

IMNLab Tutorial

This Tutorial guides the user to go through the design procedure of a wideband impedance match network for a real circuit by using IMNLab. Wideband gain block TQP3M9007 evaluation kit from Qorvo is used as the test unit. This evaluation kit will be optimized to the UHF band 470 – 862 MHz. In this tutorial only the input port is optimized.

This tutorial starts from creating a new project and importing calibration data. Refer to *IMNLab Calibration Tutorial* about how to obtain the calibration data. Then the user is guided to configure optimization parameters, such as network topology, component value constraints, frequency band, etc. Finally the user learns how to simulate and tune the impedance match network.

1. Create new project and import calibration data

1.1 Create New Project

The main interface of IMNLab is a standard multi-document frame. The user may work with multiple projects in the same time. Run the IMNLab application, the main frame is displayed as Figure 1.1.1 shown. Most icons on the tool bar are disabled. The icons will be enabled based on the progress of the project.

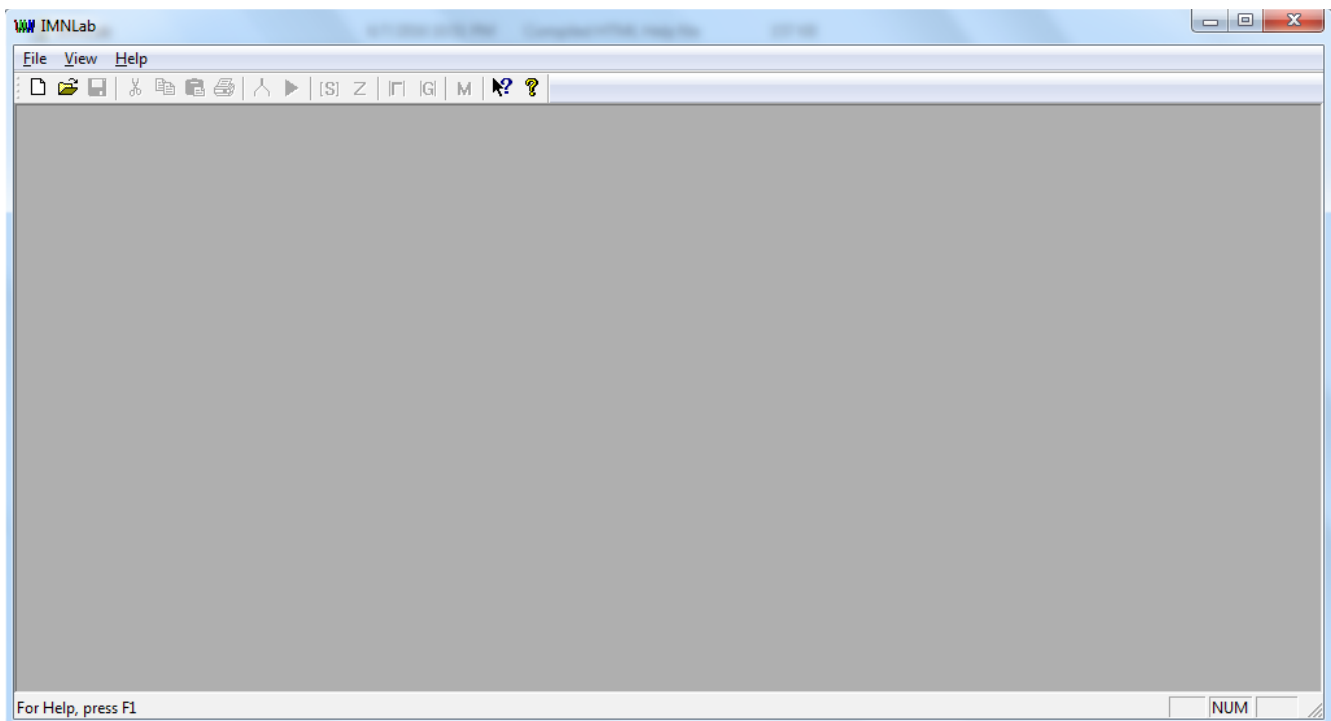


Figure 1.1.1 Main frame of IMNLab.

