced amplifier using branch coupler.

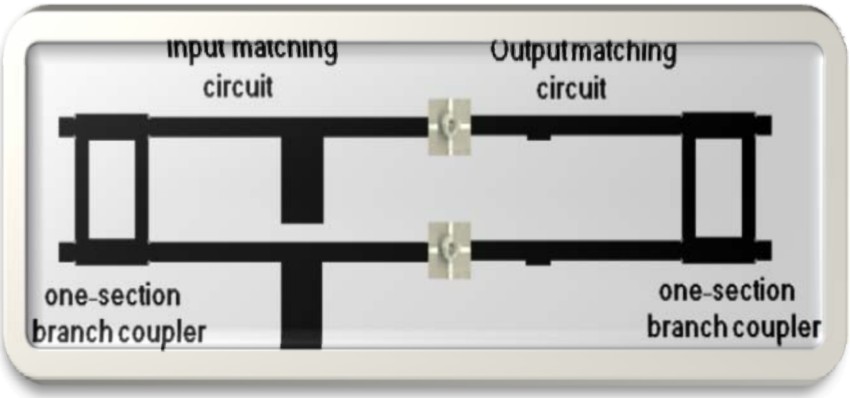

Fig. 18: The AC schematic diagram of the 3.5-4.5 broadband balanced amplifier using branch coupler.

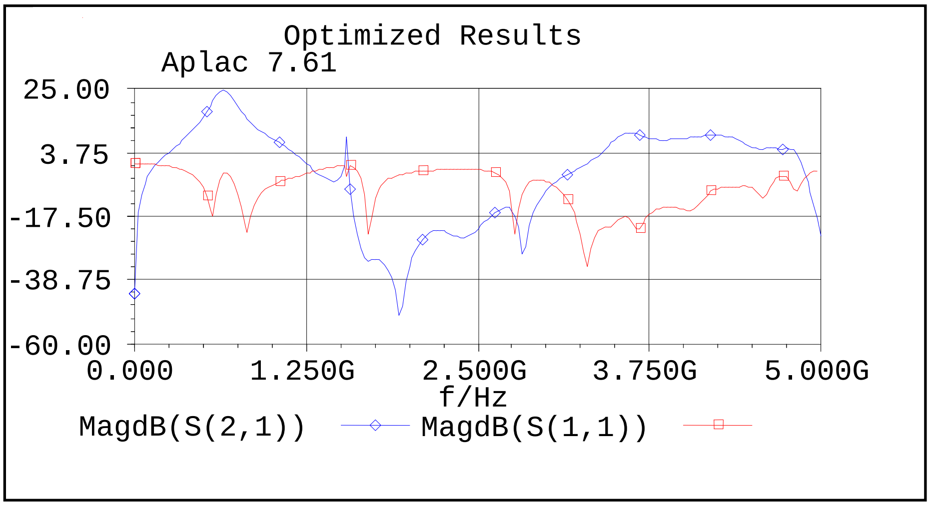

Fig. 19: The optimized S_{21}(dB), and S_{11}(dB) versus frequency (GHz) for 3.5-4.5 broadband balanced amplifier using branch coupler.

