Design of Tuning-Matching Box for NMR Coil

A project report

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Master of Technology

Under the guidance of

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Thesis Certificate

This is to certify that the thesis titled **Design of Tuning-Matching Box for NMR Coil**, submitted by **Akshay S. Petkar**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Abstract

The aim of the project was to design a tuning-matching network for a 2-port NMR load. The approach taken to do so was to replicate the behavior of the already available tuning-matching box which is working for a different range of frequencies. The idea was to understand the working of already available box. The reason to take this approach of replicating, instead of a direct design for the load was because the circuit of the 2-port load to be matched was unknown. Different 3-port circuit models have been used and the behavior of the tuning-matching box is tried to be replicated by calculating the values of the circuit components of the assumed model using the y-parameters of the tuning-matching box.

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Chapter 1

Introduction

1.1 Basic Concept of NMR

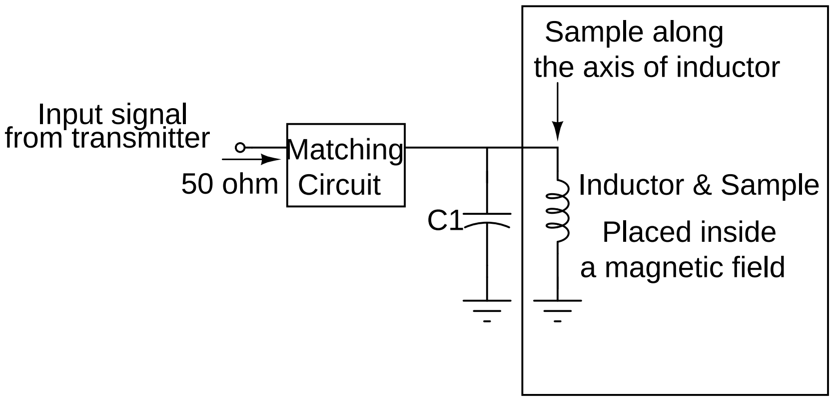

Figure 1.1: NMR System

Nuclear Magnetic Resonance (NMR) system consists of a transmitter, a tuning-matching network, a receiver, an inductor and a sample (in a solution form) placed along the axis of the inductor in a test-tube. The transmitter and receiver have not been shown in the figure 1.1 .

The inductor and the sample are placed in a magnetic field and an input signal is applied in presence of this magnetic field. Depending on the sample present inside the test-tube, the NMR system responds to the input for a particular frequency of the input signal. This response is received by the receiver and is further used to understand the molecular composition of the sample being used.

When the sample inside the test-tube changes, the frequency of input signal for which the NMR system gives a non-zero response, also changes.

1.2 Need of a Tunable Matching Network

Matching network satisfies it's usual purpose of converting the load impedance to 50 Ω so that maximum power is transferred from the transmitter to the load.

The way in which the matching happens is shown in fig1.1. The capacitor C1 resonates out the load inductor. The remaining network then converts the load resistance to 50 Ω.

The matching-network needs to be tunable, i.e., the frequency at which the circuit matches the load to 50 Ω should be able to be varied. The reason for this is straightforward. As the sample changes, the frequency at which the system will respond to the input, will also vary. Thus, a single matching network should be able to convert the load to 50 Ω at different frequencies. In-order to do so, the capacitor C1 & the capacitor used inside the matching-circuit need to be mechanically tunable.

Chapter 2

S-Parameter Measurements, Observations, Conclusions

2.1 Internal Structure of NMR 2-Port

The NMR has got two input ports. The information available is that, there exists an inductor in between these two ports.

The inductor is 2.3 μH value, with an internal resistance of 0.7 Ω. Thus, basically, the structure available is as shown in figure 2.1 .

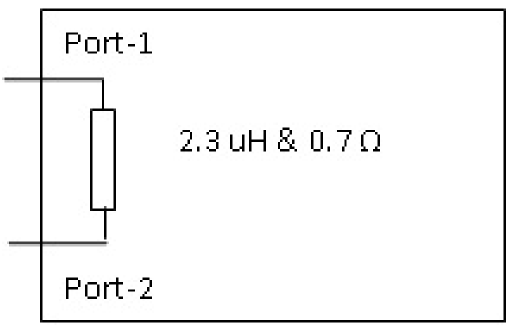

Figure 2.1: NMR

2.2 Possible Matching Techniques

How is matching supposed to be done, needs to be figured out.

2.2.1 Both NMR-Coil Input Ports Matched

There could be a possibility that the inductor is center-tapped. Thus, each port would then appear as a load of an inductor of value 1.15 μH in series with a resistance of value 0.35 ohm, and each of the ports would be needed to match to 50 Ω.

2.2.2 One of the two NMR-Coil Input Ports Matched

Another possible scenario is where the inductor is not center-tapped. Both the NMR ports are not necessarily matched to 50 Ω.

There could be a possibility that one of the ports is terminated into a reactance and looking in from the other port, whatever input impedance is seen, that impedance would be finally matched to 50 Ω through a suitable matching network.

To understand how matching is done, it is first needed to measure the input impedance of each NMR input port and each matching box output port.

2.3 Effect of Isolation between the Ports on the Input Impedance

The impedance seen looking into any port of network depends on the terminations at other ports of the network. The terminations at the other ports are sometimes insignificant if there is sufficient isolation between the port of interest and the rest of the ports in the network. Thus, it is needed to see how much isolated the ports of the network are from each other.

2.3.1 Isolation between Ports 1 and 2 of tuning-matching box (TMB)

The tuning-matching box (TMB) is a 3-port passive network. It is needed to see how much isolated the two output ports of TMB are from each other.

The circuit arrangement used is shown in figure2.2

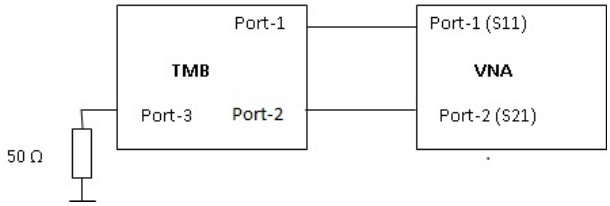

Figure 2.2: Arrangement used to measure S21 for TMB

Port-3 is terminated into 50 ohm and port-1 & port-2 are connected to the 2-ports of the Vector Network Analyser (VNA).

The TMB is first tuned to 14 MHz and then the S_{21} for the TMB is measured over the frequency range of 12 MHz to 16 MHz. The plot of S_{21} thus obtained is shown in figure 2.3

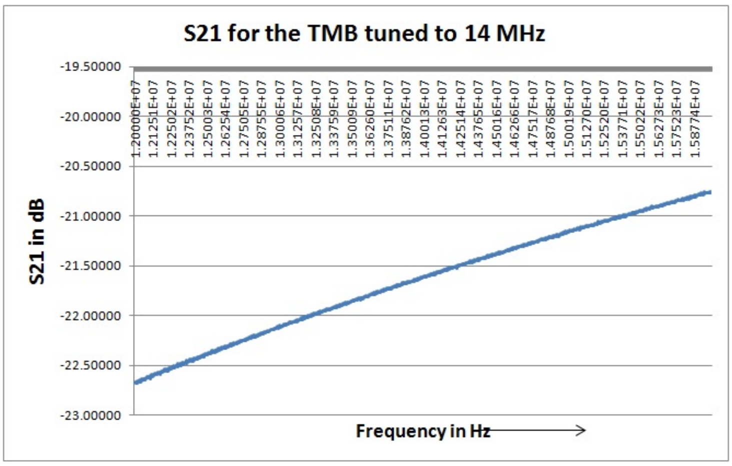

Figure 2.3: S_{21} when TMB is tuned to 14 MHz

As can be seen in the graph, S_{21} lies in the range from -22.5 dB to -20.5 dB throughout the frequency range. On the basis of the S_{21} value, it can be assumed that the port-1 & port-2 of the TMB are reasonably isolated from each other.

2.3.2 Isolation between Ports 1 and 2 of NMR

The circuit arrangement used is shown in figure 2.4

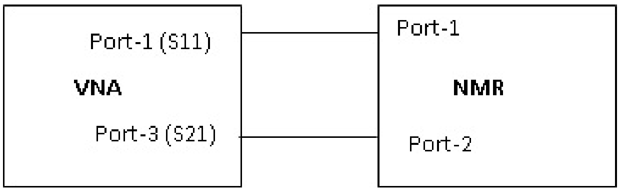

Figure 2.4: Arrangement used to measure S21 between 2-Ports of NMR-Coil

The S_{21} between two ports of NMR-Coil is plotted for the frequency range of 12 MHz to 16 MHz. The plot is as shown in figure 2.5

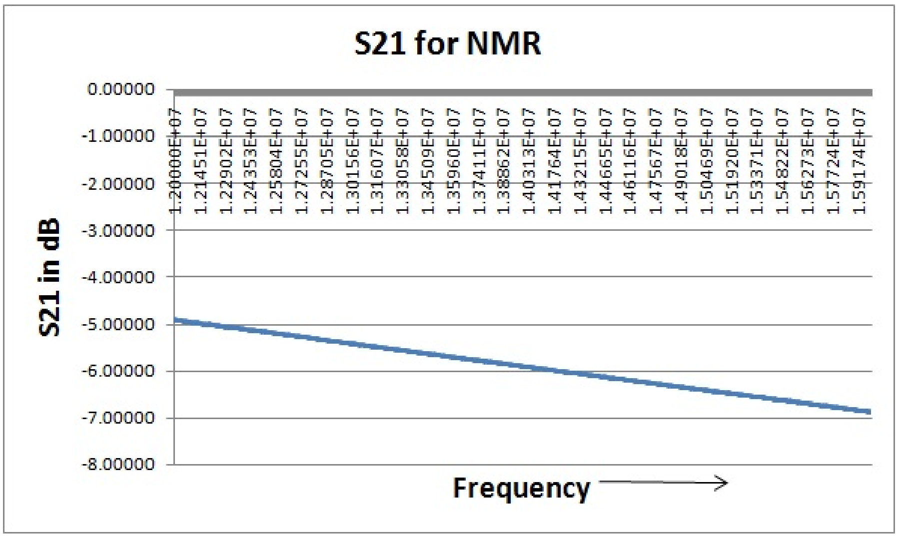

Figure 2.5: S_{21} between two ports of NMR-Coil for the frequency range 12-16 MHz

Here, it can be seen that S_{21} ranges between -7 dB to -5 dB over the complete frequency range. This S_{21} value is large and is as expected, because, an inductor is expected to be present between two ports of the NMR and thus the two ports will not be well isolated from each other.

