Design, Manufacture and Testing of Microstrip Directional Couplers

Salvador Vasques Seabra Águas
IST-Universidade de Lisboa,
Av. Rovisco Pais, 1049-001 Lisboa
e-mail: svsaguas@gmail.com;

Abstract— **The analysis and modelling of directional couplers has been a topic of considerable interest in recent years. Advances in the field of Radio Frequency and Microwave components have resulted in increased interest in efficient, precise analysis and design of these circuits. In this work three different directional couplers - the Quadrature Hybrid, the Rat-Race and the Wilkinson Power Divider – were designed, simulated, fabricated and analysed in three very different substrates, the RT DUROID 5880, the FR-4 and the EPSILAM-10.**

This was achieved with the Microstrip Line technology and the Coupled Lines technique that enable to establish the various differences between the circuits, specifically how the signal is split and what the resultant output signals look like in terms of amplitude and phase.

Keywords— Printed Circuits, Microstrip, Directional Couplers, Wilkinson Power Divider, Rat-Race, Quadrature Hybrid.

I. Introduction

The potential to distribute and combine signals is a primary function in several microwave systems, and especially functional if it can be achieved over a wide frequency range and with phase shifted signals. Moreover, passive microwave components such as directional couplers and power dividers, have played an important role in recent years and have been extensively utilized in microwave applications. The objective of such devices is to divide (or couple) a signal into n others, depending on the application and requirements. The most typical implementation of this type of circuits is to divide an input signal to feed low power amplifiers, and later recombine them.

The main purpose of this work was to design, simulate, manufacture and analyse three different directional couplers - the Quadrature Hybrid, the Rat-Race and the Wilkinson Power Divider, in three very different substrates, the RT DUROID 5880, the FR-4 and the EPSILAM-10, with the aim of studying the possible differences between the circuits, specifically how the signal is split and what the resultant output signals look like in terms of amplitude and phase (Fig. I.1).

The present research also seeks to describe the Microstrip Line technology and the Coupled Lines technique used to print the directional couplers, as well as the characterization of the main features of the three directional couplers and the even-odd mode circuit analysis, in order to understand their performance characteristics and derived scattering matrices.

Moreover, the analysis, design and manufacture of the three different directional couplers allowed to understand the overall impact of the design and of the substrate in which they were applied, in their final performance. The CST software enabled an accurate analysis of the S-parameters along with a good comprehension of the electric and power flows of the devices at the dimensioned frequency.

The results acquired with the physical devices were very similar to the simulation results, demonstrating an excellent agreement between the results and therefore validating that the methodology applied in this dissertation is appropriated to this type of circuit projection.

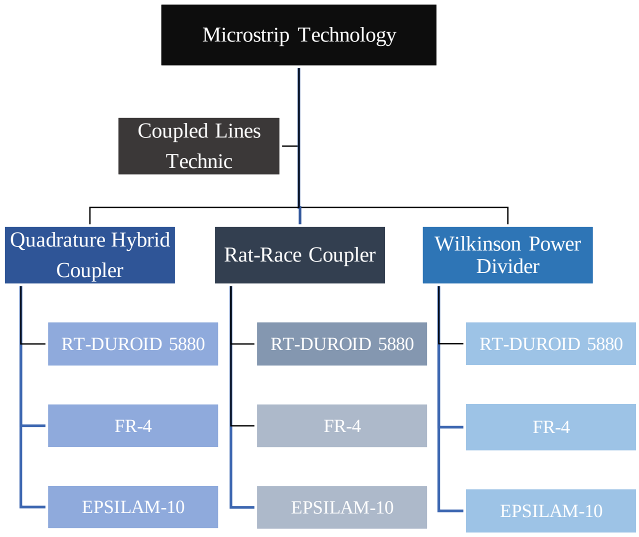

Figure I.1 Outline of the main objectives of this work

II. Computer Simulation

A. Circuit Design

In order to design the circuits three different substrate materials were selected due to their very different dielectric constant:

- RT DUROID 5880 (ε=2.2)
- FR-4 (ε=4.3)
- EPSILAM-10 (ε=10.2)

The first two substrates used for the design purpose were dimensioned to a 2 GHz frequency, since they both perform well at this value whereas the last substrate was dimensioned to 10 GHz, because it works better at this frequency.

B. Circuit Layout

The *Quadrature Hybrid* is formed by two horizontal 50Ω lines, spaced by $\frac{\lambda}{4}$, and two vertical 35,36Ω, equally spaced by $\frac{\lambda}{4}$ (Fig. 2.1).

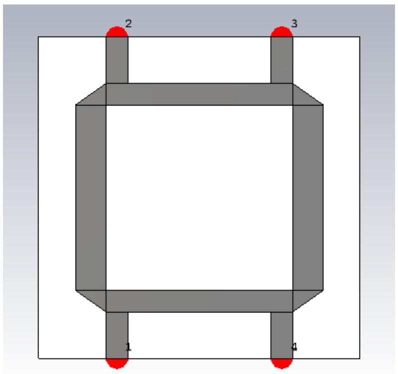

Figure 2.1 Quadrature Hybrid Computer Layout.

The *Wilkinson Power Divider* comprises two horizontal 50Ω lines, and two vertical 70,71Ω, with a length of $\frac{\lambda}{4}$ (Fig. 2.2).

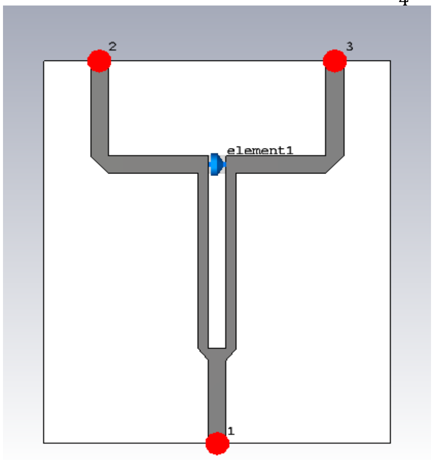

Figure 2.2 Wilkinson Power Divider Computer Layout.

