A MODIFIED WIDEBAND GYSEL POWER DIVIDER STRUCTURE

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By
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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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December 2016

Power dividers/combiners are one of the essential and crucial components of the modern RF communication systems since dividing makes RF power amplification easier to handle. As the data rates of the systems increase, the demand for wide bandwidth devices become more urgent and essential. Also, wide bandwidth systems show broadband performance in electronic warfare applications such as jamming. However, for RF power combiners/dividers increasing the bandwidth comes along with an engineering trade-off; the isolation of the divider decreases significantly. There are several studies in literature that offer various types of trivial solutions for improving both the bandwidth and the isolation performance of generic Wilkinson and Gysel power divider structures. This work concentrates on the conventional Gysel power divider structure since for high-power applications Gysel divider is preferred mainly for the feasibility of external isolation resistors. We propose a modified Gysel divider structure with a series LC circuit resonant at the center frequency to correct the impedance at the output and the isolation ports and the generic transmission line impedances optimized to adapt to this modification. We both show the interrelations of the capacitor and inductor values and also their relations to the scattering parameters and offer a guideline to choose the appropriate filter for the required application. The experimental results are presented to verify the proposed Gysel divider structure.

Keywords: Gysel power divider, wide-band divider, high-isolation, series LC filter, scattering parameters, high power applications.

ÖZET

GENİŞ BANTLI DEĞİŞTİRİLMİŞ GYSEL GÜÇ BÖLÜCÜSÜ

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Aralık 2016

RF güç bölücü ve birleştiriciler günümüz haberleşme sistemlerinin en gerekli ve kilit rol oynayan bileşenlerinden biridir; çünkü RF güç yükselteç uygulamalarının tasarımı güç bölünmesi vasıtasıyla dağılımı sayesinde kolaylaşmaktadır. Sistem gerekleri çerçevesinde veri hızları arttıkça, daha geniş bant aralığı için de talep artmakta ve aciliyet kazanmaktadır. Buna ek olarak, geniş bant aralığına sahip sistemler sinyal boğma gibi elektronik harp uygulamalarında da gösterdiği yüksek performans sebebiyle önem kazanmaktadır. Fakat, güç bölücü ve birleştiriciler için bant aralığını genişletmek karşılığında yalıtım performansından ödün vermek anlamına gelmektedir. Literatürde tipik Wilkinson ve Gysel topolojileri üzerinde hem bant genişliğini artırmak hem de yalıtım performansını iyileştirmek adına yapılan bazı açık yöntem önerileri mevcuttur. Bu çalışma tipik Gysel güç bölücü topolojisi seçilerek yapılmıştır; zira Gysel güç bölücü, yalıtım direncinin dışarıdan kapı vasıtasıyla eklenebilmesi sayesinde, yüksek güç uygulamalarında tercih edilmektedir. Çalışmamızda değiştirilmiş bir Gysel güç bölücüsü topolojisi sunmaktayız. Hem çıkış hem yalıtım kapısı hatlarına eklenen bir dizi LC filtresi sayesinde bir alçak geçirgen ve bir bant-geçirgen filtre modeli oluşturmaktadır ve bölücü boyunca bulunan empedans hatlarının değerleri bu filtrelere göre eniyilenmiştir. Biz bu LC filtredeki kapasitör ve indüktör değerlerinin hem birbirleriyle hem de saçılım parametreleriyle olan ilişkileri üzerine bağıntılar sunmaktayız ve doğru filtre değerlerini seçmek için öneride bulunmaktayız. Önerilen topolojinin doğrulanması üzerine yaptığımız deneysel çalışmalarımızın sonuçlarını da ibraz etmekteyiz.

Anahtar sözcükler: Gysel güç bölücü, geniş bantlı güç bölücü, yüksek yalıtım, dizi LC filtre, saçılım parametreleri, yüksek güç uygulamaları.

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Chapter 1

Introduction

Modern wireless communication technologies show an increasing demand for high-quality RF power divider/combiner structures, because of the advantages of these structures especially for the RF power amplifier systems. By dividing, amplifying and then combining the RF power, the stress on the active components are relieved and higher power levels can be achieved safer and easier. However, this increasing demand also comes along with the increasing requirements that the divider structures should meet.

Ideally, the divider is expected to be compact and small in size, should have high isolation in a wider band and of course should handle higher RF power. Two main topologies that are implemented in RF power dividers are Wilkinson [1] and Gysel [2] structures. The Wilkinson divider shows has a high bandwidth and compactness in size but fails to handle high power levels due to the chip resistor in the mid-section that is used for achieving high-isolation. Gysel topology on the other hand, can handle higher power levels due to the external isolation resistor and can be made compact in size; however the bandwidth, especially for high requirements like 20-dB, is much narrower. Another important difference between Wilkinson and Gysel topologies is that the flexibility to implement the n-way extension. While it is impossible to implement an n-way ($n > 2$) Wilkinson divider on a planar structure, the n-way Gysel topology can be realized so and this makes the Gysel topology to stand a step forward in n-way applications.

While the bandwidth seems not to qualify modern requirements, the high power handling capacity and the ease of implementation makes the designer be willing to implement Gysel topology extensively; therefore enhancing the performance has become a necessity.

1.1 Motivation

For a wireless communication system that requires perfect power divider response; there exists a trade-off among the demands. First, while improving the isolation performance, the insertion loss of the circuit may degrade, which is not a desirable outcome. Second, the input and output return loss can also deteriorate and become the primary limiting factor rather than the isolation, which is also disadvantageous for the system performance. Last, increasing the size also improves the bandwidth; however since technology requires even smaller circuits for the wireless systems, this is also undesirable for the performance of the Gysel power divider.

The conventional Gysel divider schematic is shown in Figure 1.1.

The 20-dB bandwidth of this structure is found as 22.8%. Moreover, the input and output return loss values are also narrow and only reaches 20-dB levels for the same frequency band.

For comparison, the 20-dB bandwidth of the Wilkinson divider is found to be 36.7%. This means, at this frequency band, despite the lumped isolation resistor of 100Ω at the middle of the structure, Wilkinson divider is more preferable due to higher bandwidth.

Nevertheless, the Gysel topology provides flexibility to the designer, since the

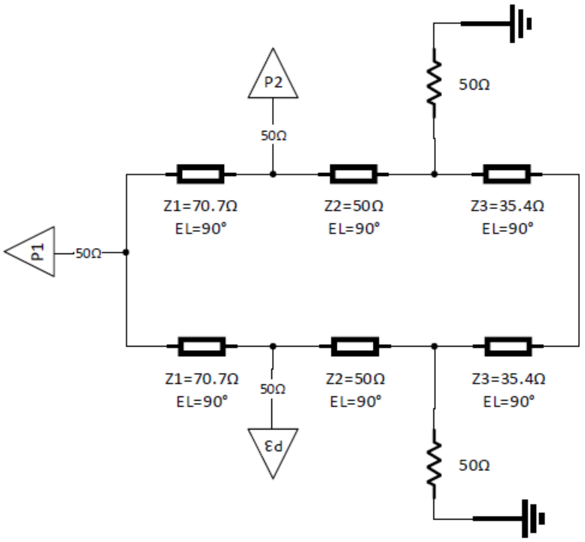

Figure 1.1: Circuit Model of Conventional Gysel Power Divider

structure is suitable for adding matching and filtering elements. Using this property of the Gysel power divider, it has been our motivation to search for a modification that would improve the isolation, insertion loss and input and output return loss properties.

1.2 Similar Works in Literature

Since the device itself has a narrow bandwidth when it is compared to the conventional Wilkinson divider, with the increasing need to higher performance divider/combiner structures, various similar works focusing on novel ways to enhance the isolation and widening the bandwidth have been published. Most of these publications date back to late 2000s and 2010s, which is also an indicator for the increasing demand.

In an 2013 study by Abbosh and Henin [3], they propose to use a single isolation resistor and to add a fourth transmission line with a variable impedance parameter so they alter the symmetrical topology. With this modification, they obtain a Gysel divider with 26.6% bandwidth but the input return loss is around 15 dB in-band and the mismatch between Port 2 and 3 are high due to asymmetry.

In a recent study in proceed by He et al. [4], an impedance matching network that consists a short-circuited shunt stub and a series stub is added to the input port. The bandwidth of this design is around 50%, the input and output return loss parameters show a similar performance.

On the other hand, in another study by Taş and Atalar [5], an optimized isolation network for the Wilkinson divider is designed and implemented and it is shown to reach a 20-dB bandwidth of 70%. These studies were the motivation for us to consider a modified Gysel divider which may indeed be comparable to the performance of these studies.

1.3 Thesis Contribution

In our proposed design, we make use of the bandpass characteristic of the series LC circuit and add series LC-sections to all of the output and isolation ports just before the 50Ω connectors. The resonance frequency of the LC network is determined as the center frequency of the operation bandwidth.

The modified Gysel power divider structure has achieved 51.2% 20-dB bandwidth at 2 GHz center frequency. It is also suitable for high-power applications and has a small size for its power handling capacity. The proposed design is characterized, analyzed and eventually implemented on PCB. Experimental measurements of the design are done and it is tested for enhanced performance.

1.4 Definition of Bandwidth

In this study, ”the bandwidth” will be used for two different meanings.

- The **operation bandwidth** or the **divider bandwidth** is the frequency interval that all the scattering parameters meet the conditions that are set for a specific design. In other words, the s-parameter(s) with the narrowest 20 dB bandwidth limits this definition.

- The **bandwidth** in general, is the frequency interval that the scattering parameter of concern, meets the condition that is set for it to satisfy in the design.

Chapter 2

Conventional Gysel Divider

This chapter will first introduce the conventional Gysel divider topology, its properties and even-odd mode analysis [6, 7] results. Then, similar works from literature that present enhanced isolation properties will be mentioned and will be used for comparison in Chapter 5.

2.1 The Original Topology

The schematic of the Gysel divider structure is presented in Figure 1.1.