2.4 General Condition to Confirm Matching

For any matching network, following is true, as shown in figure 2.6 .

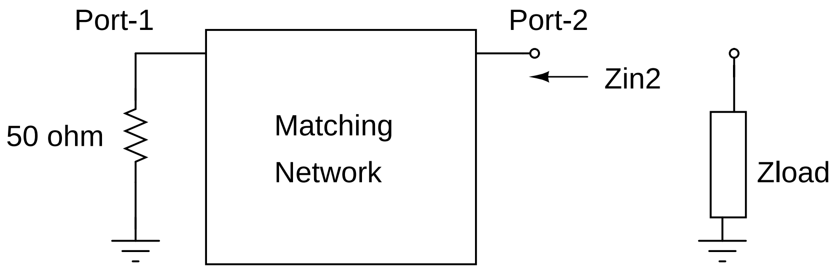

Figure 2.6: A general matching-network

Z_{load} is the load impedance. The matching network is designed such that, when Z_{load} is connected to the port-2 of the matching network, then, Z_{in1} seen should be 50 Ω for the resonant frequency for which the matching network has been designed.

Similarly, when port-1 of the matching network is terminated in 50 Ω and Z_{in2} is measured at the resonant frequency for which the network has been designed, then it is observed that, $Z_{in2} = Z^*_{load}$. This is the condition to check matching. This condition is used to determine which of the two NMR ports has been matched to 50 ohm through the TMB.

For doing this, first the input impedance of port-1 & of port-2 of the TMB and NMR need to be obtained.

2.5 Z_{in} Measurement for Port-1 & Port-2 of TMB

To obtain the input impedance, following arrangement is used, as shown in figure 2.7

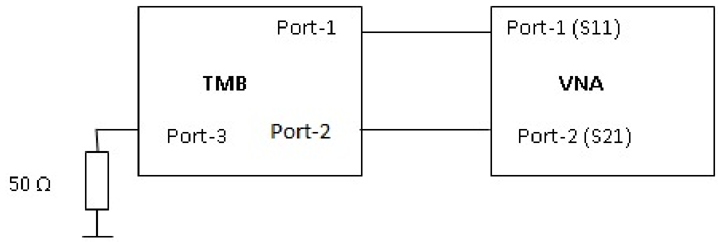

Figure 2.7: Arrangement used to measure Z_{in} for ports of TMB

Here, the value of S_{11} that has been measured will be used to calculate $Zin1$ when port-1 of the TMB is connected to the S11-port of the VNA.

The question is, what termination should be used at port-2. Since, ports 1 and 2 of the TMB are reasonably isolated from each other as was observed in the figure 2.2 , the impedance looking into port-1 should not be affected much by the termination at port-2.

A 50 ohm termination is used at port-2 of TMB, i.e. port-2 of TMB is connected to S_{21}-port of VNA. S11 for TMB is measured using VNA. The corresponding input impedance of port-1 (Z_{in1}) value at 14 MHz (the frequency at which TMB is tuned) thus obtained is listed in table-2.1

Similarly, the input impedance of port-2 (Z_{in2}) of the TMB is measured using VNA and the value of Z_{in2} at the frequency of 14 MHz is listed in table-2.1 .

Impedance	Value at 14 MHz
Zin1	0.64-j39.3
Zin2	2.95-j45.6

Table 2.1: Values of input impedances of port-1 and port-2 of TMB

2.6 Z_{in} Measurement for Port-1 & Port-2 of NMR

It is needed to measure the input impedance of the port-1 & port-2 of NMR. If say, port-1 input impedance is being measured, then, the termination at port-2 will affect the value of Z_{in} seen looking into port-1, since, the two ports of NMR are not well isolated from each other.

When the NMR and TMB are actually being used for experiments, the port-2 of NMR is connected to the port-2 of the TMB. Thus, here, while measuring the input impedance of port-1 of NMR, it makes sense to connect the port-2 of NMR to the port-2 of TMB.

Similarly, while measuring the input impedance of port-2 of NMR, port-1 of NMR will be connected to the port-1 of TMB. The circuit arrangement for measuring port-1 impedance is shown in figure 2.8

Using the S_{11}& S_{22} values of NMR, Z_{in1} & Z_{in2} of NMR are obtained. The values of Z_{in1} & Z_{in2} at the frequency of 14 MHz have been tabulated in table 2.2

Impedance	Value at 14 MHz
Zin1	157-j265
Zin2	30.7-j222

Table 2.2: Values of input impedances of port-1 and port-2 of NMR-Coil

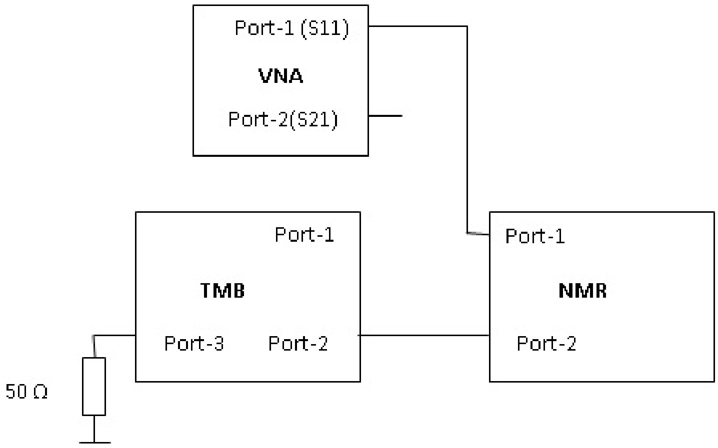

Figure 2.8: Arrangement used to measure Z_{in1} for NMR-Coil

2.7 Matching-Confirmation Condition Check for Two Ports of NMR-Coil

In-order for Zin of port-1 of NMR-Coil to be converted to 50 ohm through the matching network it is needed that,

$$Z_{in1,NMR} = Z^{*}_{in1,TMB} \tag{2.1}$$

However, referring to the table-2.1 and table-2.2, it is seen that the above condition is not satisfied.

Further, it is needed to be checked if the Zin of port-2 of NMR is converted to 50 ohm through the matching network. The condition required here would be,

$$Z_{in2,NMR} = Z^{*}_{in2,TMB} \tag{2.2}$$

However, referring to the table-2.1 and table-2.2, it is seen that the above condition is not satisfied.

Thus, it seems that neither of the two ports of NMR are getting converted to 50 Ω. This could mean that either the measurement could have gone wrong somewhere or actually, none of the two ports have been individually matched to 50 Ω.

2.8 Possible Case of Wrong S-Parameters

The Z_{in1} and Z_{in2} measurement will be wrong when the S_{11} and S_{21} are measured with improper terminations at the remaining ports of TMB.

Consider, S_{11} for TMB is being measured. When this S_{11} is measured, the port-2 is terminated into 50 Ω. What the termination at port-2 is, shouldn't matter since, for TMB, port-1 and port-2 are reasonably isolated from each other as observed from the values of S_{21} earlier. However, this isolation which seems to be sufficient might not actually be sufficient enough and the termination at port-2 might be affecting the Z_{in} looking into the port-1. Then in such a case, port-2 should be appropriately terminated.

When the NMR and TMB are actually being used practically, the port-2 of TMB is connected to the port-2 of NMR. Thus, here, instead of 50Ω termination, it is chosen to terminate port-2 of TMB into port-2 of NMR. The circuit arrangement is as shown in figure 2.9

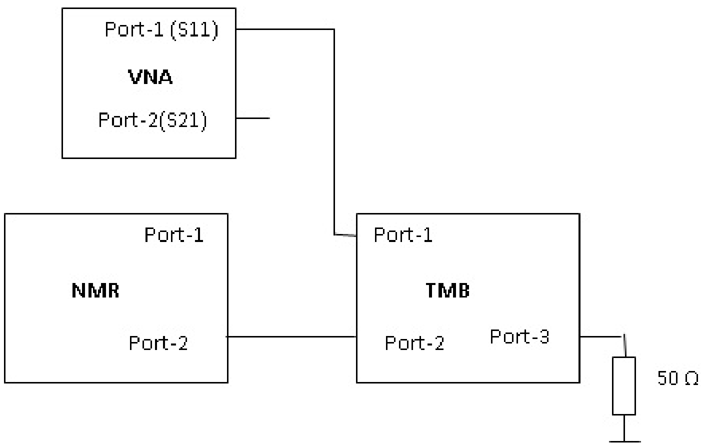

Figure 2.9: Arrangement used to measure S_{11} for TMB

However, even this termination won't be accurate. In this arrangement, as seen in figure 2.9 , the port-1 of NMR remains open and we know that the impedance looking into the port-2 of NMR will depend on the termination at port-1 of the NMR, since, the two ports of NMR are not well isolated from each other.