The *Rat-Race*, composed by a 70.71Ω circular line, with four 50Ω lines (Fig. 2.3).

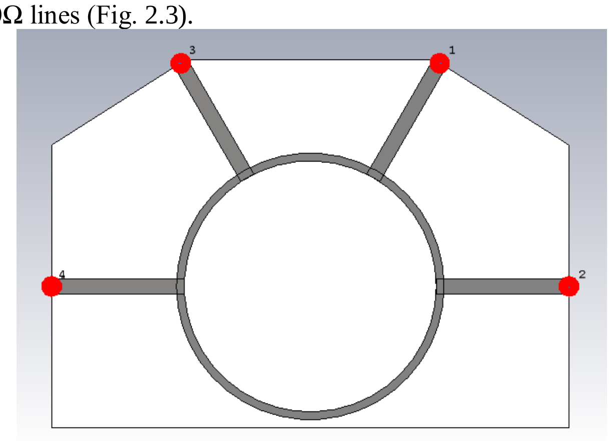

Figure 2.3 Rat-Race Computer Layout.

Since all the circuit layouts were similar for the different substrates with the exception of the respective dimensions, it was best accepted to present one image of each kind of circuit.

C. *Simulation Results*

After designing all the circuits, the CST Frequency Domain Server was used to simulate the circuits behaviour, obtaining the outcomes presented in this section.

Each circuit was dimensioned and simulated for the three different substrates: RT DUROID 5880, FR-4 and EPSILAM-10, from the lowest to the highest dielectric constant.

1. Quadrature Hybrid

a. RT DUROID 5880

The Rogers RT DUROID 5880 substrate applied in this work has a 31 mils thickness (0.787 mm), a 2.2 dielectric permittivity, with low losses and good homogeneity.

The simulations outcomes are clearly illustrated in figure 2.4.

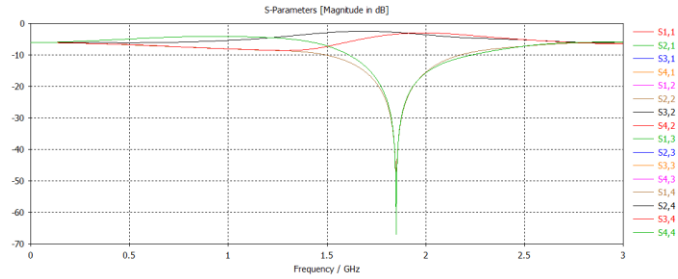

Figure 2.4 RT DUROID 5880 Quadrature Hybrid S-parameters.

These figure reveal that the circuit may not have been perfectly constructed, since it was expected to be dimensioned to 2GHz and not 1.85GHz. This difference might be a consequence of some material losses, since the chosen substrate is lossy.

Nevertheless, as expected, the phase difference between ports 2 and 3, demonstrated in figure 2.5, is almost perfect, i.e., with almost 90 degree, and maintained for nearly 0.6 GHz range. The insertion loss plot shown in figure 3.7, with the previous analysis, allows the conclusion that the microstrip was built correctly.

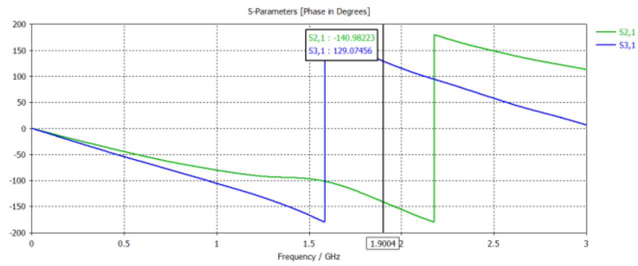

Figure 2.5 RT DUROID 5880 Quadrature Hybrid Ports 2 and 3 Phase Comparison.

b. FR-4

The FR-4 substrate employed in this study had a 62 mils thickness (1.6 mm), with a 4.3 dielectric permittivity, that also presents low losses but not as homogeneous as the previous ones.

The results obtained with this substrate were pretty similar to the ones acquired with the RT DUROID 5880 (Fig. 2.6).

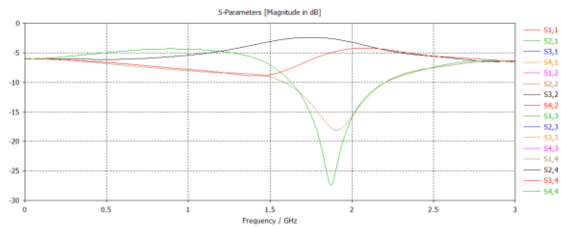

Figure 2.6 FR-4 Quadrature Hybrid S-parameters.

The analysis and comparison of the two substrates leads immediately to the conclusion that even though that both results are adequate, the RT DUROID 5880 achieves a better return loss - approx. -66 dB -, when compared with the FR-4 - approx. -27 dB -, providing, therefore, a better isolation. Moreover, the comparison of the insertion loss, shows that the outcome of the RT DUROID 5880 is better.

Nevertheless, this substrate presents an approximately 90 degree phase between the second and third port (Fig. 2.7), consistent with the theoretical analysis.