To make the topology matched at 2 GHz center frequency, the even-odd mode circuits will be helpful. In order to run the even-odd mode analysis, first the axis of symmetry should be found. Since Gysel topology is a simple and symmetric structure the horizontal axis, which will also split the 50Ω input port as two parallel 100Ω input ports. The corresponding circuit shown in Figure 2.1.

Figure 2.2 and Figure 2.3 show the upper section of the even and odd mode circuits of the conventional Gysel divider. For even mode, it is assumed that V_{g2} = V_{g3} = $2V_s$ is applied from Ports 2 and 3; and for the odd mode, it is assumed that $V_{g2} = -V_{g3} = 2V_s$.

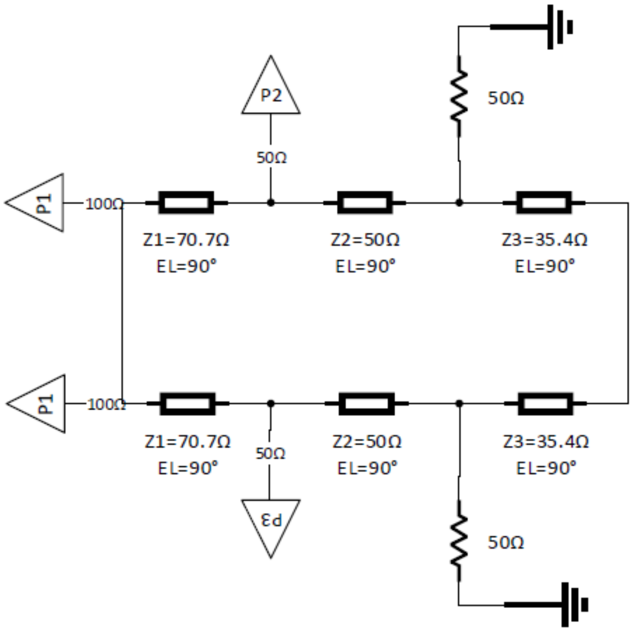

Figure 2.1: Even-Odd Mode Symmetry Scheme

Since all of the electrical lengths of the transmission lines are $\lambda/4$, the property of quarter-wave transformers in Equation 2.1 will be used, where Z denotes the characteristic impedance of the quarter-wave transmission line and Z_L is the load impedance.

$$Z_{in} = \frac{Z^2}{Z_L} \tag{2.1}$$

2.2 Even and Odd Mode Analysis

2.2.1 Even Mode Analysis

For the even mode, Port 2 sees an open-circuit looking into the isolation path therefore Port 1 sees only a quarter-wave transmission with a 50Ω load. Using Equation 2.1,

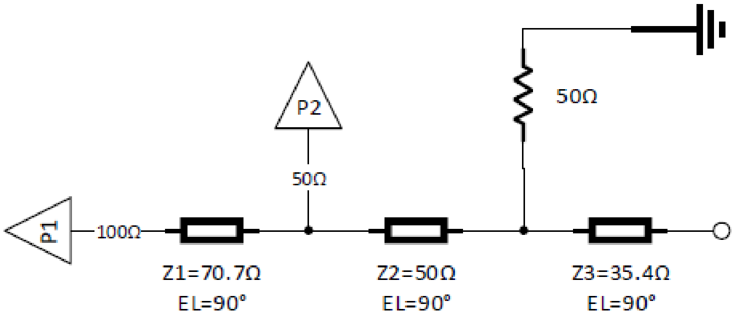

Figure 2.2: Even Mode, Conventional Gysel Divider

$$Z_{in} = \frac{70.7^2}{50} \approx 100\Omega \tag{2.2}$$

This results in $\Gamma_{1e} = 0$ since Port 1 is 100Ω.

Also, for the even-mode reflection coefficient seen from Port 2, it can be noticed that since the right-hand side is open-circuit, Port 2 faces with a quarter-wave transmission line with characteristic impedance Z1 and 100Ω load connected to it. Using Equation 2.2, $\Gamma_e = 0$.

Let the voltage at the Port 2 node be called V_2^e and the voltage at Port 1 be called V_1^e [7]. Since it is found out that Port 2 sees a matched load, and $V_{g2} = 2V_s$, $V_2^e = V_s$. Setting Port 1 as x = $-\lambda/4$ and Port 2 as x = 0;

$$V(x) = V^+(e^{-j\beta x} + \Gamma e^{j\beta x}) \tag{2.3}$$

Equation 2.3 is the general voltage equation on a transmission line. Here, Port 2 looks toward a load of 100Ω through a $\lambda/4$ transmission line of impedance 70.7Ω.

$$V_2^e = V(0) = V^+(1+\Gamma) = V_s \tag{2.4}$$

$$V_1^e = V(-\lambda/4) = jV^+(1-\Gamma) = jV_s\frac{\Gamma-1}{\Gamma+1} \tag{2.5}$$

Here Γ denotes the reflection coefficient between the quarter wave transmission line and the 100Ω load.

$$\Gamma = \frac{Z_L - Z}{Z_L + Z} = \frac{2-\sqrt{2}}{2+\sqrt{2}} \tag{2.6}$$

In the end the voltage at port 1 is found out as in Equation

$$V_1^e = jV_s\frac{\Gamma-1}{\Gamma+1} = j\sqrt{2}V_s \tag{2.7}$$

2.2.2 Odd Mode Analysis

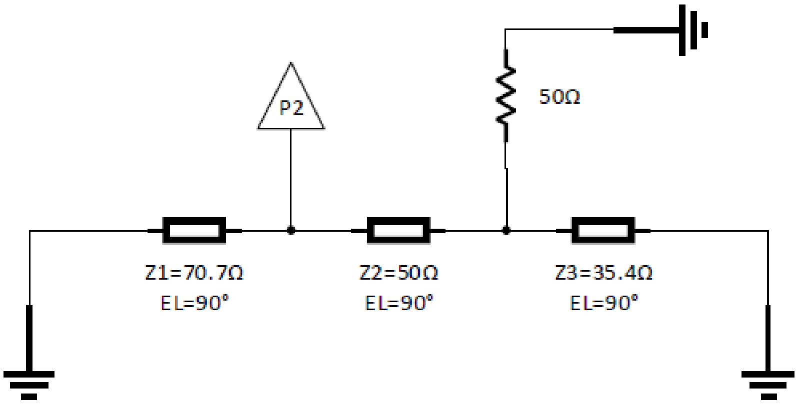

Figure 2.3: Odd Mode, Conventional Gysel Divider

Similarly, for the odd mode, the short circuit becomes an open circuit after passing from quarter-wave Z3 transmission line and makes the 50Ω isolation resistor be paralleled with an open-circuit. Since the characteristic impedance Z2 is also 50Ω, so the 50Ω load can be assumed as directly connected to the Port 2.

On the left-hand side, the short circuit again becomes and open circuit passing through the quarter-wave Z1 transmission line, therefore Port 2 is matched with 50Ω resistor. This means $\Gamma_o = 0$.

Let the voltage at the Port 2 node be called V_2^o and the voltage at Port 1 be called V_1^0. Since it is found out that Port 2 sees a matched load and $V_{g2} = 2V_s$, then $V_2^o = V_s$. Port 1 is short-circuited so $V_1^o = 0$.

To sum up, the scattering parameters of the conventional Gysel divider has been found out from the analysis listed above as:

- Input return loss

$$\Gamma_{1e} = 0 \rightarrow S_{11} = 0 \tag{2.8}$$

- Output return loss the equation 2.9 and isolation the equation 2.10

$$S_{22} = \frac{\Gamma_e + \Gamma_o}{2} \tag{2.9}$$

$$S_{32} = \frac{\Gamma_e - \Gamma_o}{2} \tag{2.10}$$

gives the result as follows:

$$\Gamma_e = 0, \Gamma_0 = 0 \rightarrow S_{22} = 0, S_{32} = 0 \tag{2.11}$$

- Insertion loss

$$S_{21} = \frac{V_1^e + V_1^o}{V_2^e + V_2^o} = \frac{j}{\sqrt{2}}. \tag{2.12}$$

S_{12}, S_{13} and S_{33} follows the same pattern from the reciprocity.

2.3 The Gysel Divider

As a result, the impedances and the electrical lengths of the transmission lines are set according to the even-odd mode analysis done above, such that the structure is matched at 2 GHz center frequency. The corresponding scattering parameters in dB for this topology is shown in Figure 2.4.

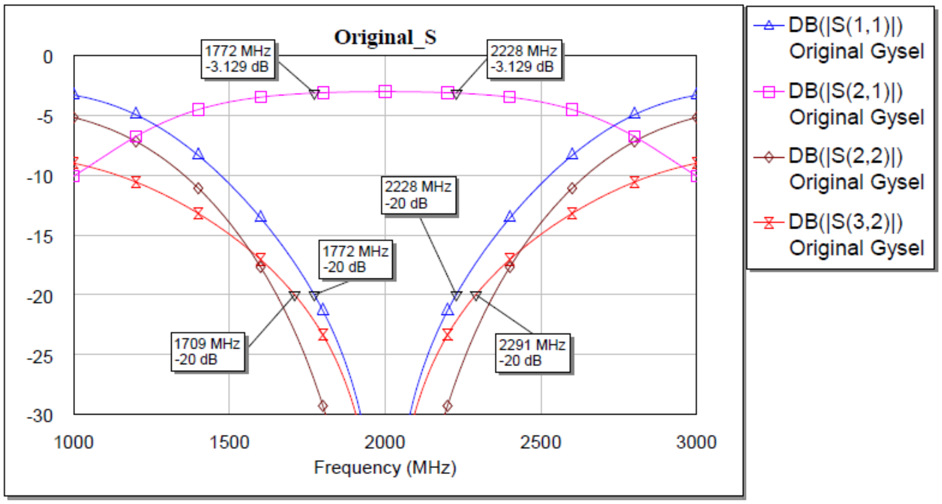

Figure 2.4: Scattering Parameters of the Original Gysel Divider

The bandwidth of the CAD simulation results of all scattering parameters can be summarized as in Table 2.1.