Practically, impedance looking into port-2 of NMR is the value of impedance when port-1 of NMR is terminated into port-1 of TMB. However, here, the port-1 of TMB is actually being connected to the S11 port of VNA and port-1 of NMR is remaining open, thus not getting terminated properly. And, because of this improper termination of port-1 of NMR, the impedance looking into port-2 of NMR remains incorrect, thus, leading to improper termination of the port-2 of the TMB when it is connected to the port-2 of NMR.

Thus, if isolation between port-1 and port-2 of TMB is not sufficient enough, then there is no way to obtain correct Zin1 and Zin2 for the ports 1 & 2 of the TMB respectively.

On the other hand, if the isolation between port-1 and port-2 of TMB is sufficient and the terminations shouldn't matter, then, neither of the two ports of NMR have been individually matched to 50 Ω.

Chapter 3

Modeling of NMR-Coil Two-Port

3.1 Expected NMR 2-port circuit

A coil of value 2.3 μH with resistance of value 0.7 Ω is expected to be present between the two ports of NMR. Initially, it was expected that, one of these two ports will be terminated into a reactance, and the other port will be matched to 50 Ω through a matching network.

However, as seen in the previous chapter, it turns out that this is not happening. None of the two ports seem to be matched to 50 Ω.

3.2 Matching Method for an Inductor Load

To move ahead, it becomes essential to understand the network which is present between the two ports of NMR.

If a simple inductor is present between two ports of NMR, then matching can be done as shown in figure 3.1

Here, the capacitor C1 that has been used, it can be a mechanically tunable capacitor. Depending on what resonant frequency is required, the C1 value can be

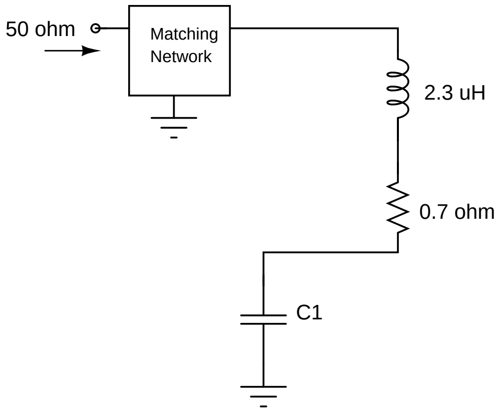

Figure 3.1: Matching a load inductor

adjusted and it will resonate out the inductor.

Later, what remains back is the resistance of 0.7 Ω. This can be matched to 50 Ω using any standard matching network. The matching network with a mechanically tunable capacitor can be used. The value of this capacitor can be adjusted in-order to set the resonant frequency of the matching network. In this way, a tuning-matching network working over a required frequency range can be obtained.

After conceptually understanding how we can proceed to design a tuning-matching network for an inductive load, what remains is to make sure if the load itself is a single inductor with some internal resistance or is the load somewhat more complicated.

3.3 Method to Confirm the Presence of Only an Inductor between Two NMR Ports

Assuming only an inductor with some series internal resistance is present, following is done, figure 3.2

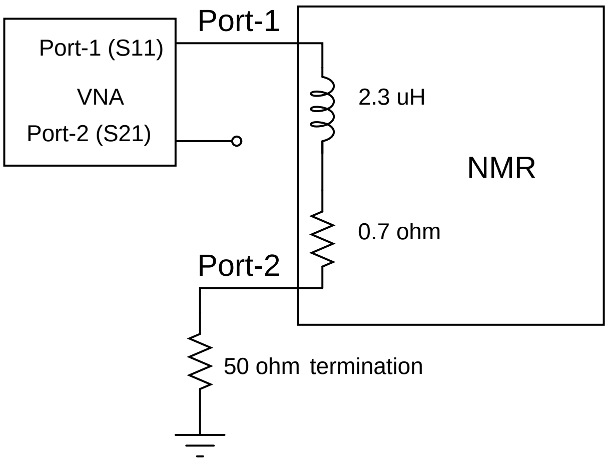

Figure 3.2: A method to check if there is just an inductor inside NMR 2-port

S11 is measured for above arrangement and correspondingly, Zin_1 is calculated using the following formula,

$$Zin_1 = Z0 \left\{ \frac{1 + S11}{1 - S11} \right\} \tag{3.1}$$

Here, the expected value of Zin_1 is,

$$Zin_1 = (50.7 + j\omega \times 2.3 \times 10^{-6})\Omega \tag{3.2}$$

Throughout the frequency range, the real part of Zin_1 should remain fixed and imaginary part should be positve and increasing with frequency.

However, the Zin1 value obtained over the frequency range of 12 MHz to 16 MHz is as shown in figure 3.3 and figure 3.4

Here, the real part of Zin_1 is decreasing with increase in frequency and throughout the frequency range, the value of the real part remains below 50 Ω. The imaginary part value is increasing with increase in the frequency, however, the value of the imaginary part remains negative throughout the frequency range.

The above observation makes it clear that, network between the two ports of NMR is not a simple inductor with some internal resistance. The network between two ports of NMR is more complicated.

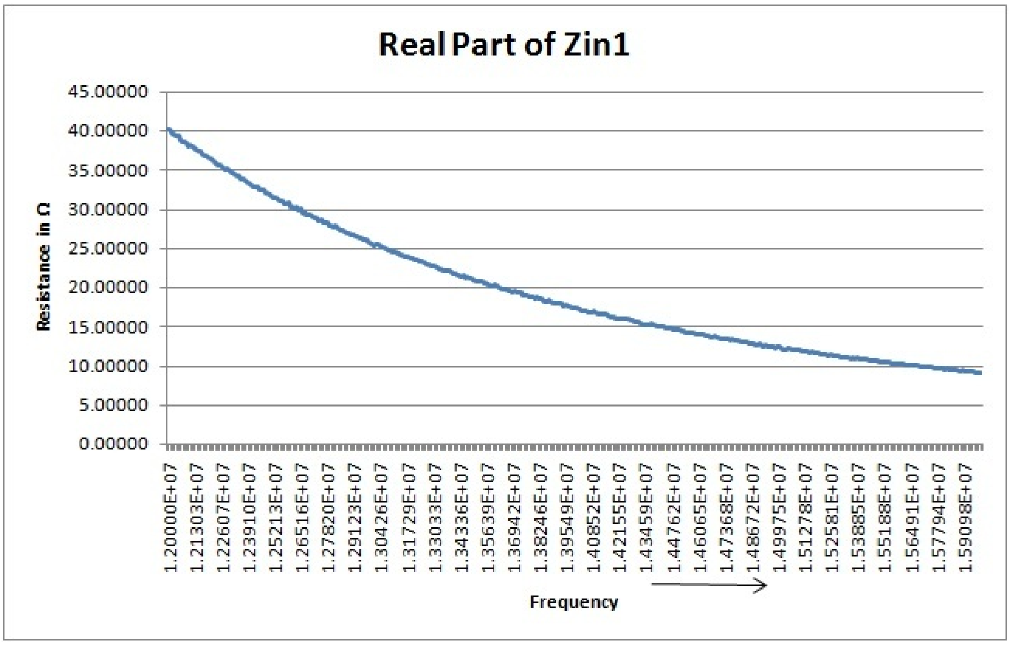

Figure 3.3: Real Part of input-impedance of NMR Port-1

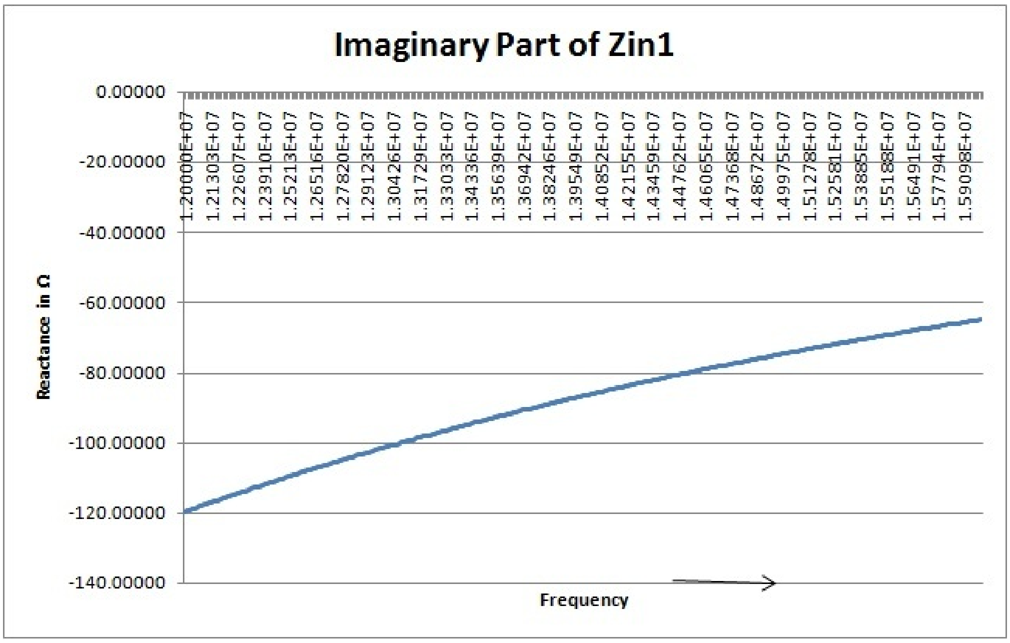

Figure 3.4: Imaginary Part of input-impedance of NMR Port-1

3.4 Possible Reactance in Parallel with 50 Ω

As seen in figure 3.3 , throughout the frequency range, the real part of Z_{in1} remains to be less than 50 Ω. This indicates that some reactance is present in parallel with the 50 Ω termination used at port-2.