Choose **File - New Project**, or simply click the icon on the tool bar, a window pops out to prompt user to import calibration data files:

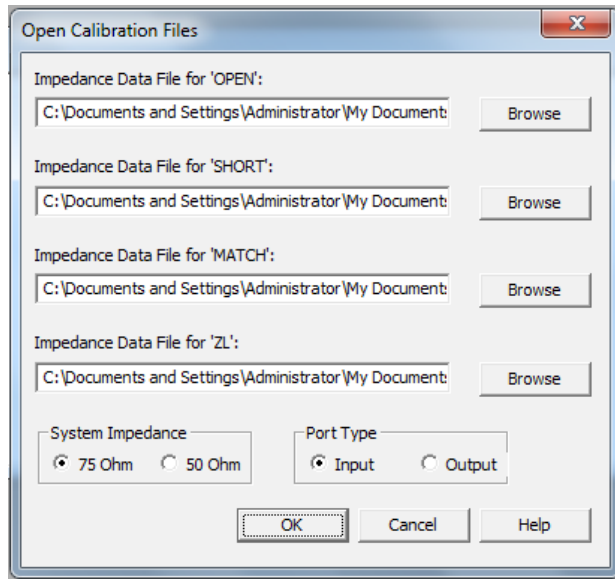


Figure 1.1.2. Default dialog for importing calibration data files.

In the interface shown in Figure 1.1.2, the user locates the calibration data files, sets system impedance and port type. For the port type of “Input”, an ideal source with source impedance equal to system impedance is assumed to calculate the transducer power gain. If the port type is set as “Output”, an ideal load with load impedance equal to system impedance is assumed to calculate the transducer power gain. For a reciprocal circuit, the port type does not affect the transducer power gain.

In this example, we set the system impedance to 50Ω, and set the port type as “Input” with accordance to the parameters of TQP3M9007 evaluation kit:

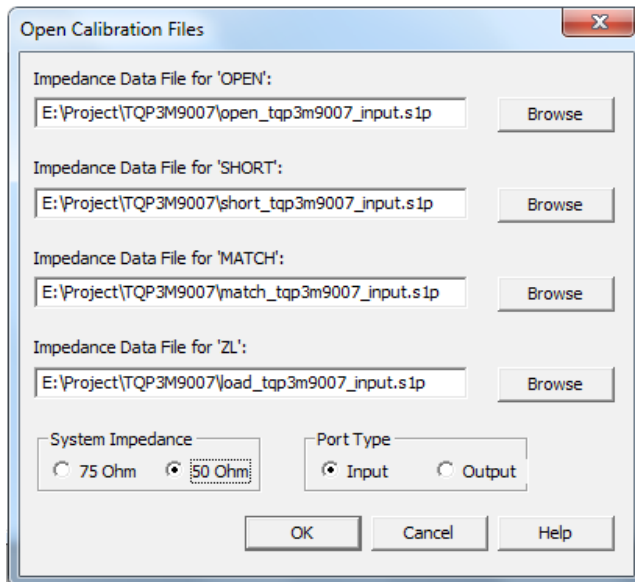


Figure 1.1.3. Customized dialog for importing calibration data files.

Clicking the “OK” button, the calibration data will be imported from the files. The user may also click “CANCEL” button to choose import the calibration data files later. The imported data files will be used to generate s-parameter, returnloss, load impedance and transducer power gain.

After valid calibration data files have been loaded successfully, the main interface is refreshed as Figure 1.1.4 shown. Several icons on the tool bar have been enabled.