Parameter	Original Gysel Divider (GHz)
S_{11}	$1.772 < f < 2.228$
S_{22}	$1.651 < f < 2.349$
S_{32}	$1.709 < f < 2.291$

Table 2.1: The 20-dB Bandwidth of the Conventional Gysel Topology for f_c=2 GHz

Examining the results above, S_{32} resides under -20 dB for a wide bandwidth of 29.1%.

The overall performance of the divider is limited by the input return loss since it is exhibits the narrowest performance; the *operation bandwidth* is **22.8%**.

2.4 Measurement Results

As these results belong to the ideal case where the real models of the transmission lines are not used, for a better and more accurate comparison, we implemented this design and got it printed to the same substrate that is used for the modified Gysel topology, Rogers 4003 with 0.035 mm copper thickness, 1.6mm dielectric thickness and 3.55 relative dielectric permittivity.

The printed original Gysel divider on the PCB is shown in Figure 2.5.

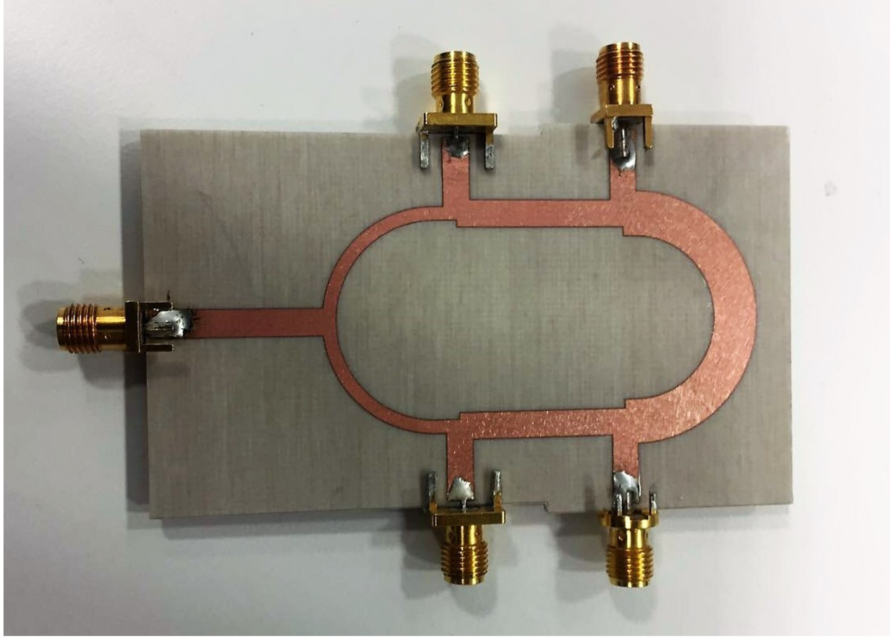

Figure 2.5: The Implemented Original Gysel Divider

The divider is tested using a calibrated Agilent Network Analyzer in the operation bandwidth. First, Port 1 of the analyzer is connected to the input port of the divider and Port 2 is connected to the one of the output ports while the other is terminated with an SMA 50Ω resistor. Then the output port is reversed and measured again. Finally for the isolation the input is terminated with an SMA

50Ω resistor and the Port 1 and 2 of the network analyzer have been connected to the output ports. The s-parameter results obtained from both of the output ports of this divider schematic are as shown in Figure 2.6 and Figure 2.7.

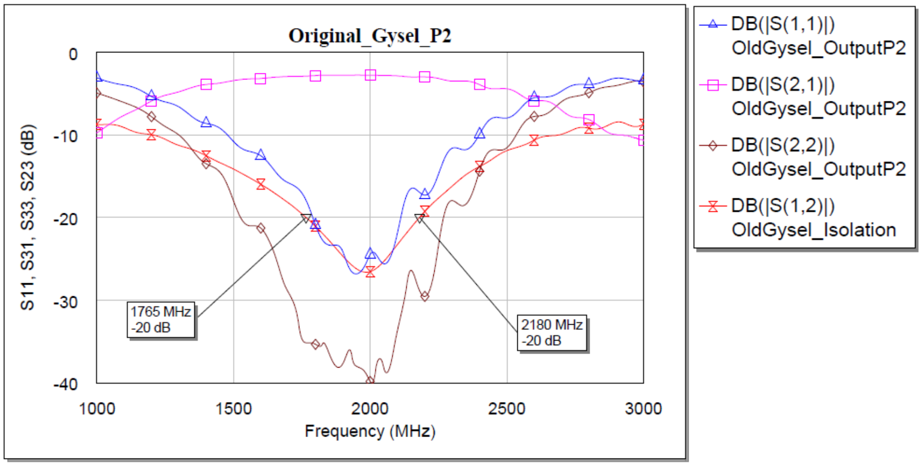

Figure 2.6: S-Parameters of the Original Gysel Divider Measurements-Output Port 1

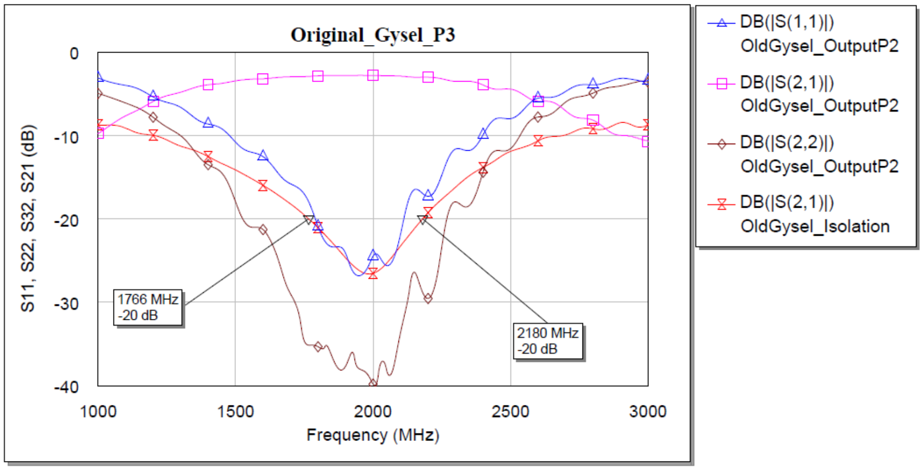

Figure 2.7: S-Parameters of the Original Gysel Divider Measurements-Output Port 2

The properties of this divider is summarized in the Table 2.2.

Examining the measurement results, S_{32} resides under -20 dB for a bandwidth of 20.75% and this is slightly worse than the CAD simulation results. These results will be revisited in Chapter 4 for comparison to the our proposed divider.

Parameter	Original Gysel Divider (GHz)
S_{11}	$1.790 < f < 2.112$
S_{22}	$1.526 < f < 2.268$
S_{32}	$1.721 < f < 2.178$

Table 2.2: The 20-dB Bandwidth of the Conventional Gysel Topology

Chapter 3

Proposed Modified Gysel Divider

This chapter will introduce the modified Gysel power divider topology and demonstrate a theoretical analysis of the novel design using even-odd mode analysis [6, 7] and Smith chart techniques [8]. The CAD software analysis steps and the linear simulation results will be discussed and the improvements will be pointed out.

Our modified Gysel power divider topology makes use of the bandpass property of series LC circuits [9]. We propose to add a single series LC network to both of the output and isolation ports, before the 50Ω port or termination. The novel topology is demonstrated in Figure 3.1.

The Gysel topology will be analysed and implemented for the n = 2 case, i.e. we will concentrate on a 2-way divider, since it is much harder to reach higher isolation levels for a 2-port design compared to higher order divisions. Ports 2 and 3 in Figure 3.1 will be referred to as output ports and Ports 4 and 5 will be considered as isolation ports. From this topology it can easily be seen that the circuit is still symmetric.

The optimum values that meet the following design requirements are extracted via AWR Microwave Office optimizer tools to start the analysis.

- To have at least 54% *20-dB bandwidth* around 2 GHz center frequency, i.e.

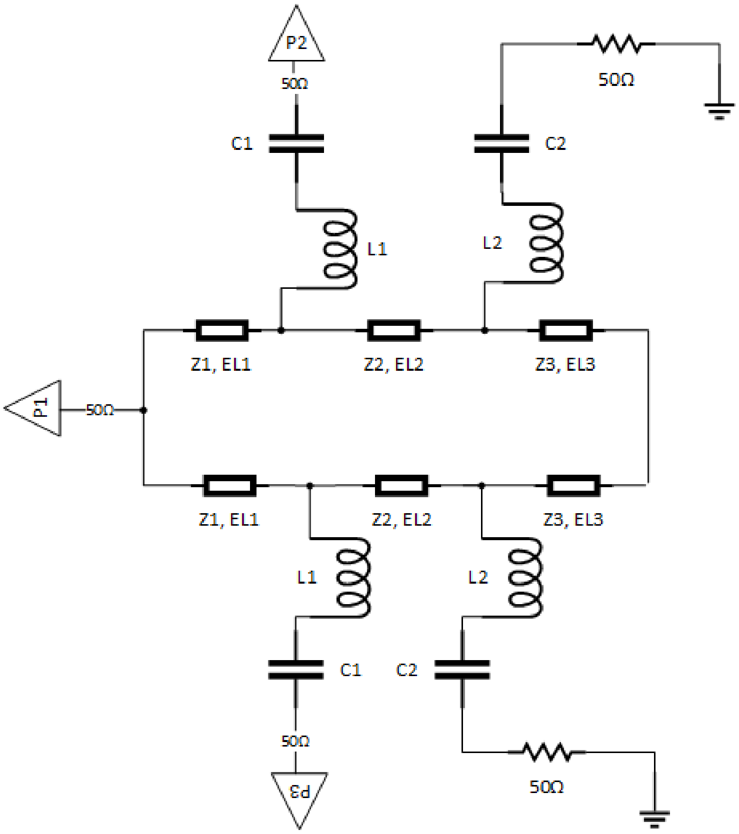

Figure 3.1: Proposed Modified Gysel Power Divider Topology

$1460MHz < f < 2540MHz$ is aimed.

- To have at least 20 dB input and output return loss in the operation bandwidth

The resulting impedance values as well as the inductor and capacitor values are summarized in the Table 3.1 and Table 3.2.