This parallel reactance should be a capacitor. The reason for reactance to be capacitor is that, as frequency increases, the value of the real part decreases. We know that,

$$R_s = \left(\frac{R_p}{1+Q^2}\right) \tag{3.3}$$

For a parallel combination of capacitor and resistor, the quality factor is given by, $Q = \omega R_p C_p$

As observed from above two equations, if a capacitor is present across 50 Ω termination, then the quality factor Q increases with frequency and the resistance Rs decreases with frequency.

It is also possible that some extra internal resistance is present across the capacitor. The possible network can thus be as shown in figure 3.5

Further, the impedance looking into port-2 is calculated with port-1 terminated with 50 Ω resistance. It turns out that Z_{in2} is exactly same as Z_{in1}, thus, showing that the NMR two port is symmetric.

Thus, the circuit model shown in figure 3.6 , can be present between NMR two ports.

3.5 NMR Two-Port Model in terms of Passive Components

There can be an impedance present in parallel with the 2.3 μH inductor in between port-1 and port-2. Thus, NMR 2-port network is modeled as shown in figure 3.7 .

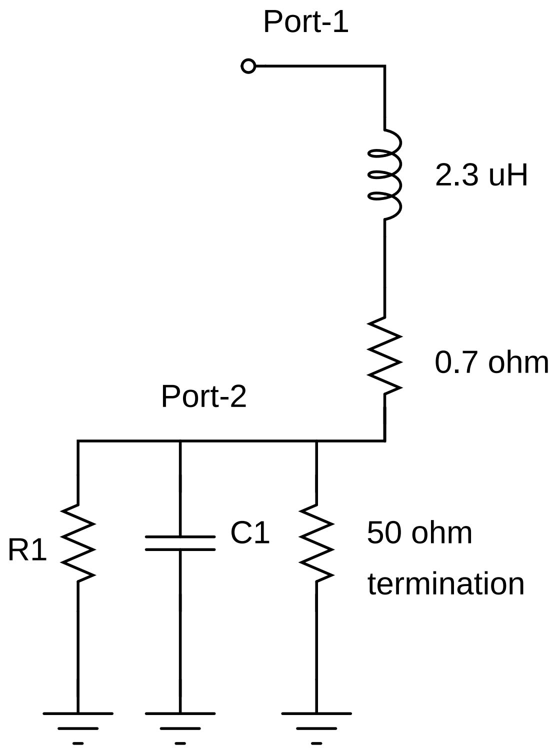

Figure 3.5: Presence of a reactance across 50 Ω termination at port-2 of NMR

Ideally, R1, R2, X1 & X2 shouldn't have been present. But because of non-idealities of circuit components, it is possible that R1, R2, X1 & X2 are present. But even then, they should have minimum interference with the working of the entire circuitry.

Since these unknown components are showing considerable effect on the Z_{in} values seen for each of the two ports, it is possible that the manufacturer of NMR equipment has put those components in the two port network. However, there is no information about the need to put those components over there, and neither is there any information about the values of the components.

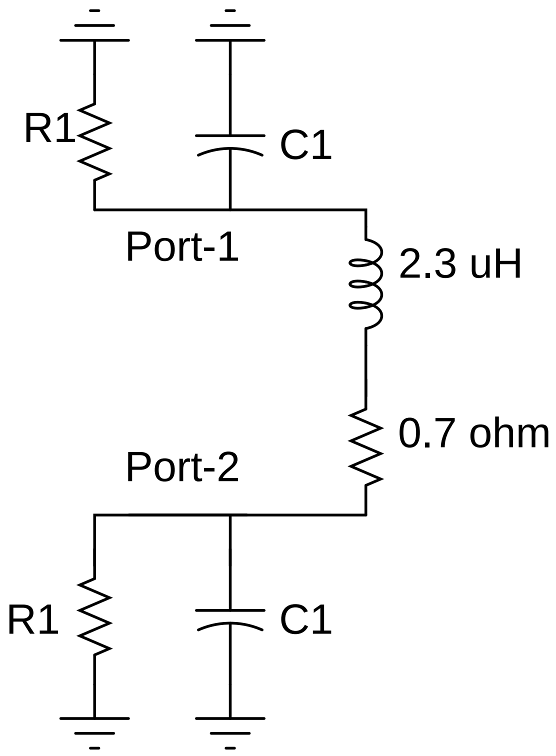

Figure 3.6: Possible NMR 2-port Model

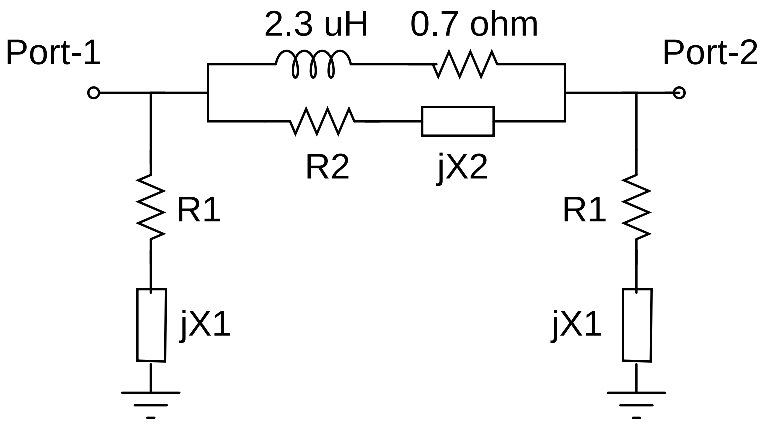

Figure 3.7: Assumed NMR 2-Port Model

3.6 Calculation of R1, R2, X1 & X2

It is needed to find out the values of R1, R2, X1 & X2. The two-port network has got fixed values of components. If the model being considered is appropriate, then throughout the frequency range, the values of R1 and R2 and the capacitor/inductor corresponding to X1 and X2 should evaluate to fixed values.

To calculate values of the unknown components, z-parameters of the 2-port network are required.The z-parameters are calculated using following formulae,

$$Z_{11} = [\frac{(1+s_{11})(1-s_{22})+(s_{12})(s_{21})}{\Delta s}] \tag{3.4}$$

$$Z_{12} = \frac{2 \times s_{12} \times Z_0}{\Delta s} \tag{3.5}$$

3 different frequencies are chosen. Table-3.1 lists the s_{11} and s_{12} values for NMR.

Frequency	**S11 (S22)**	**S12 (S21)**
13 MHz	$0.52 - j0.63$	$-0.41 - j0.34$
14 MHz	$0.44 - j0.72$	$-0.43 - j0.26$
15 MHz	$0.33 - j0.79$	$-0.44 - j0.19$

Table 3.1: s-parameter values of NMR 2-port at three frequencies

Using eq.3.4 & eq.3.5 , z-parameters are calculated and listed in table-3.2 .

Z_{11} and Z_{12} are expressed in terms of the circuit components. With two complex-valued z-parameters, four constants are available at any chosen frequency. At this frequency, when z-parameters are expressed in terms of unknown circuit components, equations are obtained for four constants and the number of unknowns also is four. These equations are solved and the values of unknown components are thus obtained.

Frequency	**Z11 (Z22)**	**Z12 (Z21)**
13 MHz	$83.03 + j45.7\Omega$	$42.91 - j35.44\Omega$
14 MHz	$57.49 + j57.31\Omega$	$4.97 - j27.27\Omega$
15 MHz	$34.29 + j62.68\Omega$	$45.82 - j19.43\Omega$

Table 3.2: z-parameter values of NMR 2-port at three frequencies

The values obtained for R1, R2, X1, X2 are tabulated in table-3.3 .

Frequency	**R1**	**X1**	**R2**	**X2**
13 MHz	0.94Ω	0.22 nF	-13.8Ω	6.25 uH
14 MHz	0.7Ω	0.22 nF	-7.18Ω	4.77 uH
15 MHz	0.76Ω	0.23 nF	-9.39Ω	3.62 uH

Table 3.3: Calculated component values for 2-port model assumed for NMR

Here, two observations are made from table-3.3 ,

1. The resistances calculated for the 2-port model of NMR are negative. However, in any practical passive circuit, negative resistances cannot be there.

2. Throughout the frequency range, the values calculated for the components are not remaining constant.

But, if the model assumed is correct, then the calculated values of the components should remain positive and constant throughout the frequency range. Since, this is not happening, it can be concluded that the model assumed is not correct.

A different model should be tried. Also, it can be tried to increase the number of components and then solve for them. This makes figuring out the NMR two-port circuit, even more difficult. With the current assumed model, it is unable to figure out the NMR 2-port circuit.

Chapter 4

Replication of TMB Behavior

As seen in the earlier chapter, the 2-port network existing between the NMR 2-port is not known completely. For designing a matching network, it is needed to know what load is being matched to the refernce impedance through the matching-network. Here, the load being matched is NMR 2-port and what exactly this load is, is not known.

4.1 Need of Replicating the available TMB Behavior

A different approach is now taken in-order to come up with a suitable matching network for NMR. It is decided to build a matching-network, which replicates the TMB behavior over complete frequency range of 13 MHz to 15 MHz.

But, it is needed for us to build a matching-network for different set of frequencies, i.e. 4 MHz to 6 MHz, then how would replicating the TMB in the range of 13 MHz to 15 MHz help?

The purpose for replicating the TMB in 13 MHz to 15 MHz range, is that, once such a network is build, the interconnections between the components will give an idea about how the circuit is working. It will tell, how the changes in values of particular components affect the circuit behavior.

Further, using this same circuit and loading it with NMR 2-port for a frequency range of interest, i.e, 4 MHz to 6 MHz, the circuit component values can be changed and the amount of matching thus obtained be observed.