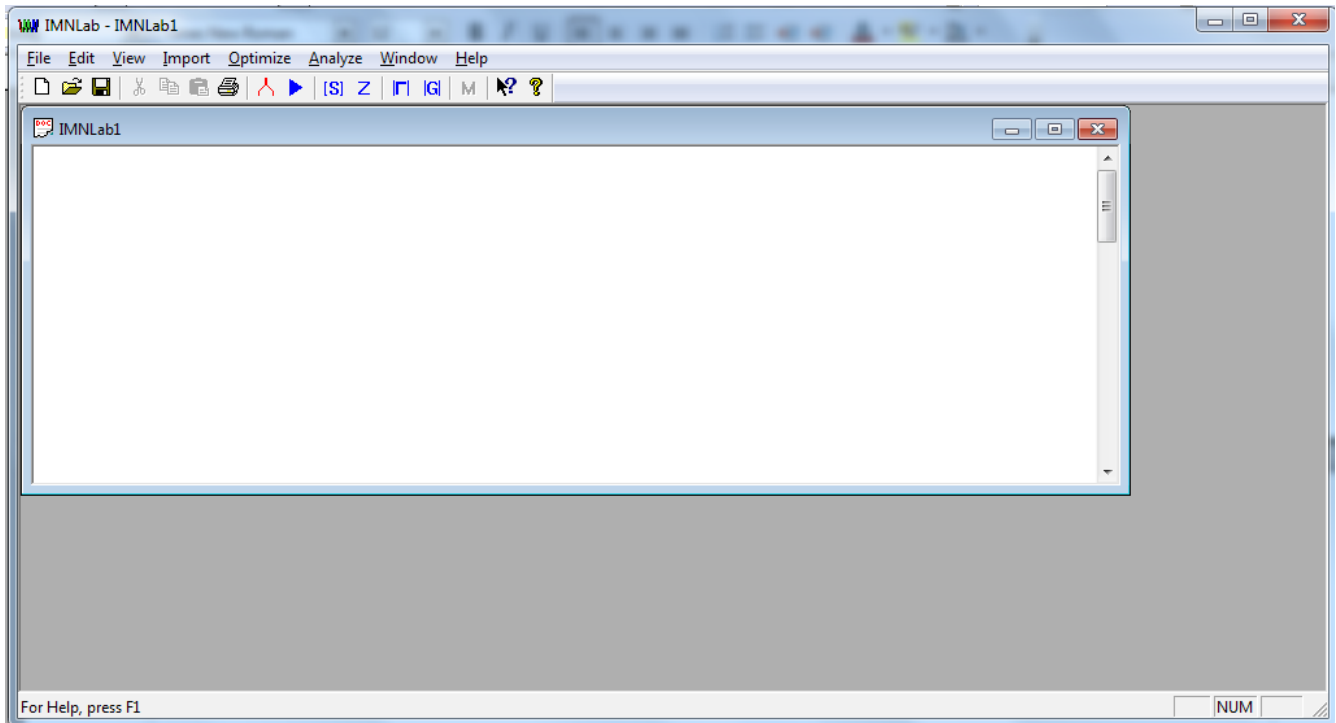



Figure 1.1.4. Main frame for IMNLab after importing calibration data.

Choose **File – Save**, or click the icon  on the tool bar, the user saves the project. Here the project is saved as “tutorial.imn”. The titles of window and document are automatically updated as Figure 1.1.5 shown.