Transmission Line	Impedance(Ω)	Electrical Length(deg)
$Z1, EL1$	70.25	90
$Z2, EL2$	60.48	90
$Z3, EL3$	35.84	90

Table 3.1: The Optimum Lossless Transmission Line Parameter Values of the Novel Gysel Power Divider

While computing the capacitance and inductance values in Table 3.2, the main concern was to make the series LC circuit resonate at the center frequency of operation. In other words, calling the center frequency f_C, the Equation 3.1 is used for the optimizations.

$$\begin{aligned} \omega_0 &= \frac{1}{\sqrt{LC}} \\ 2\pi f_0 &= \frac{1}{\sqrt{LC}} \\ C &= \frac{1}{L}\frac{1}{4\pi^2 f_0^2} \end{aligned} \tag{3.1}$$

For this case center frequency is 2 GHz, so this equation reduces to Equation 3.2.

$$C(pF) = \frac{6.3326}{L(nH)} \tag{3.2}$$

Component	Capacitance (pF)	Component	Inductance (nH)
$C1$	2.14	$L1$	3.34
$C2$	1.71	$L2$	3.99

Table 3.2: The Optimum Passive Component Parameter Values of the Novel Gysel Power Divider, $f_C = 2$ GHz

The values in Table 3.2 are extracted for $f_C = 2$ GHz; however with Equation 3.3 it is easy to calculate the capacitance value for any center freqeuncy.

$$\begin{aligned} X_C &= \frac{1}{\omega_C C} \\ C &= \frac{1}{2\pi f X_C} \end{aligned} \tag{3.3}$$

Using the values in Table 3.2 and Equation 3.3 we can obtain the following Equation 3.4 and Equation 3.5. The resonating inductance values can be easily deduced from Equation 3.1.

$$C_1(pF) = \frac{4.28}{f(GHz)} \tag{3.4}$$

$$C_2(pF) = \frac{3.42}{f(GHz)} \tag{3.5}$$

The way the series LC bandpass filter affects the performance of the Gysel divider was found out to be the tuning effect in the input impedances seen looking into input and output ports (Ports 2 and 3 in Figure 3.1). The LC network increases the bandwidth that the ports see a matched or close to a matched impedance of ±50Ω. This decreases the reflection coefficient and therefore increases the bandwidth of the divider. Using AWR Microwave Office, the input impedance looking in a specific port can be modelled as a series RL network. The Table 3.3 shows the input impedances of the traditional Gysel divider. Port 2 and Port 3 values are equal so only one of them is shown on the table.

Frequency (GHz)	Port 1 R(Ω)	Port 1 L(nH)	Port 2 R(Ω)	Port 2 L(nH)
1.4	90.04	4.38	50.44	3.32
1.5	89.36	1.07	56.32	2.20
1.6	75.93	−0.48	57.33	1.20
1.7	63.68	−0.79	55.31	0.54
1.8	55.67	−0.63	52.64	0.21
1.9	51.34	0.32	50.69	0.06
2.0	49.98	0	49.99	0
2.1	51.34	0.29	50.69	−0.05
2.2	55.67	0.51	52.64	−0.16
2.3	63.68	0.59	55.31	−0.40
2.4	75.93	0.32	57.33	−0.80
2.5	75.93	−0.64	57.33	−1.32
2.6	90.04	−2.36	50.44	−1.78

Table 3.3: The Input Impedance Model-Series RL Values, Traditional Gysel Divider

Examining this table, it is observed that the resistance increases very sharply towards the end of the bandwidth and the series inductance (or in some cases the model turns out to be capacitive) fluctuates with a high deviation for both input and output port models.

The Table 3.4 shows the input impedance models for the same ports after the series LC networks are added to the divider structure. In the following Table 3.5 Port 3 is also included since the values show a different fashion.

Frequency (GHz)	Port 1 R(Ω)	Port 1 L(nH)	Port 2 R(Ω)	Port 2 L(nH)
1.4	51.08	−0.28	56.20	−1.72
1.5	46.97	0.03	56.33	−0.08
1.6	46.10	0.23	57.2	0.12
1.7	46.78	0.30	58.66	0.25
1.8	47.95	0.25	59.97	0.28
1.9	48.87	0.13	60.45	0.25
2.0	49.17	−0.01	59.86	0.21
2.1	48.88	−0.12	58.49	0.21
2.2	48.36	−0.18	56.93	0.26
2.3	48.16	−0.18	55.81	0.34
2.4	48.98	−0.15	55.56	0.40
2.5	51.58	−0.12	56.04	0.37
2.6	56.825	−0.18	56.05	0.18

Table 3.4: The Input Impedance Model-Series RL Values, Modified Gysel Divider, Port 1 & 2

Analyzing these tables, it can be concluded that the modification provides a better matching for the input and output ports at a wider bandwidth and this explains the improvement in the performance of the Gysel topology. The variance of both the resistor and the inductance (or the capacitance) decreased significantly in the entire band of operation. At the center frequency the output ports matches to approximately 60Ω which is also the characteristic impedance of the transmission line, Z_2.

Concluding the theoretical design, the novel topology has been implemented for experimental measurements and analysis.

Frequency (GHz)	Port 3 R(Ω)	Port 3 L(nH)
1.4	56.17	-1.72
1.5	56.31	-1.40
1.6	57.16	-1.04
1.7	58.60	-0.77
1.8	59.92	-0.63
1.9	60.45	-0.57
2.0	59.91	-0.53
2.1	58.55	-0.46
2.2	56.98	-0.35
2.3	55.84	-0.22
2.4	55.57	-0.12
2.5	56.04	-0.11
2.6	56.06	-0.25

Table 3.5: The Input Impedance Model-Series RL Values, Modified Gysel Divider, Port 3

Chapter 4

Simulation and Measurement Results

This chapter will demonstrate the electromagnetic (EM) simulation and experimental measurement results of the proposed Gysel divider structure. The results will be compared to the conventional Gysel topology in Figure 1.1.

The constructed 2-way Gysel power divider structure was implemented on a Rogers 4003 substrate with $\epsilon_r = 3.55$, a dielectric thickness 1.6mm and a copper thickness 0.035mm. First, an EM simulation is run on the proposed design using the Sonnet design software. After completing fine-tuning on the software, the divider is printed. The measurement results have been taken on the Agilent network analyzer and compared with the EM simulation results and the original Gysel divider performance.

4.1 EM Simulation Results

The constructed divider was analysed firstly by breaking down the circuit to symmetric impedances and the impedance blocks were simulated one-by-one while the remaining parts were optimized again. Finally, the final single block of the divider was analysed and without any further tuning it was fabricated.

Remembering from Table 3.2, the inductance values are found to be pretty small for finding an accurate (i.e. around ±0.01 nH deviation) lumped element counterpart for this frequency band. Therefore, instead of a lumped component, the inductance is modeled as a thin, short and high impedance transmission line for exact results. Using the values provided in Table 3.2 for implementations; the resulting characteristic impedance (Z_0) and the electrical length of these transmission lines are summarized in the Table 4.1.

Inductor	$Z_0(\Omega)$	EL(deg)
L1	114.9	15
L2	127.8	16.9

Table 4.1: Lossless Transmission Line Equivalents of Inductors

The final results of this electro-magnetic simulation are shown in the following Figure 4.1.

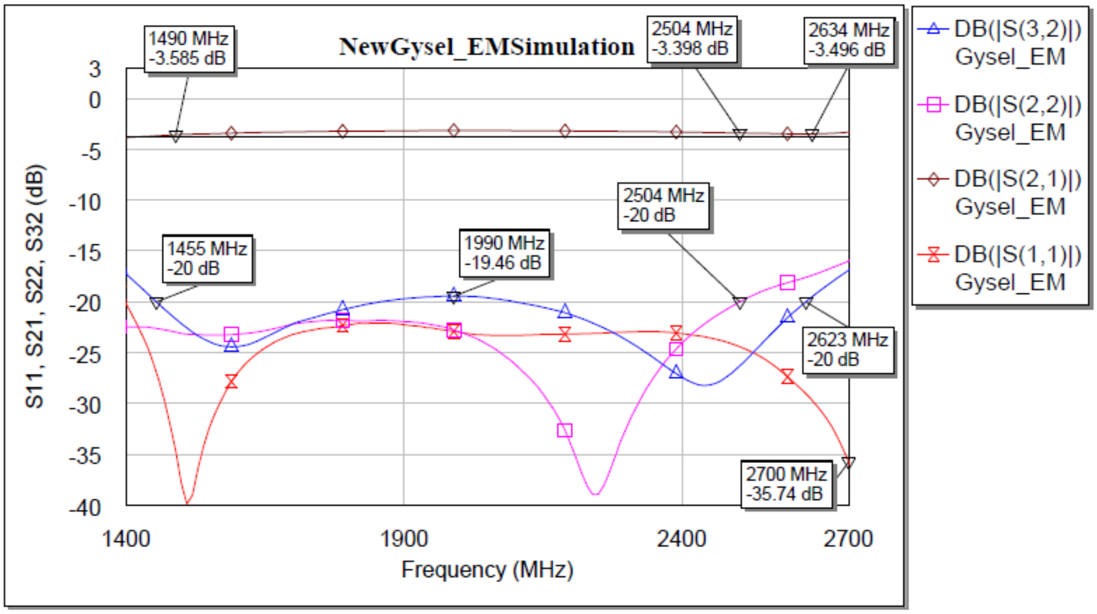

Figure 4.1: EM Simulation Results of the Proposed Gysel Divider

Here, it can be seen that the proposed divider has a much wider bandwidth compared to the original Gysel divider (detailed comparison will be at the end of section 4.2). The introduced LC-bandpass circuit not only results in higher isolation but also decreases input and output return loss parameters. Summarizing the results it is expected from the fabricated module to have:

- At least 50% *20-dB bandwidth* around 2 GHz center frequency
- Best performance for the insertion loss around 3 dB

4.2 Measurement Results

The printed novel Gysel divider is shown in the Figure 4.2. The isolation ports, which were enumerated as Port 4 and Port 5, are terminated with 50Ω SMA resistors. The decreasing order of impedances can be detected easily from the copper lines.