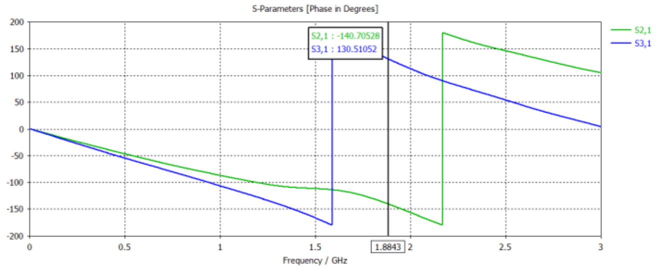

Figure 2.7 FR-4 Quadrature Hybrid Ports 2 and 3 Phase Comparison.

c. EPSILAM-10

The EPSILAM-10 model was constructed according to the already mentioned calculated dimensions (Table 4). Although it seemed to be well dimensioned, a deeper and accurately analysis revealed that this model did not work as expected (Fig. 2.8).

Based on the assumption Assuming that the model was done correctly - due to the fact that the other two were working as predicted -, it is presumed that the main reason for this circuit malfunction is the high amount of dielectric permittivity substrate for such a small circuit. For this reason, this substrate will not be considered forward in this study.

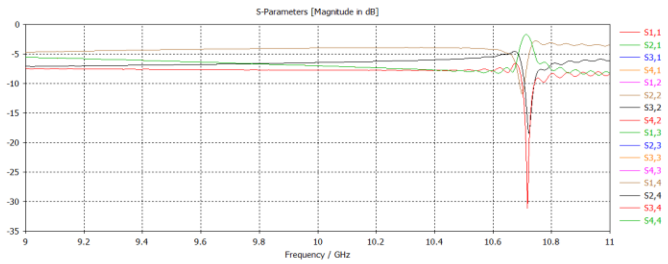

Figure 2.8 EPSILAM-10 Quadrature Hybrid S-parameters.

2. Rat-Race

a. RT DUROID 5880

This simulation started with the lowest dielectric permittivity constant substrate, which allowed to achieve a very good result, i.e. the circuit main frequency performed very close of what it was expected, achieving the 2 GHz (Fig. 2.9).

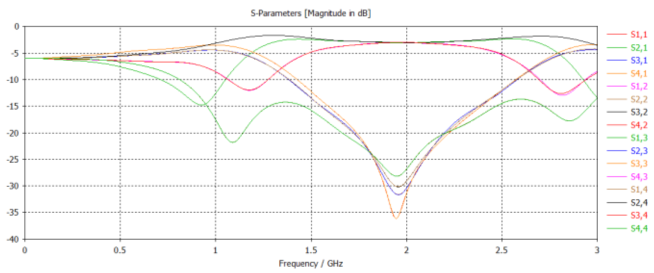

Figure 2.9 RT DUROID 5880 Rat-Race S-parameters.

Insertion loss plot performed as expected and consistent with theoretical analysis, i.e., with the phase between port 2 and port 3 (Fig. 2.10), being very close to zero degrees and the port 1 achieving -3dB.

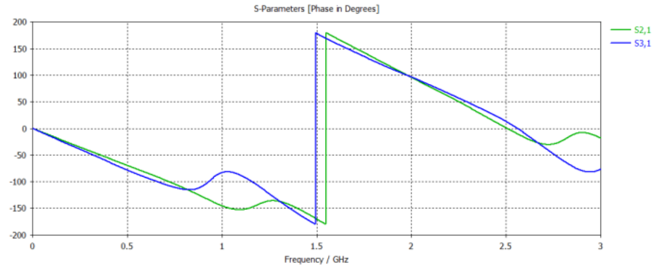

Figure 2.10 RT DUROID 5880 Rat-Race ports 2 and 3 phase comparison degree.

b. FR-4

The simulation performed with the FR-4 substrate presented results very similar to the ones achieved with the Quadrature Hybrid substrate. Both results, between the $\varepsilon_r = 2.2$ and the $\varepsilon_r = 4.3$ substrates, were closer to the values expected. The comparison between this substrate and the previous one regarding the return loss of the circuit, shows that ports 1 and 3 are less synchronized than before with ports 2 and 4 (Fig. 2.11)

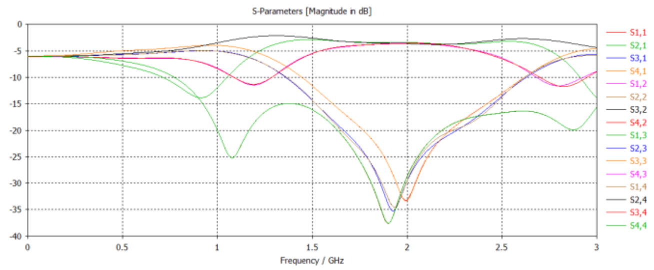

Figure 2.11 FR-4 Rat-Race S-parameters.

The transmission from the input of port 1 to the output of ports 2 and 3 show that they are close to phase, both in a -3 dB at central frequency (Fig. 2.12).

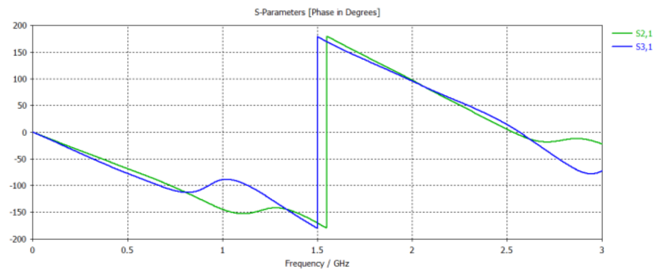

Figure 2.12 FR-4 Rat-Race Ports 2 and 3 Phase Comparison.

3. Wilkinson Power Divider

The last simulations were done with the Wilkinson Power Divider. As with the last coupler, this one was only developed for the two lowest dielectric permittivity substrates – RT DUROID 5880 and FR-4. Two different models were designed and studied, nonetheless only the best solution is presented because the data obtained were not satisfactory for the scope of this work (Fig. 2.13).