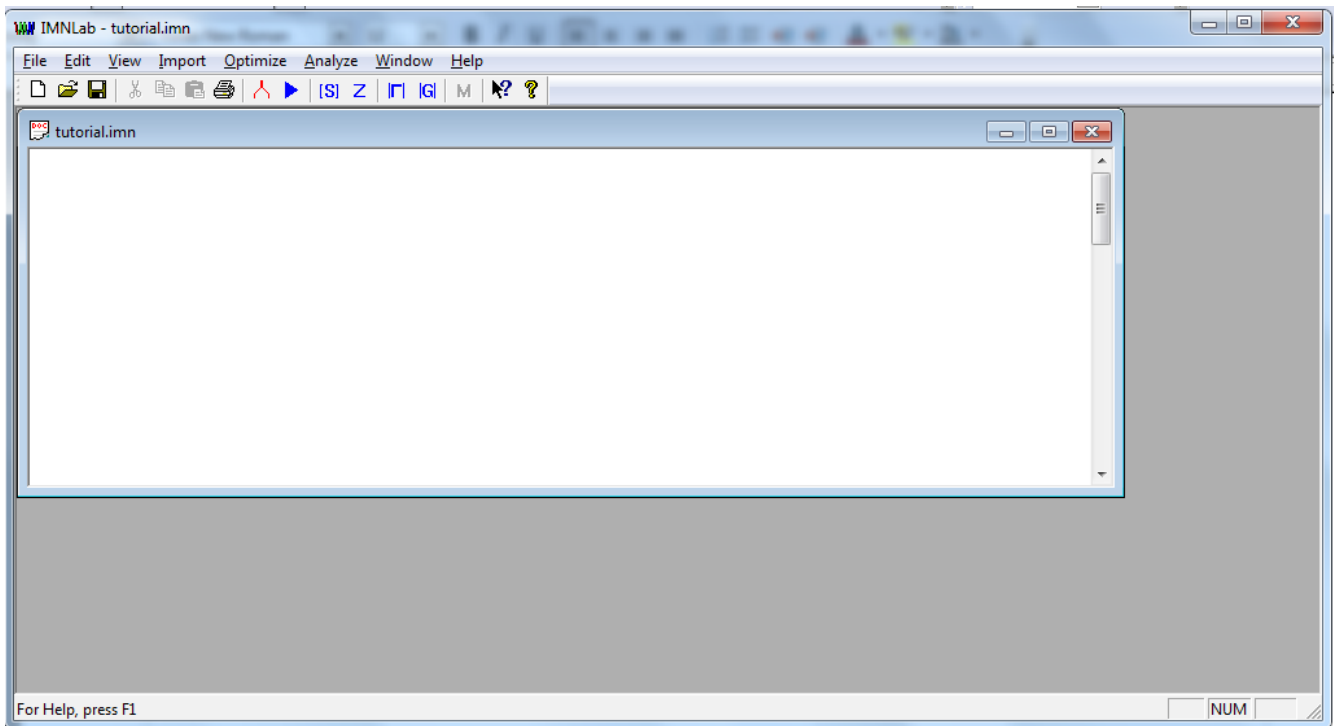




Figure 1.1.5. Main frame for IMNLab with project saved.

1.2 Re-Import Data Files

The calibration data files could be re-imported at any time. Choose **Import – Single Calibrate**, or click the icon  on the tool bar. Note that all the settings and results (such as components constraints, optimal values, frequency band, etc.) will be lost if user chooses to import the data again.

2. View Data

2.1 View S-PARAMETERS

Choose **View – View S-Parameters**, or click the icon  on the tool bar.

, the s-parameter curves are displayed as Figure 2.1.1 shown. In this window, the magnitude of S11, S21 and S22 in dB is displayed. Note that the S21 curve shown here is actually $10 \cdot \log_{10}|S12 \cdot S21|$. So strictly the curve for S21 is correct only for reciprocal circuits, i.e. $S12 = S21$. For non-reciprocal circuit, it only gives the measure for $\sqrt{|S12 \cdot S21|}$. The frequency range is the same as the imported calibration data files.

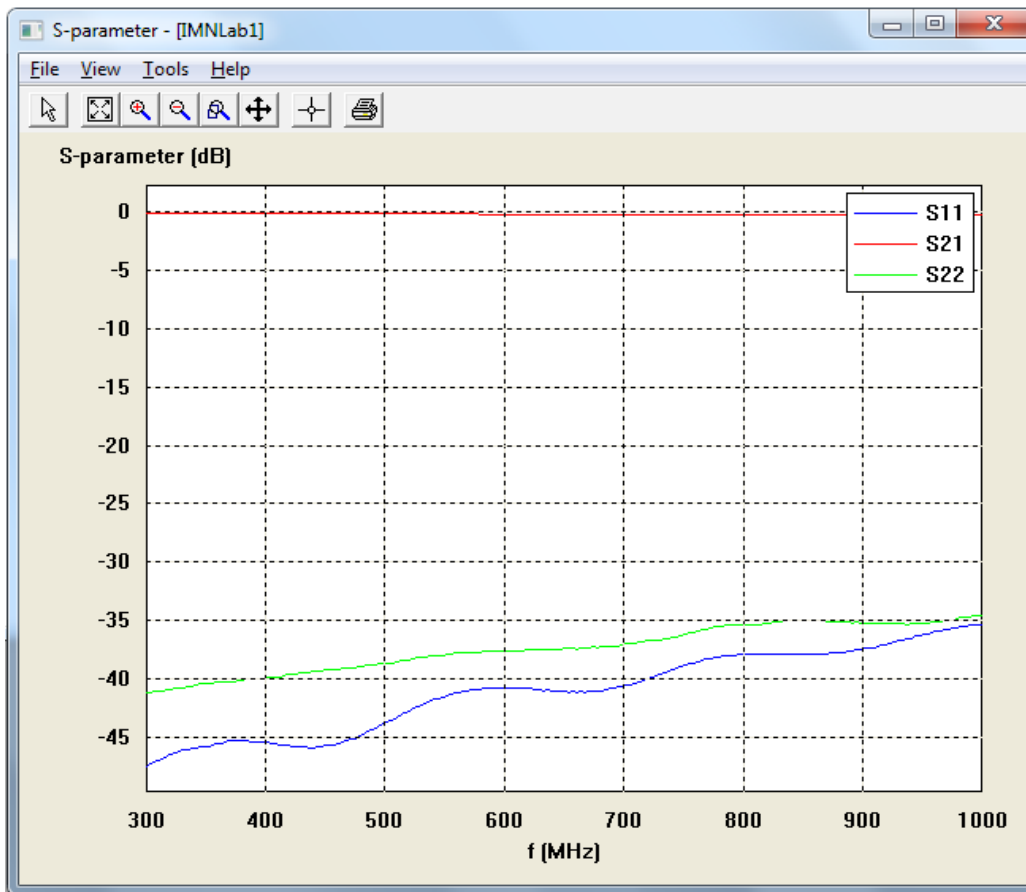











Figure 2.1.1. S-parameter curves.