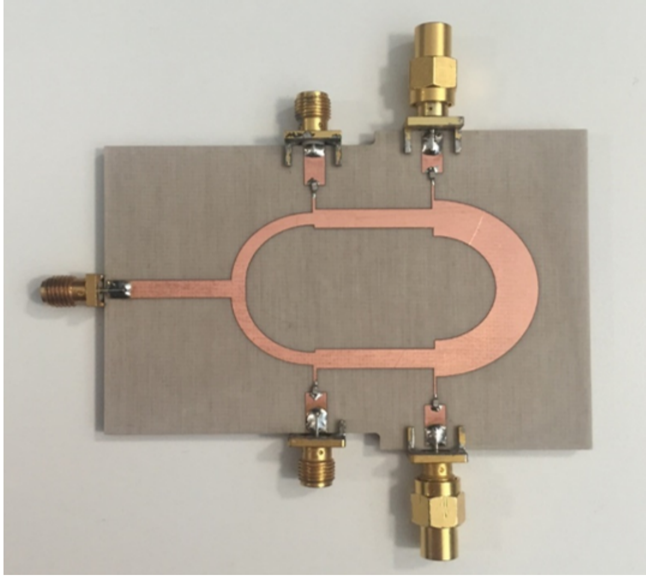

Figure 4.2: The Printed Novel Gysel Divider

The divider is tested using calibrated Agilent Network Analyzer. First, Port 1 of the analyzer is connected to the input port of the divider and Port 2 is connected to the one of the output ports while the other is terminated with an SMA 50Ω resistor. Then the measured output port is reversed. Finally for recording the isolation, the input is terminated with an SMA 50Ω resistor and the Ports 1 and 2 of the network analyzer have been connected to the output ports. The s-parameter results obtained from both of the output ports of this divider module are as shown in Figure 4.3 and Figure 4.4.

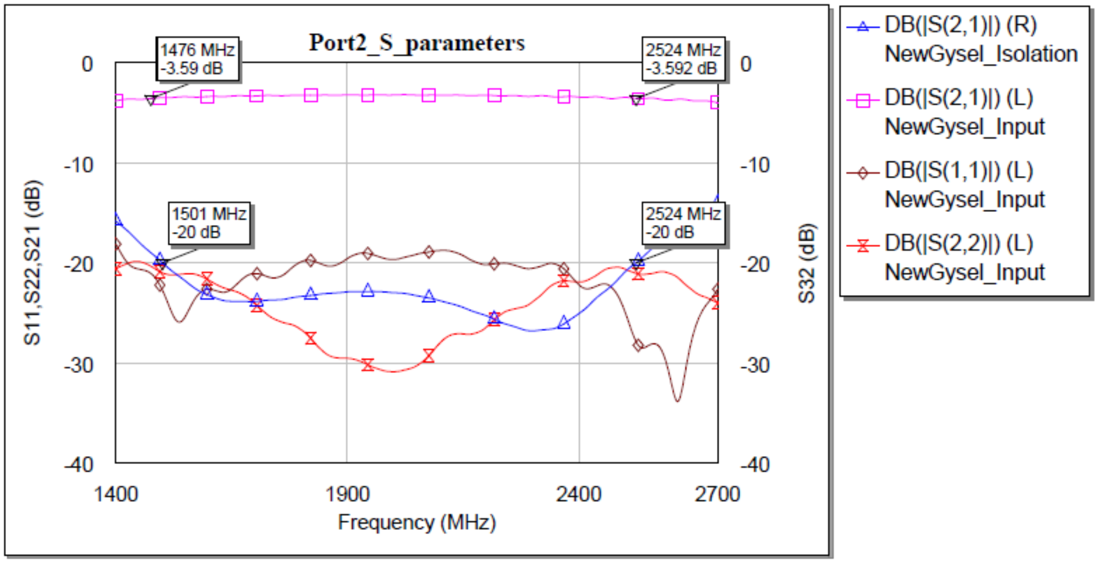

Figure 4.3: The Results Obtained from Port 2

From the results shown above we can say that the performance of this modified Gysel power divider is very close to and the isolation performance is even better than the EM simulation recordings.

Table 4.2 compares the EM simulation results to experimental results. The frequency interval is determined according to the criteria defined at the end of Section 4.1.[1]The results for the Port 3 is approximately the same so the results are expressed using the results of Port 2.

As it can be observed from this comparison, the performance of the modified Gysel divider has been enhanced significantly with the series LC network. The isolation is strictly more than 20-dB for the entire bandwidth of operation and

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[1] The small deviations up to 19dB are not taken into account for defining the bandwidth.

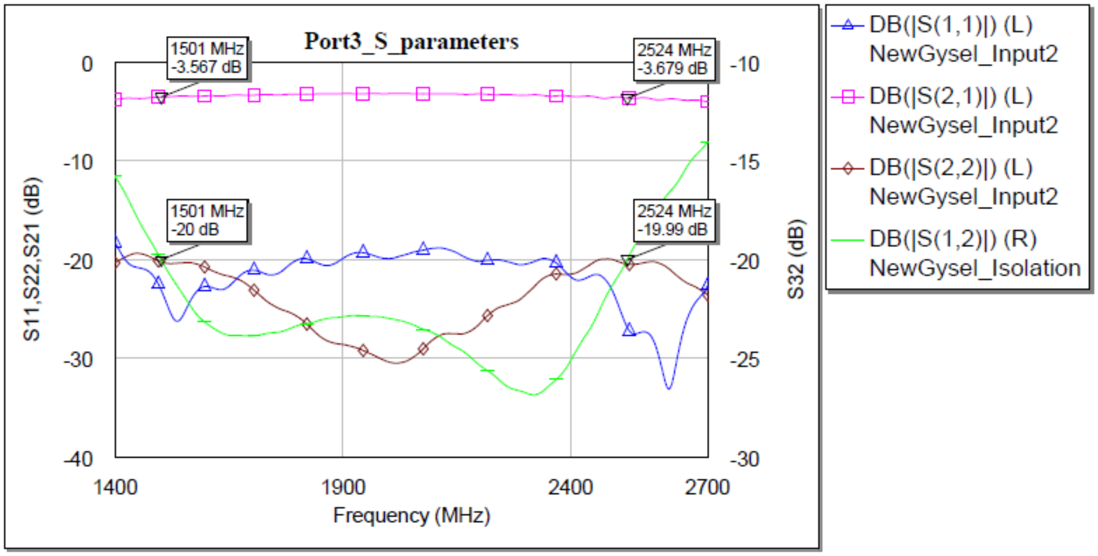

Figure 4.4: The Results Obtained from Port 3

Parameter	EM Simulation Result (GHz)	Measurement Result (GHz)
S_{11}	$1.399 < f < 2.803$	$1.430 < f < 2.780$
S_{22}	$1.355 < f < 2.504$	$1.200 < f < 2.800$
S_{32}	$1.455 < f < 2.623$	$1.501 < f < 2.524$

Table 4.2: The 20-dB Bandwidth of the Parameters for f_c=2 GHz at Port 2.

at the mid-band it is around 22-dB. The insertion loss is not higher than 3.6 dB for this frequency interval.

The comparison of the performances of the measurements taken from original Gysel topology and our modified Gysel divider are summarized in Table 4.3. The frequency interval is determined according to the criteria defined at the end of Section 4.1.[2]The results for the Port 3 is approximately the same so the results are expressed using the results of Port 2.

The Figure 4.5 shows the magnitude mismatch and Figure 4.6 shows the phase mismatch between the output ports of the modified divider.

Although the magnitude and phase mismatch tend to increase approaching the

Parameter	Original Gysel Divider (GHz)	Modified Gysel Divider (GHz)
S_{11}	$1.769 < f < 2.124$	$1.430 < f < 2.780$
S_{22}	$1.564 < f < 2.272$	$1.200 < f < 2.800$
S_{32}	$1.721 < f < 2.178$	$1.501 < f < 2.524$

Table 4.3: The 20-dB Bandwidth of the Parameters for f_c=2 GHz

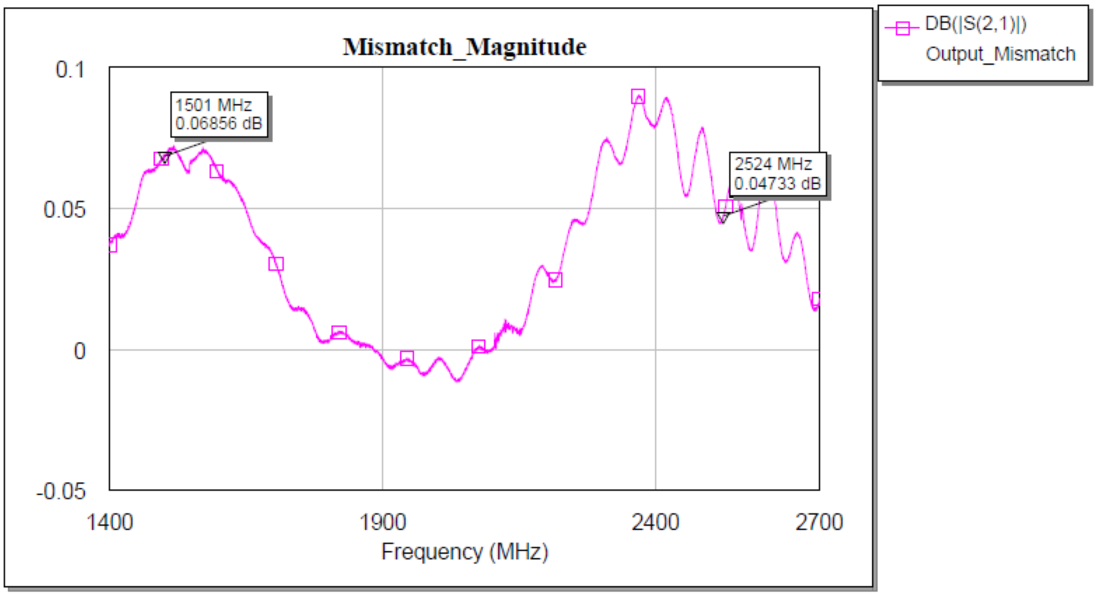

Figure 4.5: Magnitude Mismatch of the Modified Gysel Divider

end of the band, it can be claimed that the values are low and acceptable since they does not cause a degradation in the performance of the divider. In addition, it was assumed that the bandwidth and performance can be deduced from only one of the ports since the topology is symmetric and the mismatch performance proves that assumption to be true.