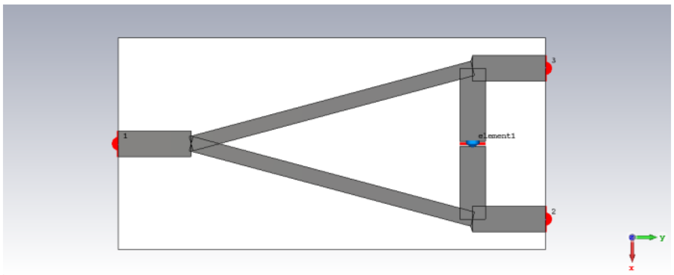

Figure 2.13 Wilkinson Power Divider First Layout.

a. RT DUROID 5880

The simulations done with the RT DUROID 5880 substrate show that even from the best model, the results were not perfect ones. In this case, ports (2) and (3) have a large reflection coefficient (Fig. 2.14).

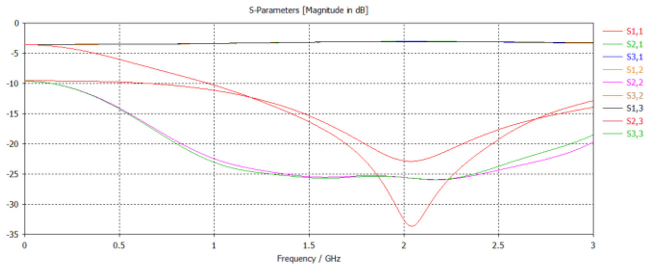

Figure 2.14 RT DUROID 5880 Wilkinson Power Divider S-parameters.

However, they have a very good insertion loss, near -3dB and are almost perfectly synchronized around the 0 degrees (Figs. 2.15).

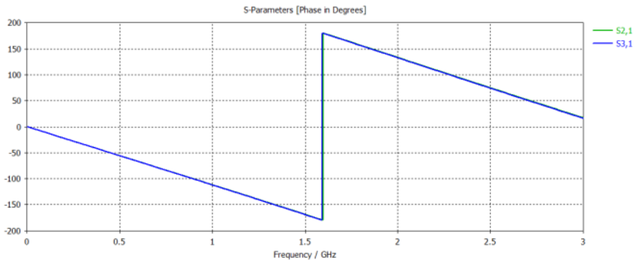

Figure 2.15 RT DUROID 5880 Wilkinson Power Divider Ports 2 and 3 Phase Comparison.

b. FR-4

The comparison between the simulated and measured results done with the FR-4 substrate presented results similar to the previous substrate. It was expected to have a port 2 and 3 narrow bandwidth instead of the wide bandwidth shown in figure 2.16.

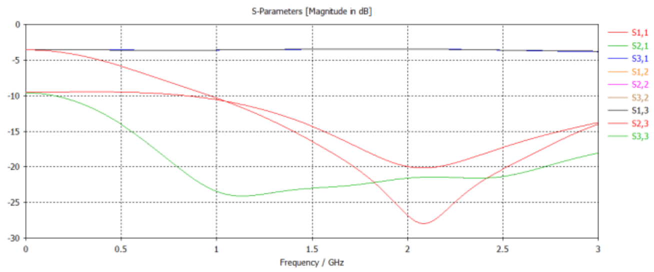

Figure 2.165 FR-4 Wilkinson Power Divider S-parameters.

Even though the ports 2 and 3 have a large bandwidth, the insertion loss performs better than the first one, presenting almost perfect synchrony with a 0 degree phase at -3dB, (Fig. 2.17).

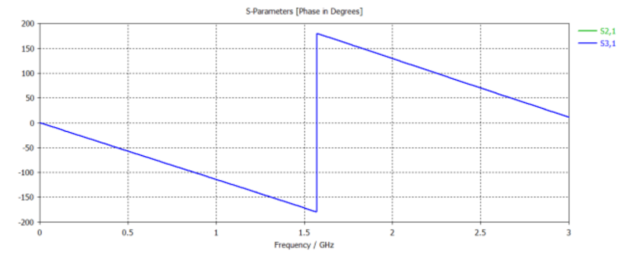

Figure 2.17 FR-4 Wilkinson Power Divider Ports 2 and Phase Comparison.

III. Circuit Manufacturing and Testing

The manufacturing process consists of several steps. The first step was to export a DXF file from CST and, with the aid of the 2D CAD software ABViewer 14, import the DXF and export it to a PDF file (Fig. 3.1).

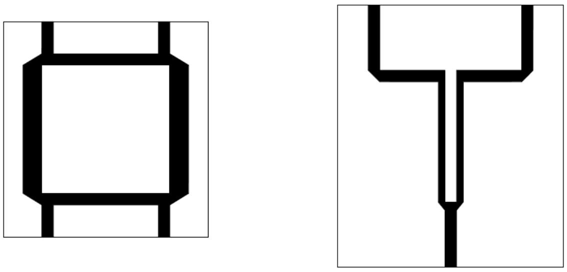

Figure 3.1 Circuit Layouts Exported.

This PDF file is later printed on a photo-sensitive acetate sheet, which allows to start the printed circuit process, described on the next subsection.

All the prototypes have been printed on the selected substrates on Laboratorio de Circuitos Impressos of Universidade de Lisboa – Instituto Superior Técnico.

Of the three substrates that were designed, constructed and simulated, only two of them have achieved adequate results – the RT DUROID 5880 and the FR-4. Furthermore, and as specified before, the FR-4 is not a homogeneous substrate, so it is expected to have different results regarding the circuit testing. For these reasons it was decided to only test the FR-4 substrate on one circuit - the Rat-Race -, and test the RT-DUROID 5880 substrate on all circuits.

A. Quadrature Hybrid

Figure 3.2 shows the prototype of the quadrature hybrid impressed on the RT-DUROID 5880 substrate.