The tool bar provides the functions of move legend, auto scale, zoom in/out/area, panning and measure. The detailed description is listed in the table 2.1.1. The tool bar functions for other parameter (impedance/returnloss/transducer gain/Monte Carlo) view windows are the same.

Table 2.1.1: Toolbar function for parameter view window

 Pick	Click this icon and move cursor on legend, press and hold left button to move legend to desired place.
 Auto Scale	Automatically scale X-Y axis.
 Zoom In	Zoom in curves with respect to the center. X-Y axis ratio kept the same.
 Zoom Out	Zoom out curves with respect to the center. X-Y axis ratio kept the same.
 Zoom In Area	Zoom in selected area.
 Panning	Click this icon, then press and hold left bottom for panning over plots.
 Measure	Click this icon. Move cursor close to the curve, then click left button to measure curve X-Y values.
 Print	Print curve(s). This function is still under construction.

2.2 View Impedance

Choose **View – View Load Impedance**, or click the icon  on the tool bar, the load impedance is displayed as Figure 2.2.1 shown. the original load impedance and the ideal load impedance are displayed together.

Note that the load impedance is the impedance at the calibration point, where the impedance match network is supposed to be inserted. Don't mix the load impedance with the impedance displayed on the network analyzer. The impedance displayed on the network analyzer is actually the transformed load impedance through a two-port network.

The ideal load impedance presents the optimal load impedance which leads to zero reflection. In general the ideal load impedance is not obtainable by inserting a lossless impedance match network with finite number of passive components. Nevertheless the ideal load impedance is still useful since it gives the clue to search for the best impedance match network.

With cross reference to the S-parameter curves shown in Figure 2.1.1, one sees that the channel is close to an ideal 50Ω transmission line. Therefore the ideal load impedance shown in Figure 2.2.1 is very close to the system impedance 50Ω . The actual load impedance is about $27+j4 \Omega$ at 300 MHz and $38+j10$ at 1 GHz. The target of optimization is to find a proper impedance match network which converts the actual load impedance as close to the ideal load impedance as possible.

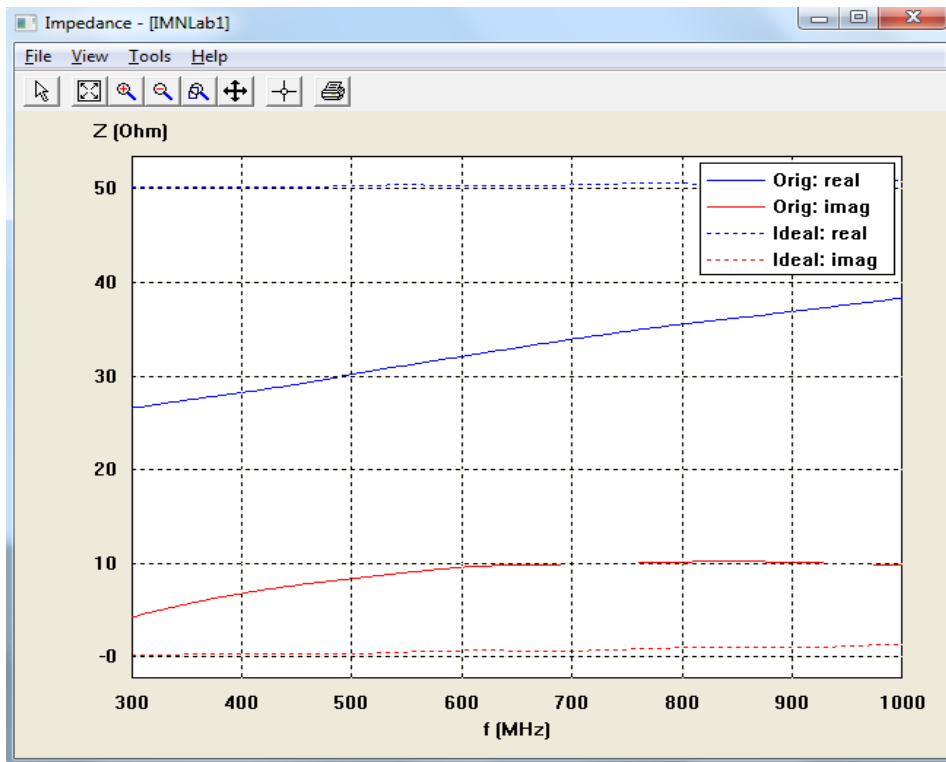


Figure 2.2.1. Load impedance curves.