From these results:

It can be deduced that the series LC network not only improves the isolation performance but all the scattering parameters especially the input and output return loss have improved altogether significantly. S_{32} resides under -20 dB for a bandwidth of 51.2% for the implemented novel topology hence **131.7%**

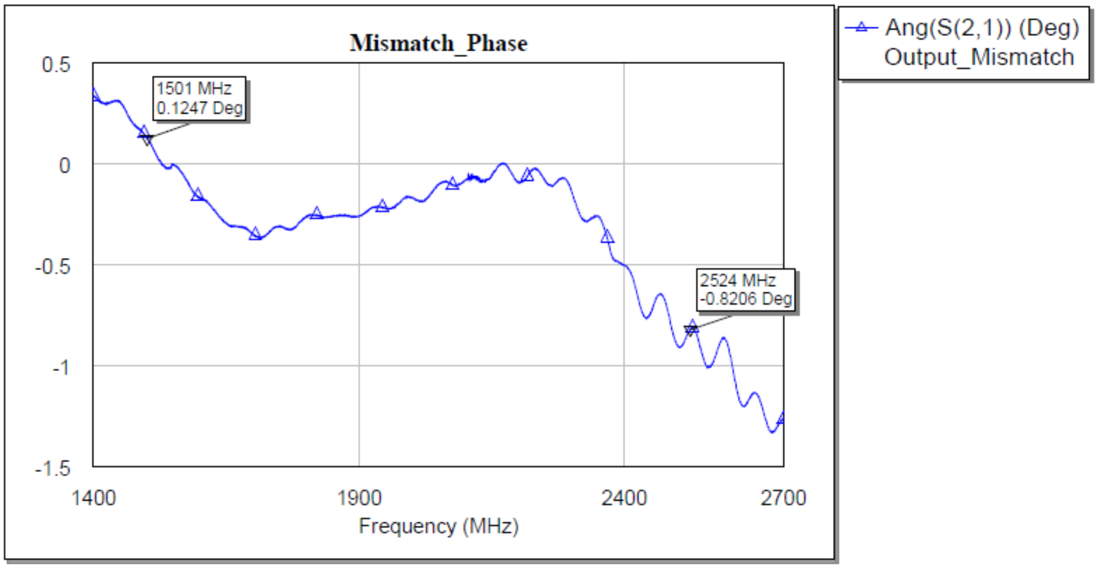

Figure 4.6: Phase Mismatch of the Modified Gysel Divider

improvement has been successfully reached with the LC bandpass filter response. The overall *divider bandwidth* is limited by S_{32} trace, and it is **51.2%**. The printed original Gysel divider has shown a narrow performance of 20.75% and the novel divider exhibited a performance of 51.2% around the same center frequency. These results ensure that the modified Gysel divider structure has demonstrated a high performance in terms of all the scattering parameters and especially a smoother isolation characteristic which was the primary aim of the modification.

Chapter 5

Extension: 3-Port and 4-Port Divider Design

In this chapter the novel topology is extended to a design proposal for 3-way and 4-way Gysel power dividers. The response of the circuits are presented and the expected improvements are discussed. The implementation of the dividers are left to a different work in the future.

5.1 3-Port Divider Design

Applying the same principles to the 3-way divider and making use of the method that was described by Ulrich Gysel [2], the topology constructed for this case in demonstrated in Figure 5.3. The important point that should not be mistaken in extending the divider to n-way topologies is that the isolation network should be interconnected and the divider should not be implemented as multiple sections but rather as a single section that directly splits into n-ways.

5.1.1 Original 3-Way Divider

Using the method of Ulrich Gysel [2], the topology for a 3-way divider is as shown in Figure 5.1.

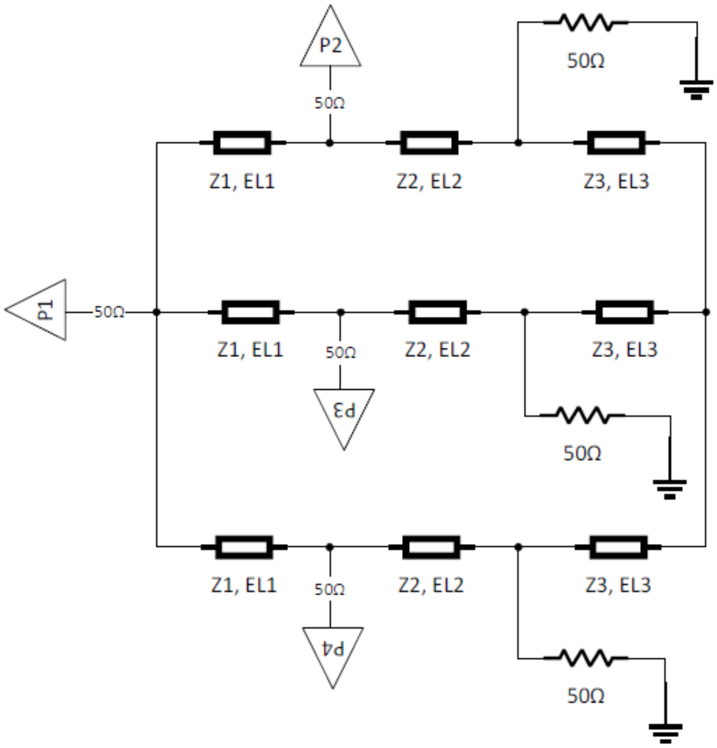

Figure 5.1: Traditional Gysel Power Divider, 3 Way

The traditional Gysel divider has a scattering parameter response shown in Figure 5.2.

The impedances of this design are demonstrated in Table 5.1.

For this original 3-way divider, S_{32} resides under -20 dB for a bandwidth of 49.3%. This is already higher than the 2-way case due to natural increase of isolation as the number of divisions increases. However, the *operation bandwidth* is limited by the input return loss (marked on S_{21} trace on Figure 5.2) and is **39.15%**. The insertion loss for this interval is lower than 5.05 dB and since it is close to the ideal value, 4.8 dB, it is in an acceptable range.

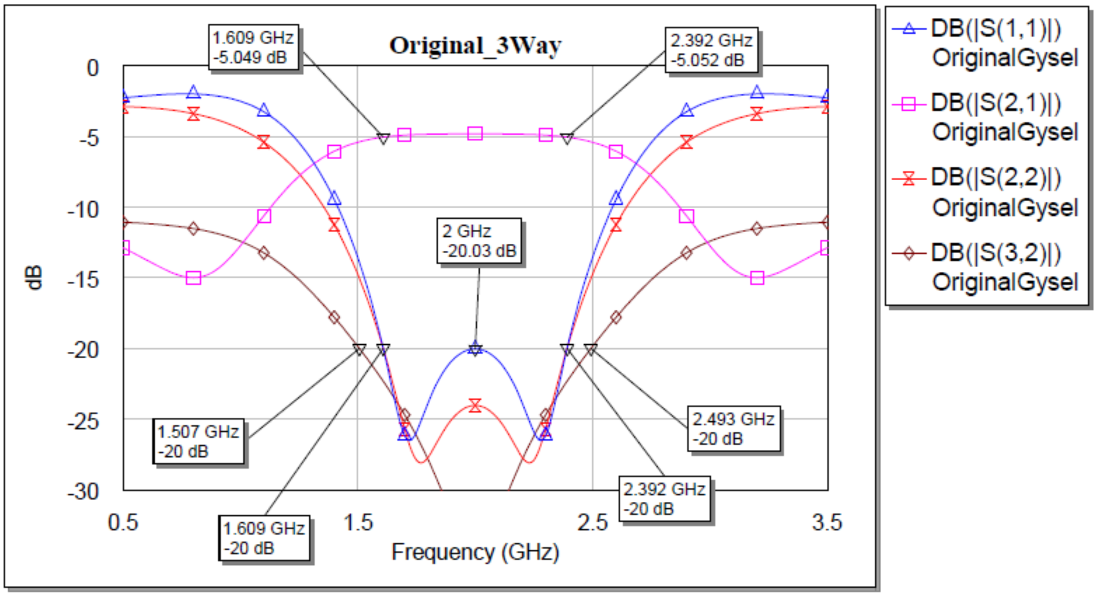

Figure 5.2: Traditional Gysel Power Divider Scattering Parameters, 3 Way

Transmission Line	Impedance(Ω)	Electrical Length(deg)
$Z1, EL1$	78.36	90
$Z2, EL2$	47.82	90
$Z3, EL3$	32.33	90

Table 5.1: The Optimum Transmission Line Parameters of the Original Gysel Power Divider, 3 Way

5.1.2 Modified 3-Way Divider

The modified design has the topology demonstrated in Figure 5.3.

Using the same methodology in 2-way design, the 3-way version is optimized in CAD. The optimization results in AWR Microwave Office are demonstrated in Table 5.2 and Table 5.3. The same criteria is applied with the single change in the criterion of the insertion loss; it should be around 4.8 dB.

The normalized values for capacitances using the same formula in Equation 3.3 are given below by Equation 5.1. The resonating inductance value can be deduced from Equation 3.1 for any frequency.