4.2 3-Port Y-parameter model and S-to-Y Conversion

The Tuning-Matching Box (TMB) is a 3-port network. This 3-port network is represented in terms of y-parameters as shown in figure 4.1

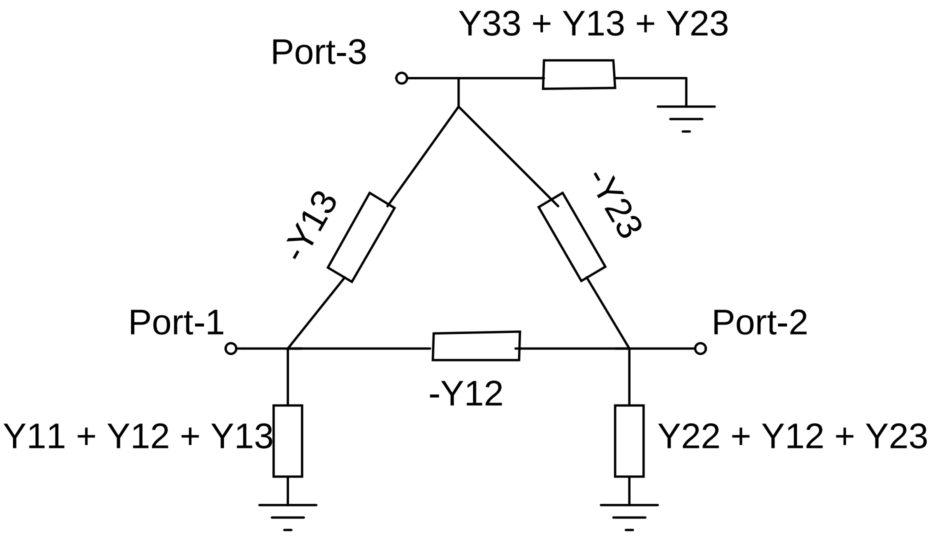

Figure 4.1: Y-parameter Model of a 3-Port Network

The s-parameters for the TMB at 13, 14 and 15 MHz are listed in table 4.1 .

Parameter	**13 MHz**	**14 MHz**	**15 MHz**
S_{11}	$-0.56 - j0.79$	$-0.26 - j0.95$	$-0.08 - j0.98$
S_{22}	$0.05 - j0.95$	$-0.08 - j0.94$	$-0.20 - j0.91$
S_{33}	$0.21 - j0.94$	$0.1 - j0.94$	$-0.02 - 0.94$
S_{12}	$0.07 - j0.02$	$0.08 - j0.01$	$0.09 - j0.01$
S_{13}	$0.003 + j0.008$	$0.004 + j0.01$	$0.005 + j0.015$
S_{23}	$0.25 + j0.03$	$0.29 - j0.001$	$0.32 - j0.042$

Table 4.1: s-parameters of TMB for three different frequencies

Parameter	**13 MHz**	**14 MHz**	**15 MHz**
Y_{11}	$1.00 + j38.7 \quad mS$	$0.40 + j26.28 \quad mS$	$21.99 + j21.89 \quad mS$
Y_{22}	$0.2 + j019.71 \quad mS$	$0.31 + j22.81 \quad mS$	$0.46 + j26.61 \quad mS$
Y_{33}	$0.14 + j016.54 \quad mS$	$0.19 + j18.92 \quad mS$	$0.25 + j21.85 \quad mS$
Y_{12}	$-0.06 - j2.22 \quad mS$	$-0.06 - j2.14 \quad mS$	$-0.07 - j2.32 \quad mS$
Y_{13}	$0.01 + j0.20 \quad mS$	$0.01 + j0.25 \quad mS$	$0.02 + j0.34 \quad mS$
Y_{23}	$-0.11j4.68 \quad mS$	$-0.15 - j6.03 \quad mS$	$-0.22 - j7.89 \quad mS$

Table 4.2: y-parameters of TMB for three different frequencies

The s-parameters are converted to y-parameters using following conversion formula,

$$Y = \sqrt{y}(I - S)(I + S)^{-1}\sqrt{y} \tag{4.1}$$

- $\sqrt{y}$: Diagonal matrix with diagonal elements being the reciprocals of the reference impedance
- I : Identity Matrix
- S : s-parameter matrix

The y-parameters thus obtained are listed in table 4.2

4.3 Problem with using simple 3-port Y-Parameter Model

Considering 14 MHz frequency, when y-parameters at this frequency are used for model in figure 4.1 & component values are calculated, following circuit is obtained, as shown in figure 4.2,

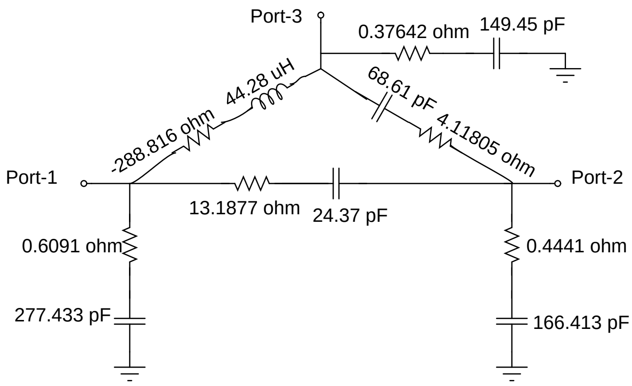

Figure 4.2: 3-Port network component values calculated for TMB at 14 MHz

There are two problems with the circuit,

- y_{13} has got a negative real part, thus giving a negative resistance in the circuit.
- For the circuit of figure 4.2 , when y-parameters for frequencies of 13 MHz and 15 MHz are calculated, there it turns out that the y-parameters obtained for these frequencies are different from the y-parameters of the TMB at these frequencies.

Reason for the second problem is that,the circuit in figure 4.2 , is not the exact replica of the TMB circuit. The circuit in figure 4.2 is just a 3-port y-parameter model.

4.4 Using 3-port T-model

In-order to obtain a circuit such that y-parameter values for all frequencies are satisfied, it is needed to add more number of impedances in the circuit.

A 3-port T-model is assumed shown in figure 4.3 ,

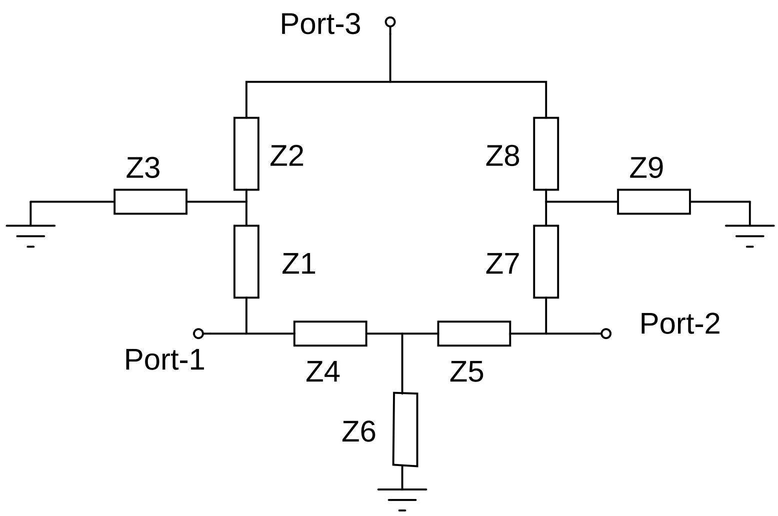

Figure 4.3: 3-Port T-model considered

Here, the number of components in figure 4.3 , have increased as compared to the number of components in figure 4.1 . However, expressing the y-parameters in terms of the components of the figure 4.3 , gives rise to very complicated expressions.

To get simpler expressions for the y-parameters, each T-network in figure 4.3 , is converted to a Δ-network as shown in figure 4.4,

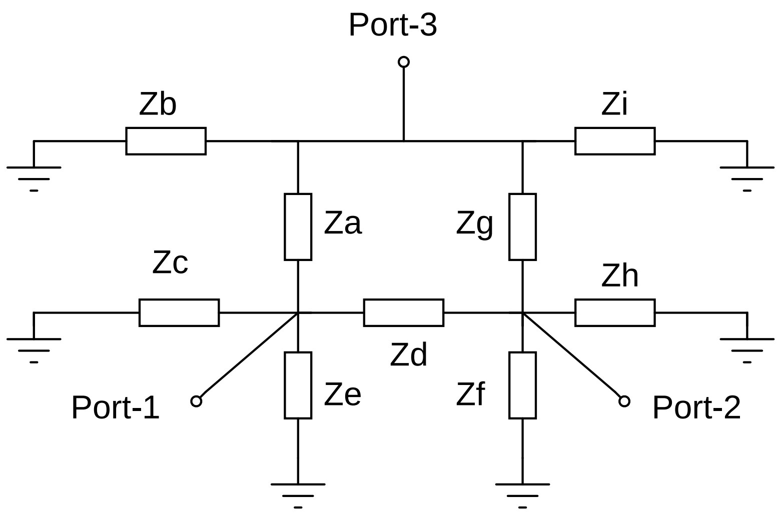

Figure 4.4: Each T-network in fig.4.3 converted to a Δ-network

Here, comparing figure 4.1 and figure 4.4, we get,

$$y_{11} + y_{12} + y_{13} = \left[\frac{1}{R_c + jX_c}\right] + \left[\frac{1}{R_e + jX_e}\right] \quad (4.2)$$

Here, the number of variables in equation 4.2 is 4. The $y_{11} + y_{12} + y_{13}$ at two frequencies 13 MHz and 15 MHz are used to calculate R_C, X_C, R_E & X_E.

Y_{12} is expressed as,

$$y_{12} = \left[\frac{1}{R_a + jX_a}\right] \quad (4.3)$$

We want to use y_{12} values of TMB at 13 MHz and 15 MHz. For this to be possible, an extra impedance $R_p + jX_p$ is inserted in parallel with $R_a + jX_a$.