2.3 View Returnloss

Choose **View – View Returnloss**, or click the icon on the tool bar, the returnloss curves are displayed in Figure 2.3.1. A theoretical bound for lossless impedance network work is also plotted as a reference. In general this theoretical bound is not reachable, while it helps to assess that an impedance match network is how close to the theoretical limitation.

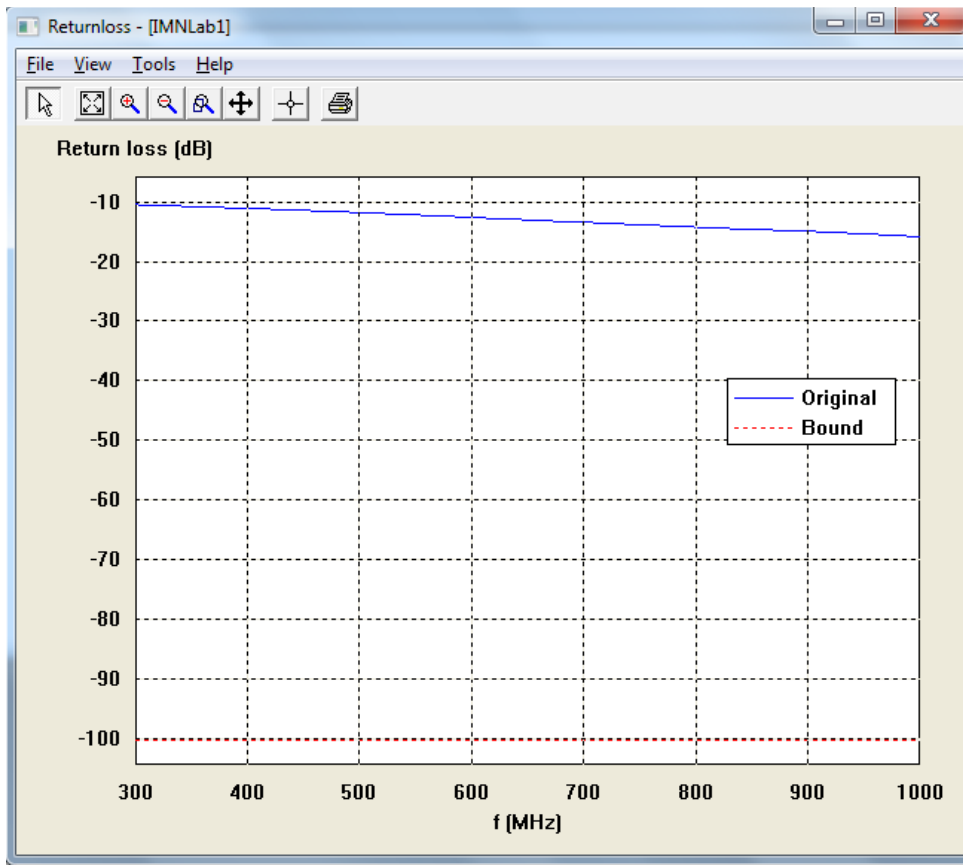



Figure 2.3.1. Returnloss curves.

2.4 View Transducer Gain

Choose **View – View Transducer Gain**, or click the  icon on the tool bar, the transducer gain is displayed as Figure 2.4.1 shown.