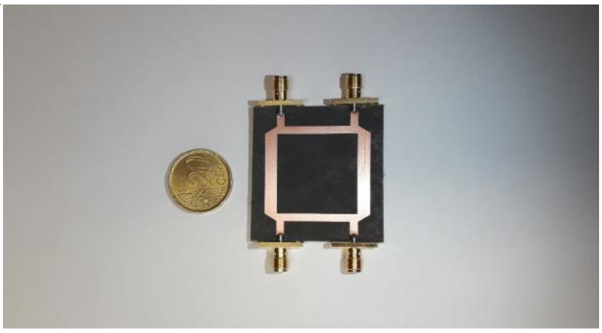

Figure 3.2 RT DUROID 5880 Quadrature Hybrid Prototype

Figure 3.3 shows the Quadrature Hybrid coupler S parameters with an operating frequency from 100 MHz to 3 GHZ. It could be concluded that the output presented is very similar to the simulated one, presented in figure.

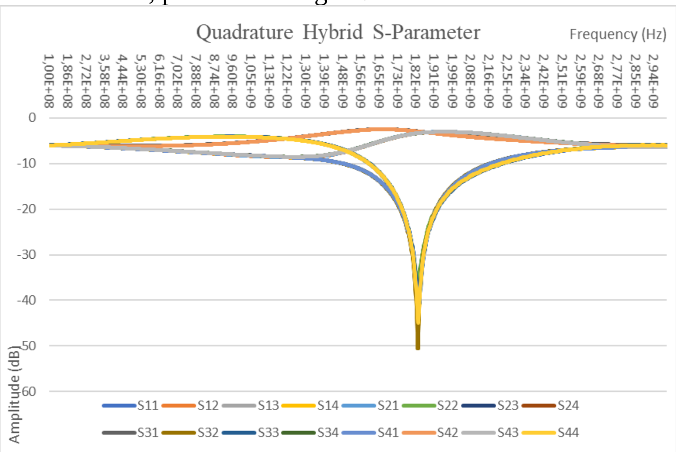

Figure 3.3 RT-DUROID 5880 Quadrature Hybrid S-parameters.

As happened in the simulation there is a small deviation of the centre frequency, but all ports achieve a lower than -35 dB at around 1,83 GHz (Table 1), revealing that the device is correctly isolated.

Table 1 RT-DUROID 5880 Quadrature Hybrid Return Loss Values.

Parameters	Centre Frequency (GHz)	Max Return Loss (dB)	Band > 15dB (GHz)
S11	1.830	-36.31	1.702 - 2.008
S22	1.830	-35.32	1.704 - 2.004
S33	1.834	-41.81	1.704 - 2.012
S44	1.832	-44.86	1.704 - 2.008

It is observed that there is an approximately -3dB equal power split between the 2 and 3 output ports, leaving port 4 isolated. The measured results are approximated the same as the theoretical and the simulated ones.

The simulated and measured phase results are alike, showing almost perfect quadrature between (2) and (3) (Fig. 3.4).

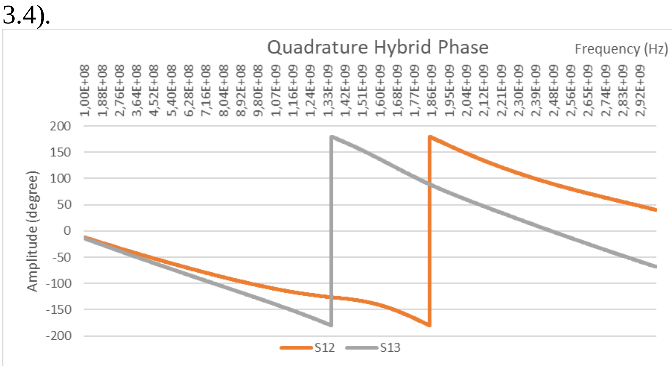

Figure 3.4 RT-DUROID 5880 Quadrature Hybrid Ports 2 and 3 Phase Comparison.

B. *Rat-Race*

The Rat-Race, being one of the best simulation results circuit, has been chosen to be produced in both substrates, first in the RT-DUROID 5880 and later on the FR-4. The results are exhibited on this section.

1) RT-DUROID 5880

Figure 3.5 shows the prototype of the Rat-Race circuit impressed on the RT-DUROID 5880 substrate. It was done with the 2,2 dielectric permittivity substrate and then the PCB was finished by welding the circuit connectors, one for each port.

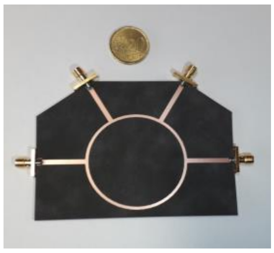

Figure 3.5 RT DUROID 5880 Rat-Race Prototype.

This circuit also suffered a centre frequency shifting, figure 3.6, possibly from manufacturing errors, like inaccuracy when cutting the printed circuit board.

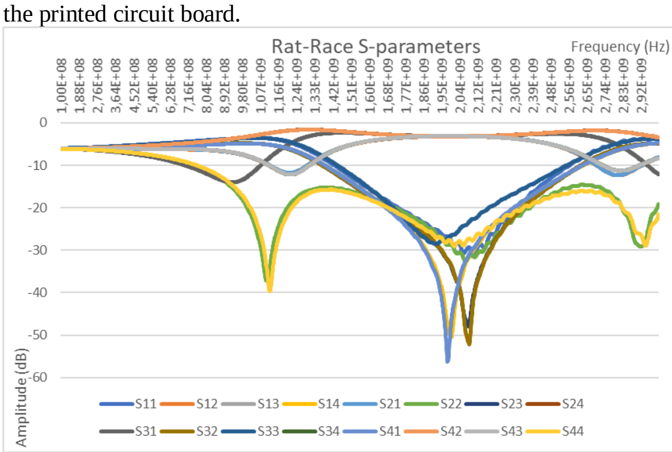

Figure 3.6 RT DUROID 5880 Rat-Race S-parameters.