Transmission Line	Impedance(Ω)	Electrical Length(deg)
$Z1, EL1$	78.4	90
$Z2, EL2$	60.1	90
$Z3, EL3$	41.9	90

Table 5.2: The Optimum Transmission Line Parameters of the Novel Gysel Power Divider, 3 Way

Component	Capacitance (pF)	Component	Inductance (nH)
$C1$	2.92	$L1$	2.17
$C2$	1.77	$L2$	3.58

Table 5.3: The Optimum Passive Component Parameters of the Novel Gysel Power Divider at $f_C = 2$GHz, 3 Way

$$\begin{aligned} C_1(pF) &= \frac{5.84}{f(GHz)} \\ C_2(pF) &= \frac{3.54}{f(GHz)} \end{aligned} \tag{5.1}$$

The corresponding scattering parameter results are presented in Figure 5.4. Comparing the performances of two dividers, it can be observed that similar to the 2-way case the bandwidth of all scattering parameters have improved.

On the other hand, S_{32} resides under -20 dB for a bandwidth of 71.7% at 2 GHz center frequency after the LC bandpass filter effect. However, still *divider bandwidth* is limited by input and output return loss limitations and is found out to be **56.8%** (marked on S_{21} trace on Figure 5.4). On the other hand, it is a great improvement in the performance. The insertion loss has increased a little and it is now lower than only 5.3 dB, but it is still acceptable. It can be concluded that the LC network increases the performance of the Gysel topology for 3-way case too.

The Table 5.4 summarizes the bandwidth improvement of the novel topology for 3-way case.

Parameter	Original Gysel Divider	Modified Gysel Divider
$DividerBandwidth(20dB)$	39.15%	56.8%

Table 5.4: The Comparison of Original and Novel Topologies, 3 Way

5.2 4-Port Divider Design

5.2.1 Original 4-Way Divider

Using the method of Ulrich Gysel [2] again, the topology for a 4-way divider is as shown in Figure 5.5.

The original 4-way Gysel power divider has the scattering parameter as shown in Figure 5.6.

The impedance parameters for this design are slightly different than the previous cases and is demonstrated in Table 5.5.

Transmission Line	Impedance(Ω)	Electrical Length(deg)
$Z1, EL1$	90.5	90
$Z2, EL2$	45.2	90
$Z3, EL3$	30.5	90

Table 5.5: The Optimum Transmission Line Parameters of the Original Gysel Divider, 4 Way

S_{32} resides under -20 dB for a bandwidth of 60.6%. This is even higher than the original 3-way case. However, again the *divider bandwidth* is limited by the input return loss (marked on S_{21} trace on Figure 5.6) and is **37.4%**. The insertion loss for this interval is less than 6.3 dB which is close to the ideal value, 6 dB, and is in an acceptable range.

5.2.2 Modified 4-Way Divider

Applying the same principles again to construct the 4-way divider, the topology is shown in Figure 5.7 is constructed.

The optimization results in AWR Microwave Office are demonstrated in Table 5.6 and Table 5.7.

Transmission Line	Impedance(Ω)	Electrical Length(deg)
$Z1, EL1$	90.5	90
$Z2, EL2$	51.7	90
$Z3, EL3$	41.8	90

Table 5.6: The Optimum Transmission Line Parameters of the Novel Gysel Power Divider, 4 Way

Component	Capacitance (pF)	Component	Inductance (nH)
$C1$	2.9	$L1$	2.18
$C2$	2.1	$L2$	3.02

Table 5.7: The Optimum Passive Component Parameters of the Novel Gysel Power Divider at f_C = 2GHz, 4 Way

The normalized values for capacitances using the same formula in Equation 3.3 are given below by Equation 5.2. The resonating inductance value can be deduced from Equation 3.1 for any frequency.

$$\begin{aligned} C_1(pF) &= \frac{5.8}{f(GHz)} \\ C_2(pF) &= \frac{4.2}{f(GHz)} \end{aligned} \tag{5.2}$$

The corresponding scattering parameter results are presented in Figure 5.8.

Comparing the performances of two dividers, S_{32} now resides under -20 dB for a bandwidth of 69.4% at 2 GHz center frequency. However, still the *divider* *bandwidth* is defined by input and output return loss limitations and is found out to be **43.8%** (marked on S_{21} trace on Figure 5.8). The only problem that may arise in the implementation step for this divider is that the Z_1 impedance corresponds to a very narrow transmission line of width 1.1mm. This may become a factor that should be considered in the fabrication step. All in all, it can be concluded that the LC network increases the performance of the Gysel topology for 4-way case too.

The Table 5.8 summarizes the bandwidth improvement of the novel topology for 4-way case.

Parameter	Original Gysel Divider	Modified Gysel Divider
$Divider Bandwidth (20dB)$	37.4%	43.8%