Similarly, for using values of y_{13} & y_{23} at 13 MHz and 15 MHz, extra impedances are added in parallel with appropriate impedances in figure 4.4. The final circuit thus obtained is as shown in figure 4.5 .

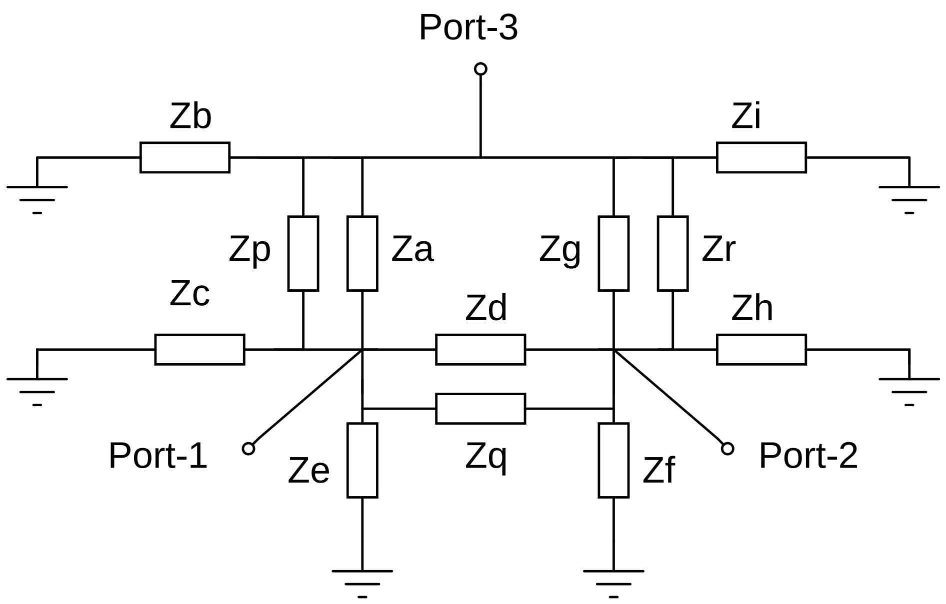

Figure 4.5: Network Model which enables to use y-parameters at two frequencies

4.5 Conversion of the Calculated Component Values from Delta-to-Star

Using y-parameters at 13 MHz & 15 MHz, component values are calculated. The values obtained for model of figure 4.5 are tabulated in the table-4.3 .

As seen in the table, some component values that are obtained are impractical. However, a conversion from delta-to-star can result in giving practically possible values of components.

Component	Resistance		Reactance	
Z_A	-84.56	Ω	4.43	nF
Z_B	-0.39	Ω	9.04	μH
Z_C	0.37	Ω	69.72	pH
Z_D	-429.85	Ω	19.11	pF
Z_E	-0.37	Ω	1.14	μF
Z_F	-7.33	Ω	2.17	μH
Z_G	1.29	Ω	0.16	nF
Z_H	0.78	Ω	0.23	nF
Z_I	0.23	Ω	164.22	pF
Z_P	84.54	Ω	51.76	nH
Z_Q	407.48	Ω	20.52	pF
Z_R	-1.62	Ω	1.4	μH

Table 4.3: Values of components of model in fig.4.5 for 14 MHz

4.5.1 Conversion from delta-to-star when Z_a is present in the Δ-network

The value of Z_a that has been obtained, consists of negative real part. Thus, for every delta-to-star conversion between port-1 & port-3, Z_a has to be a part of the Δ-network being converted to star.

There are eight such possibilities,

1. Delta $\equiv Z_c$- Z_a - Z_b

$$Z_m = \frac{Z_a Z_b}{Z_a + Z_b + Z_c} \tag{4.4}$$

By using similar formula, Z_n & Z_o are calculated.

The calculated values are listed in table 4.4

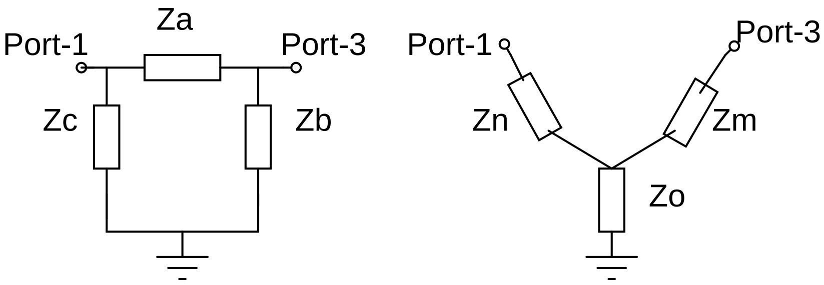

Figure 4.6: Zc-Za-Zb

$$
\begin{aligned}
Z_m &= -84.0885 + j6.846 \quad \Omega \\
Z_n &= 0.0028 + j0.0421 \quad \Omega \\
Z_o &= 0.3668 - j0.0362 \quad \Omega
\end{aligned}
$$

Table 4.4: Delta-to-Star conversion for combination-1

2. Delta $\equiv Z_e$- Z_a - Z_b The evaluated values are listed in table 4.5

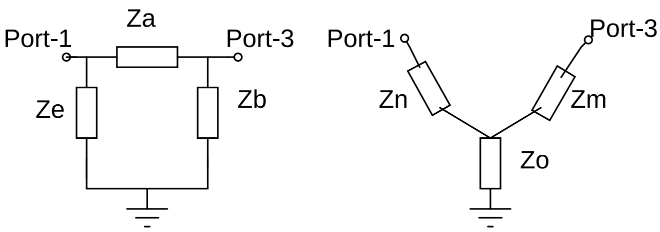

Figure 4.7: Ze-Za-Zb

$$
\begin{aligned}
Z_m &= -84.074 + j6.929 \quad \Omega \\
Z_n &= -0.0023 - j0.0422 \quad \Omega \\
Z_o &= -0.3673 + j0.0316 \quad \Omega
\end{aligned}
$$

Table 4.5: Delta-to-Star conversion for combination-2

3. **Delta** $\equiv Z_e$- Z_a - Z_i The evaluated values are listed in table 4.6

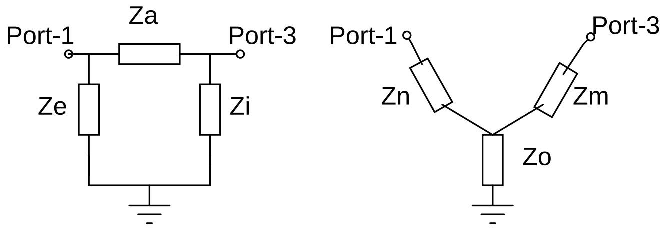

Figure 4.8: Ze-Za-Zi

$$\begin{aligned} Z_m &= -35.6 - j41.92 \quad \Omega \\ Z_n &= -0.2124 + j0.1712 \quad \Omega \\ Z_o &= -0.1563 - j0.1826 \quad \Omega \end{aligned}$$

Table 4.6: Delta-to-Star conversion for combination-3

4. **Delta** $\equiv Z_c$- Z_a - Z_i The evaluated values are listed in table 4.7

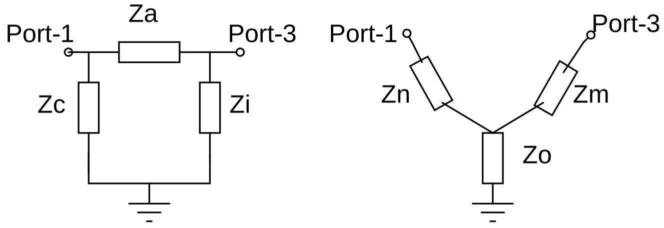

Figure 4.9: Zc-Za-Zi

$$\begin{aligned} Z_m &= -35.96 - j41.97 \quad \Omega \\ Z_n &= 0.21 - j0.1757 \quad \Omega \\ Z_o &= 0.16 + j0.1806 \quad \Omega \end{aligned}$$

Table 4.7: Delta-to-Star conversion for combination-4

5. **Delta** $\equiv Z_d$- Z_A - Z_g The evaluated values are listed in table 4.8

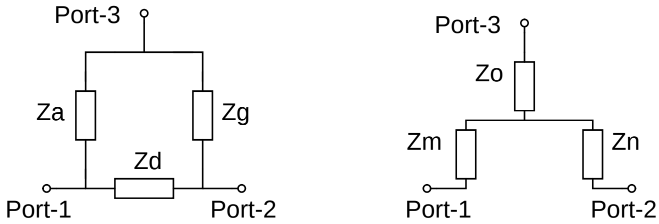

Figure 4.10: Zd-Za-Zg

$$
\begin{aligned}
Z_m &= -73.8 - j4.56 \quad \Omega \\
Z_n &= 3.05 - j65.27 \quad \Omega \\
Z_o &= -5.6156 - j4.4555 \quad \Omega
\end{aligned}
$$

Table 4.8: Delta-to-Star conversion for combination-5

6. **Delta** $\equiv Z_q$- Z_a - Z_g The evaluated values are listed in table 4.9

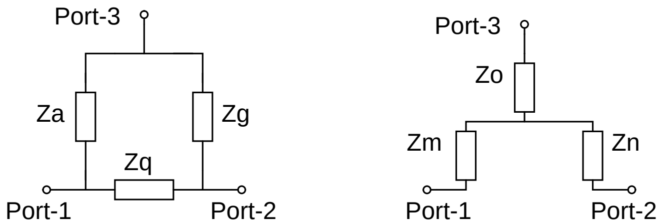

Figure 4.11: Zq-Za-Zg

$$
\begin{aligned}
Z_m &= --80.3425 - j14.918 \quad \Omega \\
Z_n &= 12.093 - j71.18 \quad \Omega \\
Z_o &= -7.79 + j3.278 \quad \Omega
\end{aligned}
$$