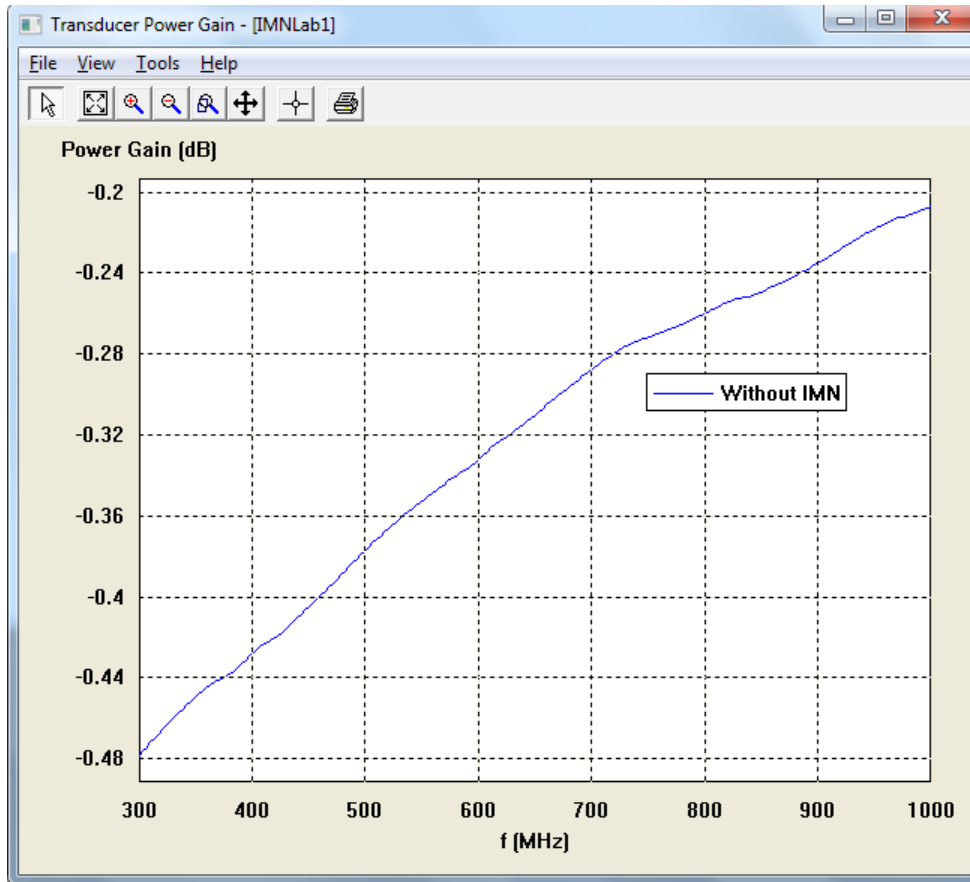


Figure 2.4.1. Transducer power gain curve.

Transducer power gain is defined as the ratio of the power delivered to the load and the maximum available power from the source. Transducer power gain can never be higher than 0 dB for a passive network. By inserting a proper impedance match network, the reflection can be reduced and thus more power is fed to the load, i.e. higher transducer power gain is obtained.

3. Impedance Match Network Optimizing

After importing the calibration data to IMNLab, it is ready to search for optimal impedance match network. The user may need to customize optimization parameters before starting optimization.

3.1 Configure Impedance Match Network

Choose **Optimize – Config Network**, the network configuration interface is popped-up as Figure 3.1.1 shown. Currently IMNLab only supports the topology of generalized ladder structure. Other topology structures may be added in the future. The user first sets the number of branches. Each branch is composed with one resistor, one inductor and one capacitor in series. Note that branch 1 is the closest branch to the load of Device Under Test (DUT). The branch with highest index is furthest to DUT, while closest to vector network analyzer. Even branches are serial branches. Odd branches are shunt branches.