Data shows that besides centre frequency shifting - possibly from circuit making errors, like inaccuracy when cutting the printed circuit board – this circuit also has short amplitudes variation when at the centre frequency. As all ports achieve a lower than -27dB at around 2 GHz, suggests, even though that the circuit works correctly it should have been projected for a higher centre frequency.

Table 2 shows that the device bandwidth is approximately 1585 – 2364 MHz, providing a very good bandwidth, of around 750 MHz, for an hand-made circuit.

Table 2 RT DUROID 5880 Rat-Race Return Loss Values.

Parameters	Centre Frequency (GHz)	Max Return Loss (dB)	Band > 16dB (GHz)
S11	2.104	-31.03	1.578 - 2.422
S22	2.064	-32.51	1.374 - 2.578
S33	1.920	-28.60	1.585 – 2.364
S44	2.008	-29,06	1.408 – 2.624

It is observed that there is a -3 dB equal power split between the second and third output ports, leaving port four isolated.

The S12 and S13 response loss is almost perfect, since their amplitude is around -3dB, and they are almost synchronized in phase, figure 3.7. The S14 response loss parameter, is also very good, obtaining an over -50dB isolation.

The measured results are approximated the same as the theoretical and the simulated ones.

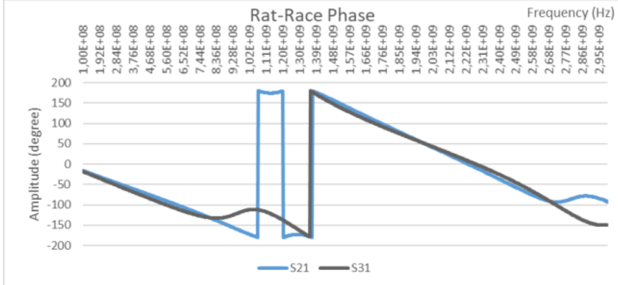

Figure 3.7 RT DUROID 5880 Rat-Race Ports 2 and 3 Phase Comparison.

2) FR-4

Figure 3.8 shows the prototype of the Rat-Race circuit impressed on the FR 4 substrate. Firstly, the circuit was printed on the board and then the four ports were weld to the substrate. This device is smaller than the last one, due to the fact that it was dimensioned for a higher dielectric permittivity substrate.

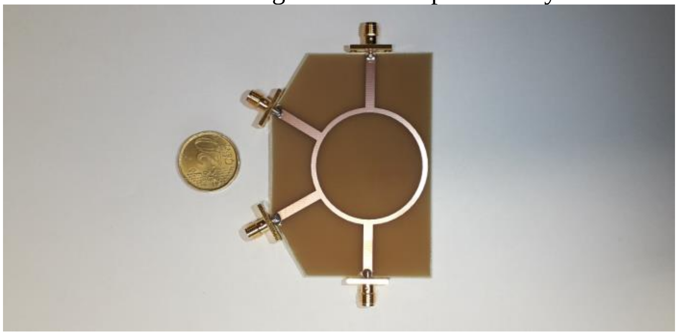

Figure 3.8 FR-4 Rat-Race Prototype.

This circuit was fabricated and measured with a Vector Network Analyzer (VNA), which was calibrated to measure the respective S-parameters. This enabled to compare the theory with the simulations and the measured results.

Figure 3.9 shows the Rat-Race coupler S parameters with an operating frequency of 2GHz.It could be concluded that the output presented is very similar to the simulated one, being noticeable a slight frequency shift. As stated before, the main reason for this effect is the homogeneity of the substrate, i.e. since being non-homogeneous leads to non-symmetry, the power that is delivered to each port is not equal.

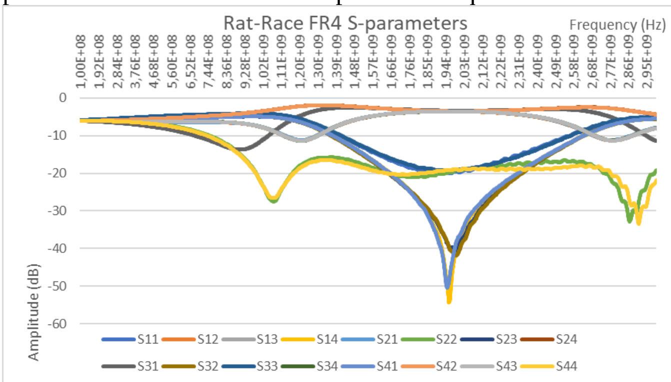

Figure 3.9 FR-4 Rat-Race S-parameters.

As happened in the RT DUROID 5880 substrate, there is a slight frequency variation around centre frequency, but all ports achieve a lower than -19 dB at around 2GHz, revealing even though that the device works correctly it should have been projected for a higher centre frequency.

Table 3 FR-4 Rat-Race Return Loss Values.

Parameters	Centre Frequency (GHz)	Max Return Loss (dB)	Band > 15dB (GHz)
S11	1.962	-20.04	1.598 - 2.320
S22	1.954	-19.84	0.906 – 3.000
S33	1.892	-19.14	1.610 – 2.332
S44	1.872	-19.75	0.900 – 3.000

Table 3 displays the band variation for each port, revealing that this device would work well during approximately 700 Hz, from 1.610 GHz to 2.320 GHz.

The insertion losses presented show some good results. It is observed that there is a -3dB equal power split between the second and third output ports, leaving port four isolated. The S12 and S13 parameters are almost flawless, obtaining an -3dB around amplitude, and being again, nearly synchronized in phase (Fig. 3.10). Moreover, the S14 parameter shows a value of closely -55dB, providing a very good ports 1 and 4 isolation relation.