Table 4.9: Delta-to-Star conversion for combination-6

7. **Delta** $\equiv Z_d$- Z_a - Z_r. The evaluated values are listed in table 4.10

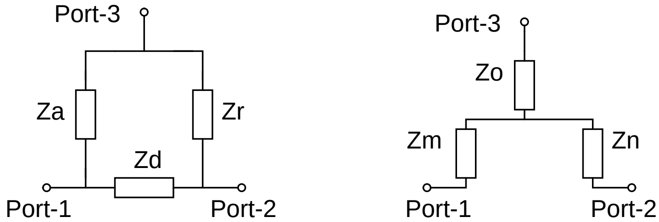

Figure 4.12: Zd-Za-Zr

$$\begin{aligned} Z_m &= -86.33 - j18.884 \quad \Omega \\ Z_n &= -0.235 + j117.8 \quad \Omega \\ Z_o &= 8.98 + j9.644 \quad \Omega \end{aligned}$$

Table 4.10: Delta-to-Star conversion for combination-7

8. **Delta** $\equiv Z_q$- Z_a - Z_r. The evaluated values are listed in table 4.11

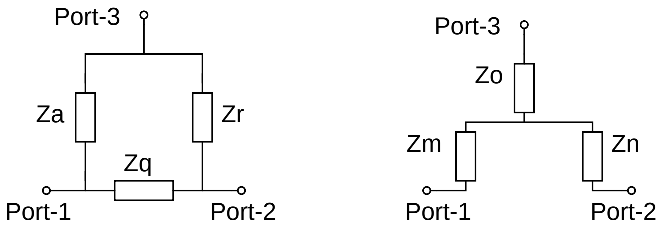

Figure 4.13: Zq-Za-Zr

$$\begin{aligned} Z_m &= -105.05 - j4.86 \quad \Omega \\ Z_n &= -3.95 + j142.91 \quad \Omega \\ Z_o &= 14.369 - j8.592 \quad \Omega \end{aligned}$$

Table 4.11: Delta-to-Star conversion for combination-8

Above eight delta networks converted to star network represent every possible delta network of which Z_A can be a part. And for each of these delta networks converted to star networks, at least one of the impedances in resulting star network has got a negative real part. Thus, for the T-network model considered, it is not possible to get practically possible values of components such that, the y-parameters of the TMB for 13 MHz as well as 15 MHz are satisfied by the developed circuit.

4.6 Model Simplification by Reducing the Number of Components

After observing that a practically possible circuit to replicate TMB was not achievable by using y-parameters at two frequencies 13 MHz and 15 MHz, there is an option of proceeding ahead by adding more number of components and using y-parameters at more number of frequencies. However, this will complicate the y-parameter expressions in terms of circuit components and this also doesn't guarantee that some practically possible circuit will be achievable after evaluating all the component values by solving the equations.

Instead of complicating the circuit, it is actually tried to be simplified. Earlier, it was tried to achieve a circuit to replicate the behavior of TMB across the entire frequency range from 13 MHz to 15 MHz.

Now, to simplify the circuit, it is decided to replicate the TMB behavior at a single tuned frequency. The network model used, is again a T-network model, but here, in this model, each branch of the network will consist only either a resistor, a capcitor or an inductor.

4.7 Expression of Y-Parameters in Terms of T-network Impedances

Let the network be as shown in figure 4.14,

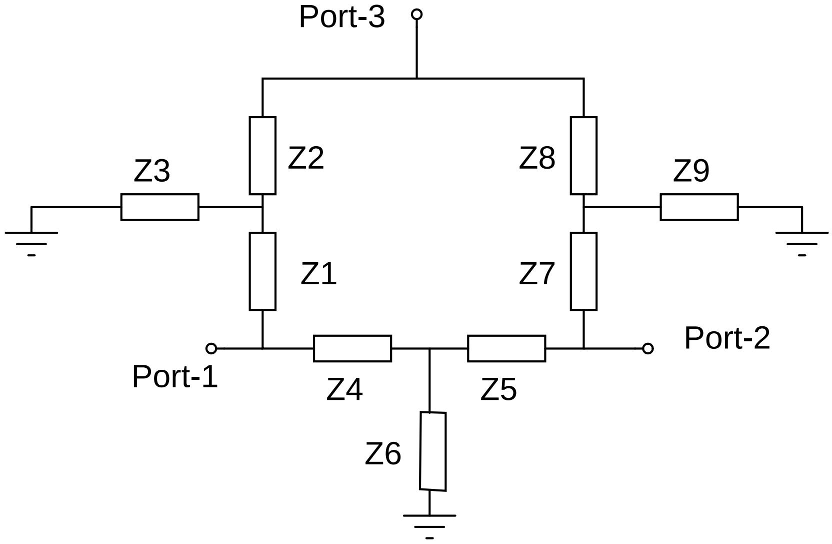

Figure 4.14: 3-Port T-model

The y-parameter model is as shown in figure 4.15,

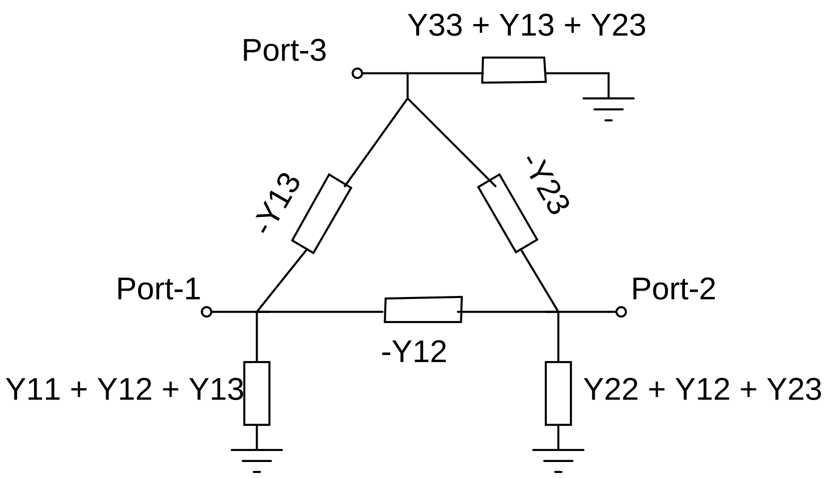

Figure 4.15: 3-port y-parameter model

Comparing T-model and y-parameter model, following relations are obtained,

$$(-y_{13})^{-1} = \left[z_1 + z_2 + \frac{z_1 z_2}{z_3}\right] \tag{4.5}$$

$$(-y_{12})^{-1} = \left[z_4 + z_5 + \frac{z_4 z_5}{z_6}\right] \tag{4.6}$$

$$(-y_{23})^{-1} = \left[z_7 + z_8 + \frac{z_7 z_8}{z_9}\right] \tag{4.7}$$

$$y_{11} + y_{12} + y_{13} = \left[z_1 + z_3 + \frac{z_1 z_3}{z_2}\right]^{-1} + \left[z_4 + z_6 + \frac{z_4 z_6}{z_5}\right]^{-1} \tag{4.8}$$

$$y_{22} + y_{12} + y_{23} = \left[z_5 + z_6 + \frac{z_5 z_6}{z_4}\right]^{-1} + \left[z_7 + z_9 + \frac{z_7 z_9}{z_8}\right]^{-1} \tag{4.9}$$

4.8 Method to Decide the Choice of a Resistor, Capacitor or Inductor in a T-network Branch

Next step is to decide what component to put in a branch. The decision is made on the basis of y_{12}, y_{13} and y_{23}.

Following example gives an idea of how components are decided.

$$(-y_{13})^{-1} = \left[z_1 + z_2 + \frac{z_1 z_2}{z_3}\right] \tag{4.10}$$

At 14 MHz,

$$(-y_{13})^{-1} = (-288.816 + j3895.0232)\Omega \tag{4.11}$$

Here, Z_1, Z_2, Z_3 should be chosen such that the real part of ${y_{13}}^{-1}$ remains negative and imaginary part remains positive.

For example, following circuit is chosen as shown in figure 4.16

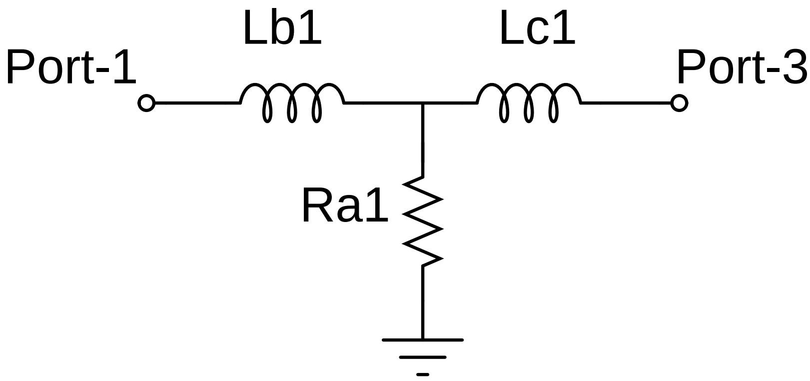

Figure 4.16: Example T-network between port-1 & port-3

$$(-y_{13})^{-1} = \frac{-\omega^2 L_{b1} L_{c1}}{R_{a1}} + j\omega(L_{b1} + L_{c1}) \tag{4.12}$$

Here, if L_{b1}, L_{c1} & R_{a1} have positive values, then $(-y_{13})^{-1}$ evaluates to a negative real-part and a positive imaginary-part. Thus, this choice of circuit components has a possibility to evaluate to a practically possible solution.