Table 5.8: The Comparsion of Original and Novel Topologies, 4 Way

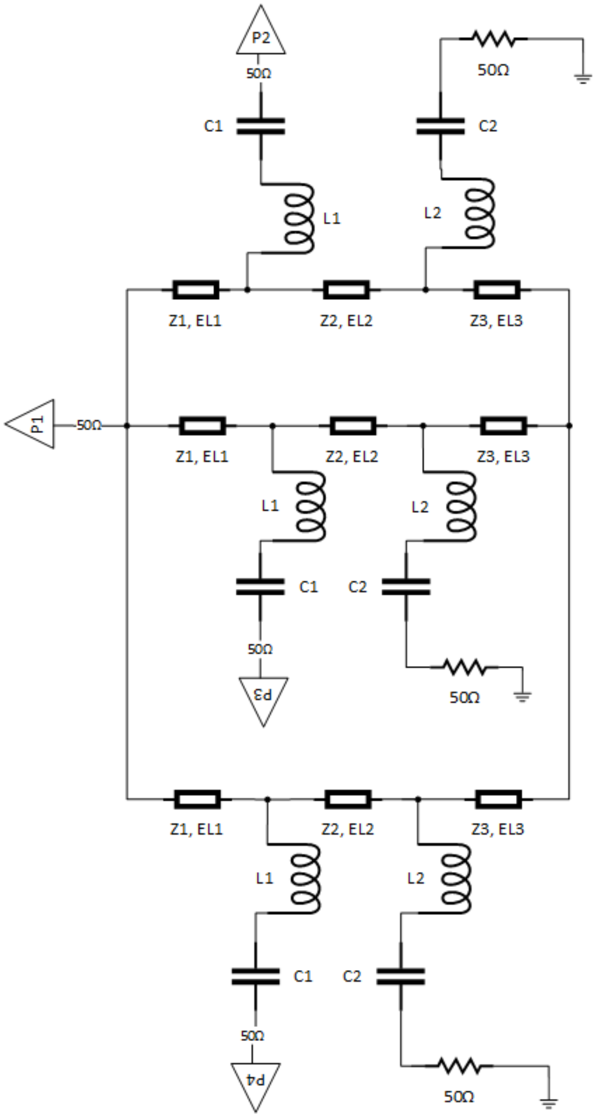

Figure 5.3: The Novel Topology for Gysel Power Divider, 3 Way

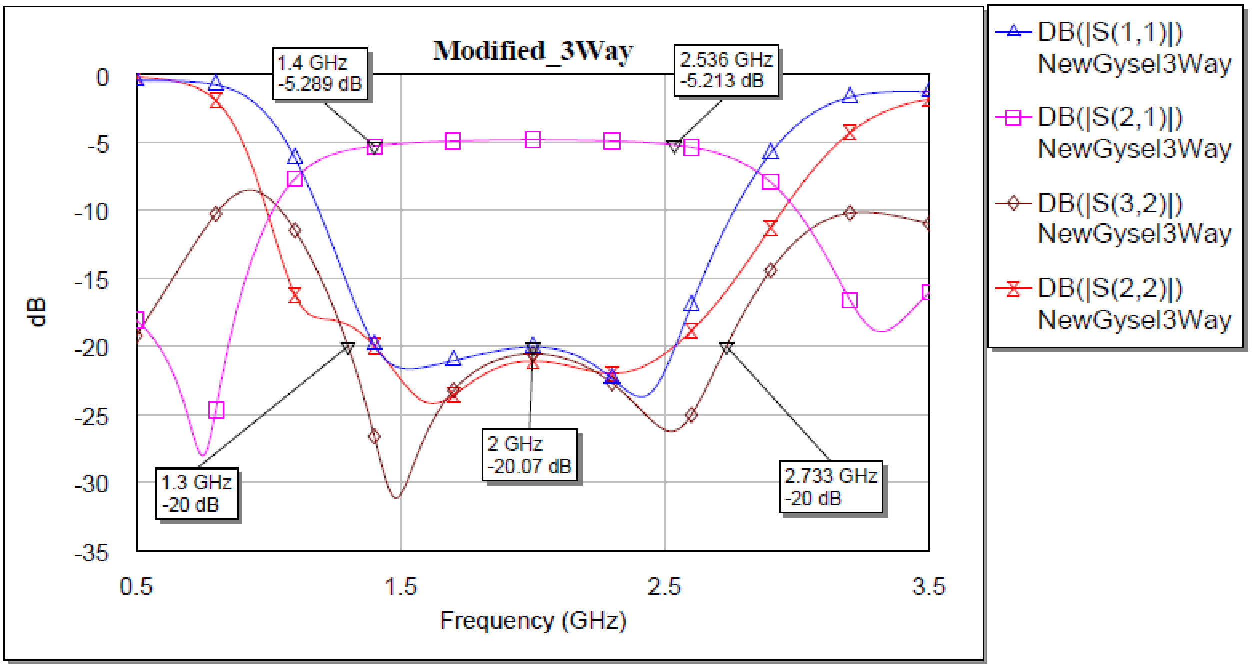

Figure 5.4: Novel Gysel Divider Scattering Parameters, 3 Way

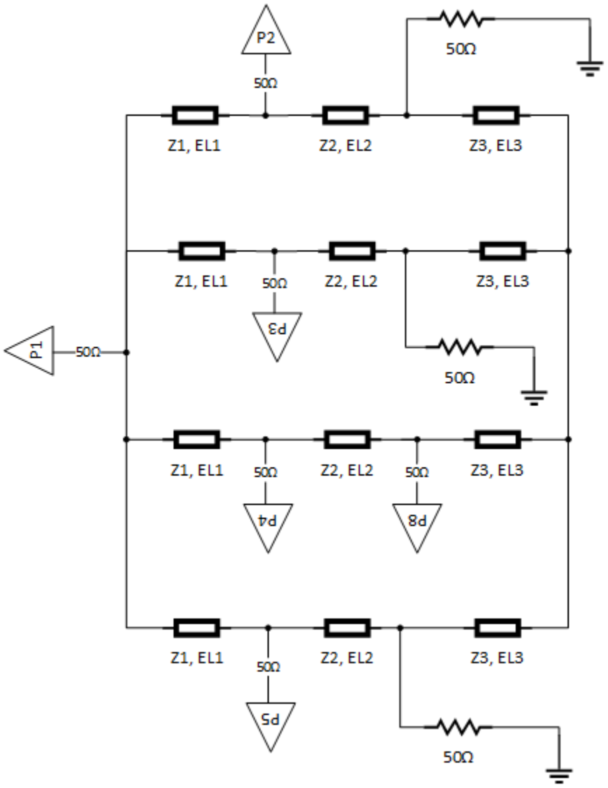

Figure 5.5: Traditional Gysel Power Divider, 4 Way

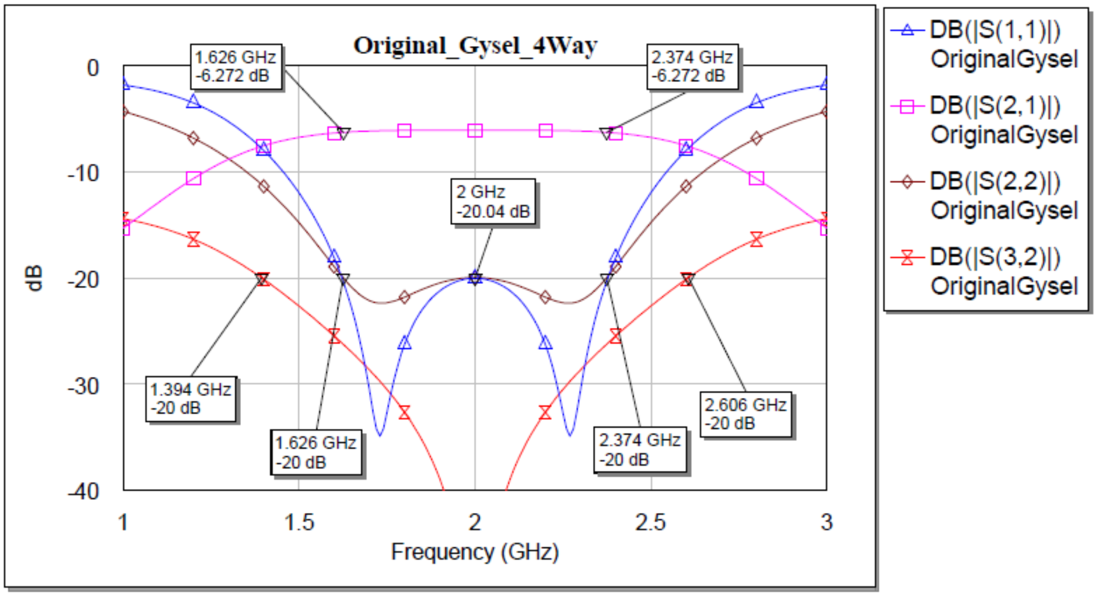

Figure 5.6: Traditional Gysel Power Divider Scattering Parameters, 4 Way

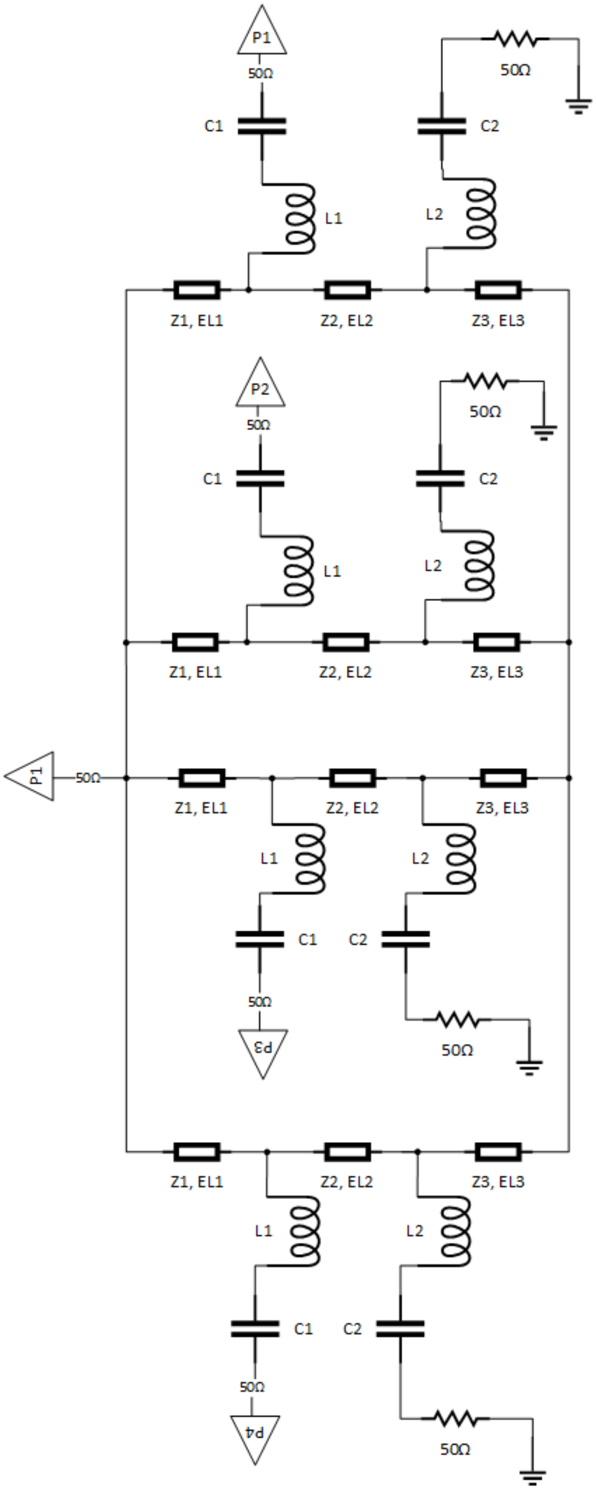

Figure 5.7: The Novel Topology for Gysel Power Divider, 4 Way

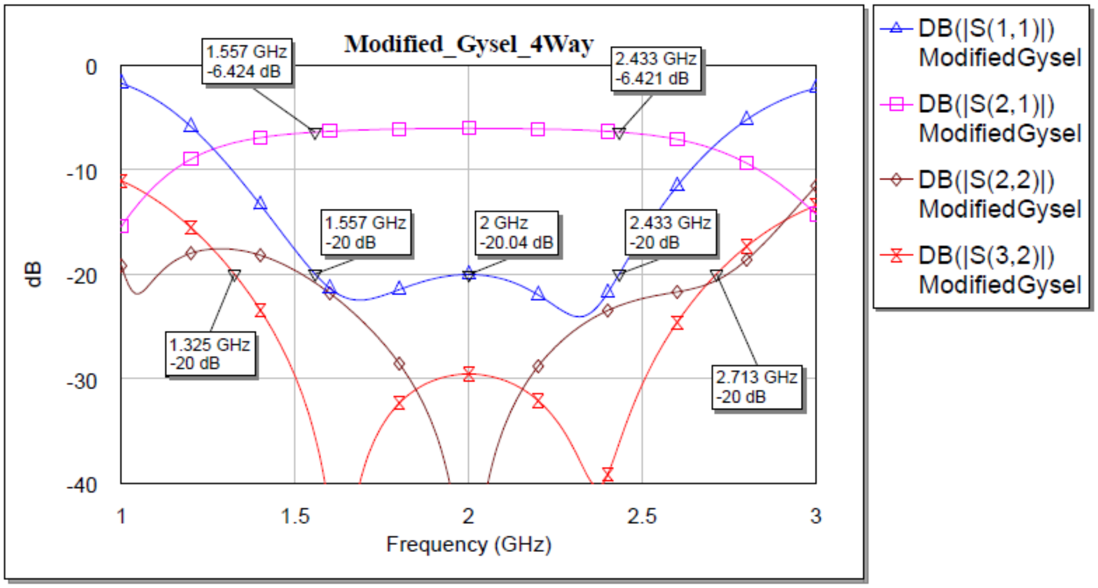

Figure 5.8: Novel Gysel Divider Scattering Parameters, 4 Way

Chapter 6

Conclusion

In this thesis, a modified Gysel power divider topology with wider bandwidth is designed. The novel design has been analysed, the limits of the proposed method is highlighted and the improvement achieved by the divider circuit is discussed. The novel Gysel divider is also implemented on a PCB and measured experimentally.

The novel 2-way design has presented improved scattering parameter characteristics in both comparing to the conventional topology and similar modified divider topologies in literature. The isolation parameter, which is the measure of reflection between the output ports, resides above 20 dB for a wide bandwidth of 51.2% at 2GHz center frequency. This value is also the divider bandwidth, and the improvement is 146.7%. This property makes the topology utilizable for modern wireless communication systems, that already require high-performance characteristics.

Another advantage of this 2-way topology is that all scattering parameters, have also demonstrated an increased performance level, increasing the bandwidth. In addition, the mismatch of the output ports are in acceptable range so the reciprocity of the circuit could be preserved as desired.

A disadvantage that the topology brings is that the width of the PCB has to be increased to open up a space for the series LC structure. For applications that require strict dimension requirements, this can be a potential problem.

Considering the n-way case for this modification; even though the isolation parameter continuously increases due to the added new branches, the method demonstrated to have limitations on other scattering parameters. The effect of the modification has shown itself especially on improvement in the input and output return loss, which can be a possible discussion for further investigations. Nevertheless, the series LC network improves the performance of the topology for simulated n-way cases which is the strength of the design.

To sum up, together with the power handling capacity of the implementation, the novel Gysel power divider design has contributed to the literature as it was aimed to have. Due to the much wider bandwidth of operation, the novel divider will improve the performance of the communication system.

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