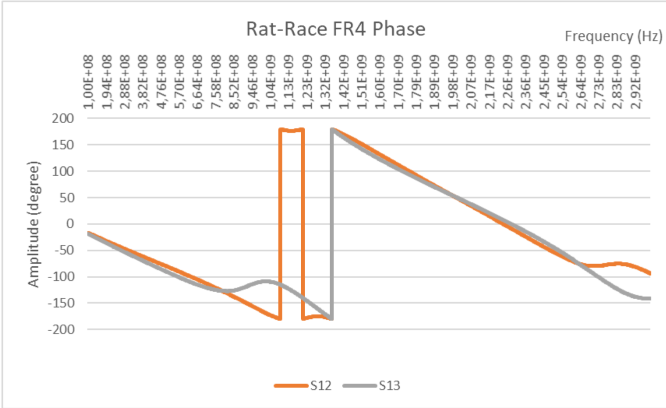

Figure 3.10 FR-4 Rat-Race Ports 2 and 3 Phase Comparison.

C. Wilkinson Power Divider

Figure 3.11 shows the prototype of the Wilkinson Power Divider circuit impressed on the RT-DUROID 5880 substrate. As on the other devices, the PCB was finished by welding the connectors to the ports, but this time this circuit had a 100-ohm resistor weld that connects both branches.

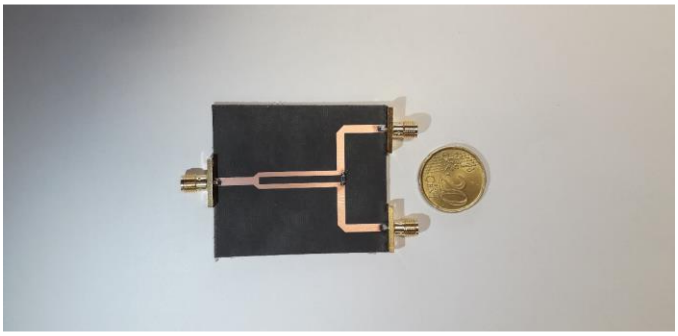

Figure 3.11 RT-DUROID 5880 Wilkinson Power Divider prototype.

This circuit was fabricated and measured with a Vector Network Analyzer (VNA), which was calibrated to measure the respective S-parameters, that enabled the comparison between the theory, the simulations and the measured results.

Figure 3.12 shows the wilkinson power divider coupler S-parameters with an operating frequency of 2GHz. It is visible the non-perfect return loss parameters by S22 and S33, possibly because of design problems.

It could be concluded that the output presented is very similar to the simulated one, that presented the same wide bandwidth.

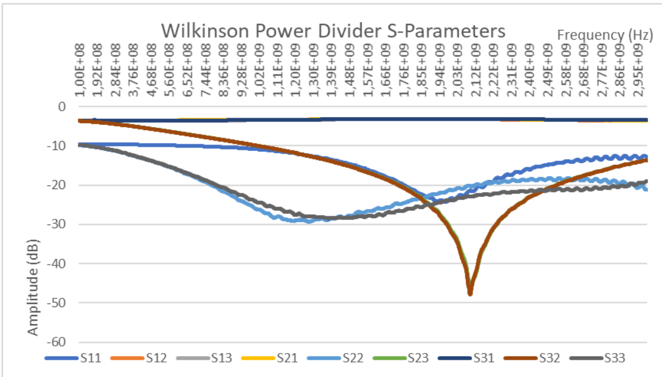

Figure 3.12 RT DUROID 5880 Wilkinson Power Divider S-parameters.

Isolation was measured at around 1968 MHz. As happened before, a slight frequency oscillation near the centre frequency is noticeable, suggesting an amplitude increase to stabilize the circuit, but all ports achieving a lower than -20dB at around 2 GHz.

Table 4 RT DUROID 5880 Wilkinson Power Divider Return Loss Values.

Parameters	Centre Frequency (GHz)	Max Return Loss (dB)	Band > 15dB (GHz)
S11	1.968	-24.2	1.512 - 2.476
S22	1.270	-29.3	0.538 – 3.000
S33	1.374	-28.5	0.542 – 3.000

The factors explained above can be seen on the S22 and S33 very wide bands, around 2.5 GHz, when compared to the circuit working band, around 900 MHz (Table 4).

The insertion losses presented show that the circuit achieved good results. It is observed that the S12 and S13 values are very good, near -3dB, and port 2 and port 3 have also a very good isolation factor of almost -50 dB. This reveals that all the signal entering port 1, gets divided between 2 and 3, with no signal from one to the other, i.e. that there is an equal power split between the 2 and 3 output ports, leaving port 4 isolated. Also, these two ports are perfectly synchronized in phase (Fig. 3.13).

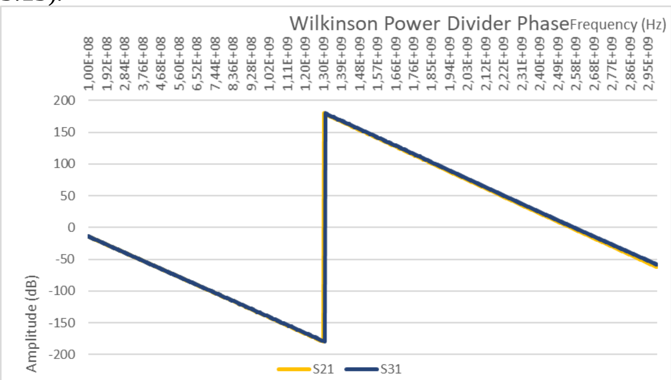

Figure 3.13 RT DUROID 5880 Wilkinson Power Divider Ports 2 and 3 Phase Comparison.