Similarly, there are a few other choices of components which might lead to a practically possible solution. Possible combinations of components are listed below in the table-4.12 & table-4.13 .

Z_1	Z_2	Z_3
L_{b1}	L_{c1}	R_{a1}
R_{b1}	L_{c1}	C_{a1}
L_{b1}	R_{c1}	C_{a1}

Table 4.12: Possible Components in branches of T-network between ports 1 & 3

Z_4	Z_5	Z_6
C_{b2}	R_{c2}	C_{a2}
R_{b2}	C_{c2}	C_{a2}
C_{b2}	R_{c2}	L_{a2}
R_{b2}	C_{c2}	L_{a2}
C_{b2}	L_{c2}	R_{a2}
L_{b2}	C_{c2}	R_{a2}
R_{b2}	C_{c2}	R_{a2}
C_{b2}	R_{c2}	R_{a2}
R_{b2}	R_{c2}	L_{a2}

Table 4.13: Possible Components in branches of T-network between ports 1 & 2

4.9 Example to Calculate Component Values using Y-Parameters

One combination from table-4.12 & table-4.13 forms a pair. 27 such pairs are possible. For each of these pairs, component values are calculated and it is seen if they are practically possible or not.

An example to calculate component values using a pair is shown below. The circuit used, is shown in figure 4.17 .

Referring to figure 4.17 we get,

$$(-y_{13})^{-1} = R_{B1}(1 - \omega^2 L_{C1} C_{A1}) + j\omega L_{C1} \tag{4.13}$$

$$(-y_{13})^{-1} = -288.816 + j3895.0232 \tag{4.14}$$

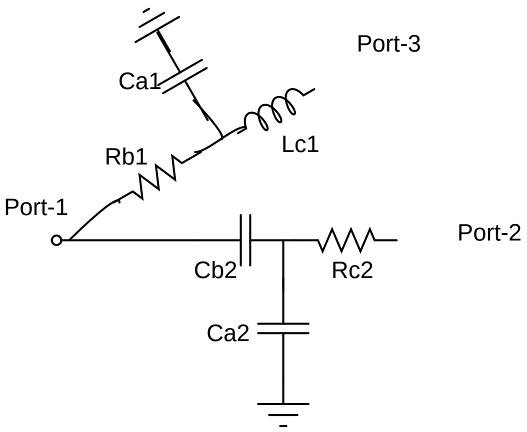

Figure 4.17: 3-Port T-model considered

Thus, $\omega L_{C1} = (3895.0232)\Omega$

$$(-y_{12})^{-1} = R_{C2}\left(1 + \frac{C_{A2}}{C_{B2}}\right) - \frac{j}{\omega C_{B2}} \tag{4.15}$$

$$(-y_{12})^{-1} = (13.18777 - j466.517664)\Omega \tag{4.16}$$

Thus, $\frac{1}{\omega C_{B2}} = (466.517664)\Omega$

$$(y_{11}+y_{12}+y_{13}) = \left\{R_{B1} - \frac{R_{B1}}{\omega^2 L_{C1} C_{A1}} + \frac{1}{j\omega C_{A1}}\right\}^{-1} + \left\{\frac{-1}{\omega^2 C_{A2} C_{B2} R_{C2}} + \frac{1}{j\omega C_{A2}} + \frac{1}{j\omega C_{B2}}\right\}^{-1} \tag{4.17}$$

- Replace ωL_{C1} by 3895.0232.
- Express R_{B1} in terms of ωC_{A1}.
- Replace $\frac{1}{\omega C_{B2}}$ by 466.517664.

$$(y_{11}+y_{12}+y_{13}) = \left\{\frac{3895.0232}{288.816}\omega L_{B1} + j\omega L_{B1}\right\}^{-1} + \left\{\frac{-466.517664}{\omega C_{A2} R_{C2}} - j\frac{13.18777}{\omega C_{A2} R_{C2}}\right\}^{-1} \tag{4.18}$$

Let, $\frac{1}{\omega L_{B1}} = X$ and $\omega C_{A2} R_{C2} = Y$. Further rationalizing the expression and replacing $(y_{11} + y_{12} + y_{13})$ by it's value, following is obtained,

$$0.3627086mS = \frac{13.4861753}{182.87692} X + \frac{-466.517664}{217.81265 \times 10^3} Y \tag{4.19}$$

$$24.3998mS = -\frac{1}{182.87692} X + \frac{13.18777}{217.81265 \times 10^3} Y \tag{4.20}$$

Solving above equations, the component values are calculated. For each pair of combinations, the component values which come out to be negative, have been tabulated in the table-4.14 & table-4.15 below,

Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**Negative Components**
L_{b1}	L_{c1}	R_{a1}	C_{b2}	R_{c2}	C_{a2}	$L_{b1} = -1.69nH$, $R_{a1} = -8.98\Omega$, $C_{a2} = -26.24pF$
L_{b1}	L_{c1}	R_{a1}	R_{b2}	C_{c2}	C_{a2}	$C_{a2} = -0.3nF$, $R_{b2} = -1.27\Omega$
L_{b1}	L_{c1}	R_{a1}	C_{b2}	R_{c2}	L_{a2}	$R_{a1} = -4.17\Omega$, $L_{b1} = -3.79\Omega$
L_{b1}	L_{c1}	R_{a1}	R_{b2}	C_{c2}	L_{a2}	$L_{b1} = -2.76\mu H$, $R_{a1} = -3.22k\Omega$, $L_{a2} = -0.5\mu H$
L_{b1}	L_{c1}	R_{a1}	C_{b2}	L_{c2}	R_{a2}	$L_{b1} = -1.575nH$
L_{b1}	L_{c1}	R_{a1}	L_{b2}	C_{c2}	R_{a2}	$L_{b1} = -1.575nH$
L_{b1}	L_{c1}	R_{a1}	R_{b2}	C_{c2}	R_{a2}	$L_{b1} = -1.575nH$
L_{b1}	L_{c1}	R_{a1}	C_{b2}	R_{c2}	R_{a2}	$L_{b1} = -2.57\mu H$
L_{b1}	L_{c1}	R_{a1}	R_{b2}	R_{c2}	L_{a2}	$L_{b1} = -1.575nH$

Table 4.14: Negative Valued Components for each of the 27 pairs of T-network combinations

As seen in the table-4.14, for each pair of combinations, there exists at-least one component whose value is negative, thus being practically not possible.

Z1	Z2	Z3	Z4	Z5	Z6	Negative Components
R_{b1}	L_{c1}	C_{a1}	C_{b2}	R_{c2}	C_{a2}	$R_{c2} = -301.25\Omega$, $C_{a2} = -25.44pF$
R_{b1}	L_{c1}	C_{a1}	R_{b2}	C_{c2}	C_{a2}	$C_{a2} = -160.7pF$
R_{b1}	L_{c1}	C_{a1}	C_{b2}	R_{c2}	L_{a2}	-301.25Ω
R_{b1}	L_{c1}	C_{a1}	R_{b2}	C_{c2}	L_{a2}	$C_{a1} = -81.47pF$, $L_{a2} = -0.36\mu H$
R_{b1}	L_{c1}	C_{a1}	C_{b2}	L_{c2}	R_{a2}	$L_{c2} = -5.08\mu H$
R_{b1}	L_{c1}	C_{a1}	L_{b2}	C_{c2}	R_{a2}	$L_{b2} = 0.222\mu H$
R_{b1}	L_{c1}	C_{a1}	R_{b2}	C_{c2}	R_{a2}	$R_{a2} = -705\Omega$
R_{b1}	L_{c1}	C_{a1}	C_{b2}	R_{c2}	R_{a2}	$C_{a1} = -81.5pF$
R_{b1}	L_{c1}	C_{a1}	R_{b2}	R_{c2}	L_{a2}	$R_{b2} = -692\Omega$
L_{b1}	R_{c1}	C_{a1}	C_{b2}	R_{c2}	C_{a2}	$C_{a2} = -24.31pF$
L_{b1}	R_{c1}	C_{a1}	R_{b2}	C_{c2}	C_{a2}	$C_{a2} = -0.28nF$
L_{b1}	R_{c1}	C_{a1}	C_{b2}	R_{c2}	L_{a2}	$C_{a1} = 2.92pF$
L_{b1}	R_{c1}	C_{a1}	R_{b2}	C_{c2}	L_{a2}	$L_{a2} = -0.466\mu H$
L_{b1}	R_{c1}	C_{a1}	C_{b2}	L_{c2}	R_{a2}	$L_{c2} = -5.3\mu H$
L_{b1}	R_{c1}	C_{a1}	L_{b2}	C_{c2}	R_{a2}	$R_{c1} = -8.114M\Omega$
L_{b1}	R_{c1}	C_{a1}	R_{b2}	C_{c2}	R_{a2}	$R_{c1} = -8.114M\Omega$
L_{b1}	R_{c1}	C_{a1}	C_{b2}	R_{c2}	R_{a2}	$R_{c1} = -5.266k\Omega$
L_{b1}	R_{c1}	C_{a1}	R_{b2}	R_{c2}	L_{a2}	$L_{c2} = -5.3\mu H$

Table 4.15: Negative Valued Components for each of the 27 pairs of T-network combinations

As seen in the table-4.15, for each pair of combinations, there exists at-least one component whose value is negative, thus being practically not possible.

Chapter 5

Conclusion

Designing a tuning-matching box for NMR 2-port load by replicating the TMB has been tried. It is seen that, the circuit models tried are not giving practically possible component values for the circuit. Adding more number of variables (components) to the circuit model & using y-parameters of TMB for more number of frequencies can be kept on trying, until an appropriate solution is reached. If a simple approach to design is to be taken, then, 2-port load circuit of NMR needs to be known, so that, a suitable matching network can be designed for this known load.

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