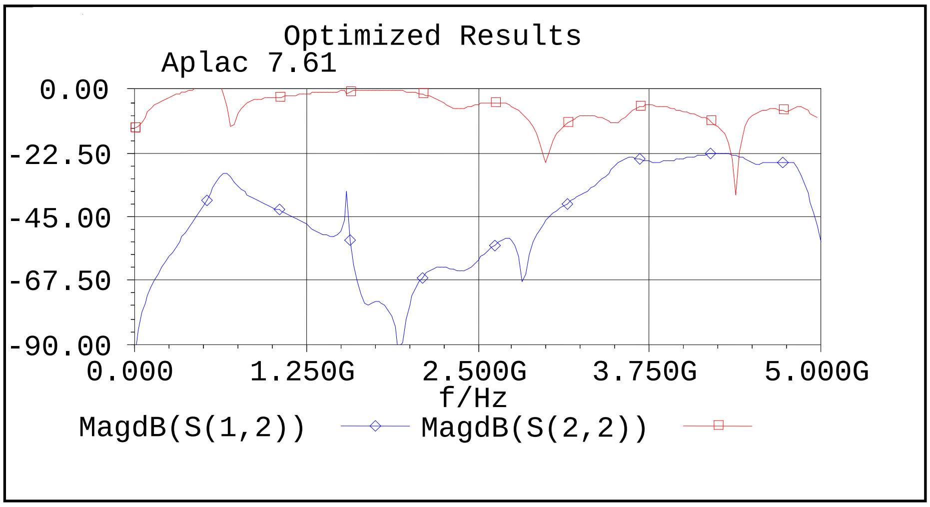

Fig. 20: The optimized S_{12}(dB), and S_{22}(dB) versus frequency (GHz) for 3.5-4.5 broadband balanced amplifier using branch coupler.

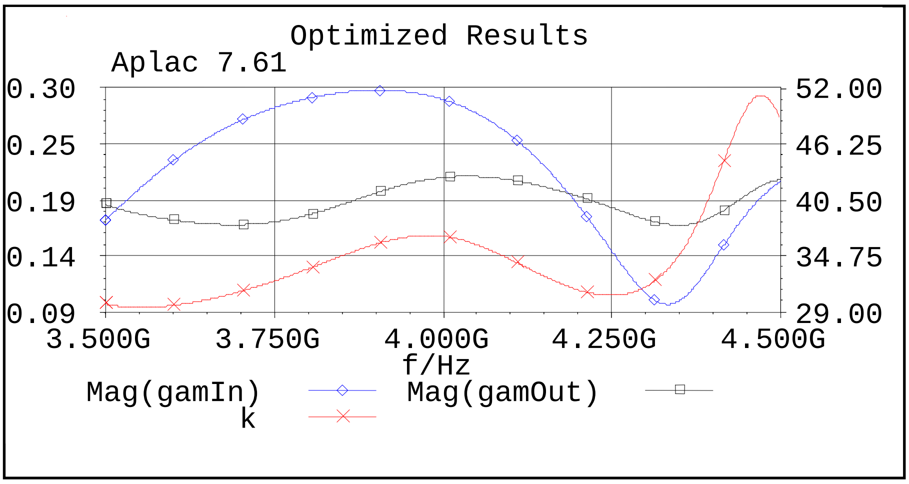

Fig. 21: Stability factor (K), input reflection coefficient (gamIn) and output matching coefficient (gamOut) for broadband balanced amplifier using Lange coupler.

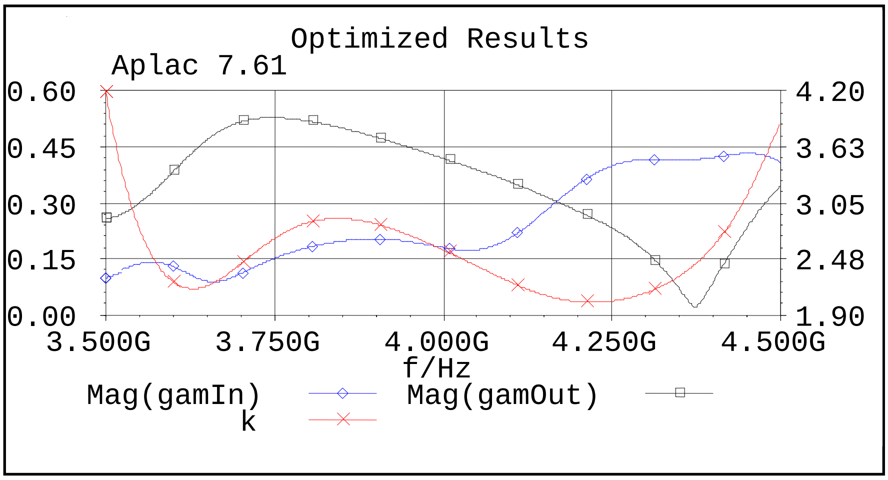

Fig. 22: Stability factor (K), input reflection coefficient (gamIn) and output matching coefficient (gamOut) for broadband balanced amplifier using branch coupler.