IV. Conclusions

The work presented indicates that the Quadrature Hybrid, the Rat-Race and the Wilkinson Power Divider directional couplers can be built using simple microstrip manufacture techniques and coupled lines techniques. Moreover, regarding the 3 substrates that were designed, constructed and simulated, only 2 of them achieved adequate results – the RT- DUROID 5880 and FR-4, so the EPSILAM 10 had to be discharged as it was not suitable to this kind of approach. Furthermore, as the FR-4 is not a homogeneous substrate, it was only tested on the Rat-Race circuit. The RT-DUROID 5880 substrate proved to work adequately on all circuits. The comparison of figure 4.1 with the one in chapter 1 (Fig. 1.1), shows the gap between the initial proposal and the possible one.

Nevertheless, the results obtained indicate that the proposed couplers design and fabrication work very well over their frequency bands for all the couplers.

Furthermore, the analysis, design and manufacture of the three different directional couplers permitted to recognize the overall impact of the design and of the substrate in which they were applied, in their final performance. The simulation results attained with the CST software sanctioned a deeper analysis of the S-parameters, as well as a better understanding of the electric and power flows of these devices at the dimensioned frequency.

Finally, the results acquired with the physical devices were very similar to the simulation results, demonstrating an excellent agreement between the results, which allows to conclude that the methodology used in this dissertation is appropriated to this type of circuit projection.

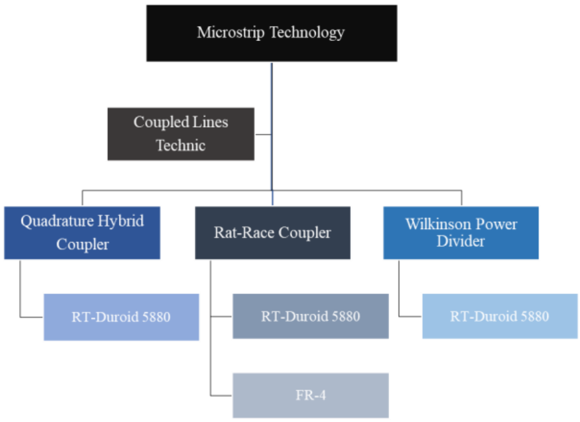

Figure 4.1 Outline of the main work done in this paper.

References

[1] S. Shelar e N. Kolhare, "Design And Analysis of Hybrid Coupler," International Journal of Engineering Research & Technology, May 2014.

[2] "History of microstrip," microwave101, 20 February 2019. [Online]. Available: https://www.microwaves101.com/encyclopedias/history-of-microstrip.

[3] S. B. Cohn, "Slot Line on a Dielectric Substrate," IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, Vols. 17, nº 10, pp. 768-778, 1969.

[4] T.-L. Wu, "Transmission Lines and Components," em Microwave Filter Design, Department of Electrical Engineering of National Taiwan University, 2011.

[5] M. V. Schneider, in Microstrip lines for microwave integrated circuits, BSTJ, 1969, pp. 1421-1444.

[6] R. E. Collin, Foundations for Microwave Engineering, McGraw-Hill International Editions, 1992.

[7] M. Kobayshi, "A dispersion formula satisfying recent requirements in microstrip CAD," IEEE Trans. Microwave Theory Tech, Vols. 36, pp. 1246-1250, 1988.

[8] D. M. Pozar, in Microwave Engineering, New York, Wiley, 1998, pp. 160-167.

[9] E. Tutkur, "Wideband Direction Couplers and Power Splitters," Thesis for the degree of Master of Science, 2014.

[10] S. B. Cohn, "History of Microwave Passive Components with Particular Attention to Directional Couplers," IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, vol. 9, nº MTT-32, pp. 1046-1053, 1984.

[11] K. C. Gupta, R. Garg e I. J. Bahl, Microstrip Lines and Slotlines, Dedham: Artech House, 1979.

[12] T. J. Rouphael, "Microwave Network Design and Analysis," 2014. [Online]. Available: https://www.sciencedirect.com/topics/engineering/directional-couplers. [Accessed 21 February 2019].

[13] H.-X. Xu, G.-M. Wang e K. Lu, "Microstrip Rat-Race Couplers," pp. 117-129, June 2011.

[14] M. Moubadir, H. Aziz, A. Mohameda e I. B. Naima Amar Touhami, "Miniaturized Design of Rat-race Coupler by Utilizing T-Shape Stubs," International Conference Interdisciplinarity in Engineering, Vols. 1, nº 11, January 2017.

[15] J. Stiles, "The 180º Hybrid," The 180 Degree Hybrid, 09 04 2007.

[16] "Advantages of Rat Race Coupler | disadvantages of Rat Race Coupler," RF Wireless World, [Online]. Available: http://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-Rat-Race-Coupler.html. [Acedido em 15 02 2019].

[17] J. Reed e G. J. Wheeler, "A Method of Analysis of Symmetrical Four-Port Networks," em IRE Transactions on Microwave Theory and Techniques, 1956, pp. 246-252.

[18] "Quadrature Couplers," microwave101, 2019. [Online]. Available: https://www.microwaves101.com/encyclopedias/quadrature-couplers. [Acedido em 08 March 2019].

[19] J. Corsini, J. Malaver e S. Lushllari, “90 Degree Hybrid Coupler,” pp. 23-24, 25 April 2013.

[20] “Wilkinson Power Divider,” Wikipedia, 2019. [Online]. Available: https://en.wikipedia.org/wiki/Wilkinson_power_divider. [Acedido em 20 March 2019].

[21] “Advantages of Wilkinson power divider or combiner | disadvantages of Wilkinson power divider or combiner,” RF Wireless World, [Online]. Available: http://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-Wilkinson-Power-Divider-Combiner.html. [Acedido em 11 02 2019].

[22] W. J. Getsinger, “Microstrip dispersion model,” IEEE Trans. Microwave Theory Tech., Vols. 21, pp. 34-39, 1973.