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. 1.1).

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.

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 (\(\varepsilon=2.2\))
- FR-4 (\(\varepsilon=4.3\))
- EPSILAM-10 (\(\varepsilon=10.2\))

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 \(\frac{3}{4}\), and two vertical 35,36Ω, equally spaced by \(\frac{3}{4}\) (Fig. 2.1).
The Wilkinson Power Divider comprises two horizontal 50Ω lines, and two vertical 70.71Ω, with a length of $\frac{\lambda}{4}$ (Fig. 2.2).

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

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.

   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.

   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).
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.

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.

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).

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).

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).
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).

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

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.

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).

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).

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.
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.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Centre Frequency (GHz)</th>
<th>Max Return Loss (dB)</th>
<th>Band &gt; 15dB (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>1.830</td>
<td>-36.31</td>
<td>1.702 - 2.008</td>
</tr>
<tr>
<td>S22</td>
<td>1.830</td>
<td>-35.32</td>
<td>1.704 - 2.004</td>
</tr>
<tr>
<td>S33</td>
<td>1.834</td>
<td>-41.81</td>
<td>1.704 - 2.012</td>
</tr>
<tr>
<td>S44</td>
<td>1.832</td>
<td>-44.86</td>
<td>1.704 - 2.008</td>
</tr>
</tbody>
</table>

It is observed that there is an approximately -3 dB 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 Phase.

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.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Centre Frequency (GHz)</th>
<th>Max Return Loss (dB)</th>
<th>Band &gt; 16dB (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>2.104</td>
<td>-31.03</td>
<td>1.378 - 2.422</td>
</tr>
<tr>
<td>S22</td>
<td>2.064</td>
<td>-32.51</td>
<td>1.374 - 2.578</td>
</tr>
<tr>
<td>S33</td>
<td>1.920</td>
<td>-28.60</td>
<td>1.585 - 2.364</td>
</tr>
<tr>
<td>S44</td>
<td>2.008</td>
<td>-29.06</td>
<td>1.408 - 2.624</td>
</tr>
</tbody>
</table>

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 welded 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.

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.

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>
<thead>
<tr>
<th>Parameters</th>
<th>Centre Frequency (GHz)</th>
<th>Max Return Loss (dB)</th>
<th>Band &gt; 15dB (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>1.962</td>
<td>-20.04</td>
<td>1.598 - 2.320</td>
</tr>
<tr>
<td>S22</td>
<td>1.954</td>
<td>-19.84</td>
<td>0.906 – 3.000</td>
</tr>
<tr>
<td>S33</td>
<td>1.892</td>
<td>-19.14</td>
<td>1.610 – 2.332</td>
</tr>
<tr>
<td>S44</td>
<td>1.872</td>
<td>-19.75</td>
<td>0.900 – 3.000</td>
</tr>
</tbody>
</table>

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.

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.

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...
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).

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.

### 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.

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### REFERENCES