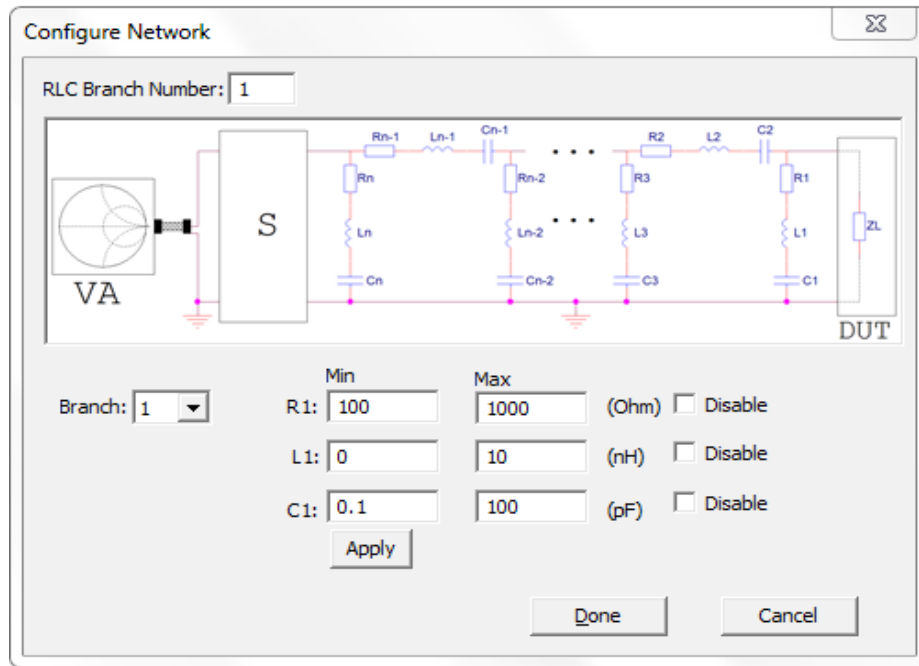


Figure 3.1.1. Interface for configuring impedance match network

After setting the number of branches, the user should specify the lower/upper bounds for each component value. If the lower bound is set to be equal to the upper bound, fixed value is used during optimizing process. Resistors can also be used to obtain better returnloss if some loss is acceptable. Click “Apply” button to store the bounds. The branch index automatically jumps to the next one. If the highest branch index has been reached, the branch index is reset back to 1. The drop-down list box could be used to select any branch.

In this example, we set the branch number to 3. The component bounds are listed in Table 3.1.1. In this example lossless impedance match network is desired, so all the resistor values are set to zero. After configuring all the lower/upper bounds, click ”Done” button to exit.

Table 3.1.1. Component lower/upper bounds

Branch	R (Ω)		L (nH)		C (pF)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	0	0	0	30	0.1	10
2	0	0	0	20	1	100
3	0	0	0	30	0.1	10

3.2 Configure Impedance Match Network

Choose **Optimize – Config Optimization**, the optimization configure dialog is popped-up as Figure 3.2.1 shown.

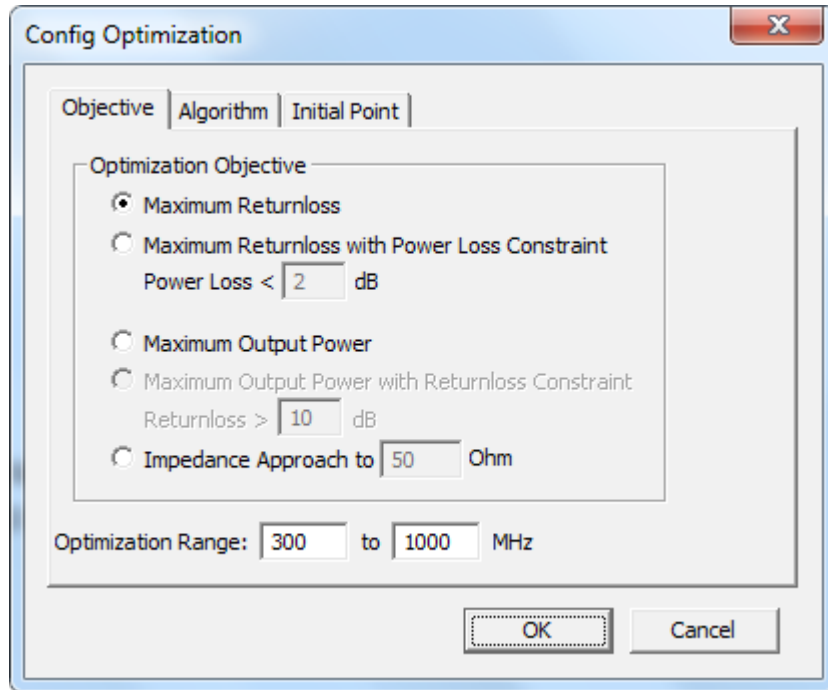


Figure 3.2.1. Interface for configuring optimization parameters

There are three tabs inside “Config Optimization” dialog. The first tab is “Objective.” This tab is used to set optimization target and frequency band.

Four optimization objectives are available:

- **“Maximum Returnloss”**: Maximize the minimum returnloss over the set frequency band. This option is recommended to design a lossless impedance match network;
- **“Maximum Returnloss with Power Loss Constraint”**: Maximize the minimum returnloss over the set frequency band, while keeping the power loss at a certain level. This option is useful to design a lossy impedance matching network;
- **“Maximum Output Power”**: Maximize the minimum transducer power gain over the set frequency band;
- **“Impedance Approach to”**: Match the load impedance to a set value. This option is useful to control the impedance at one point of the circuit. For example, if a lowpass filter is inserted after a gain block, 50 Ω output impedance of the gain block is desired to simplify the filter design.

The default frequency band is set to the same as calibration data files. While the user may modify the default values. In this example, we set the objective to maximize returnloss and modify the frequency band from 300 - 1000 MHz to 400 – 900 MHz. This is shown in Figure 3.2.2.

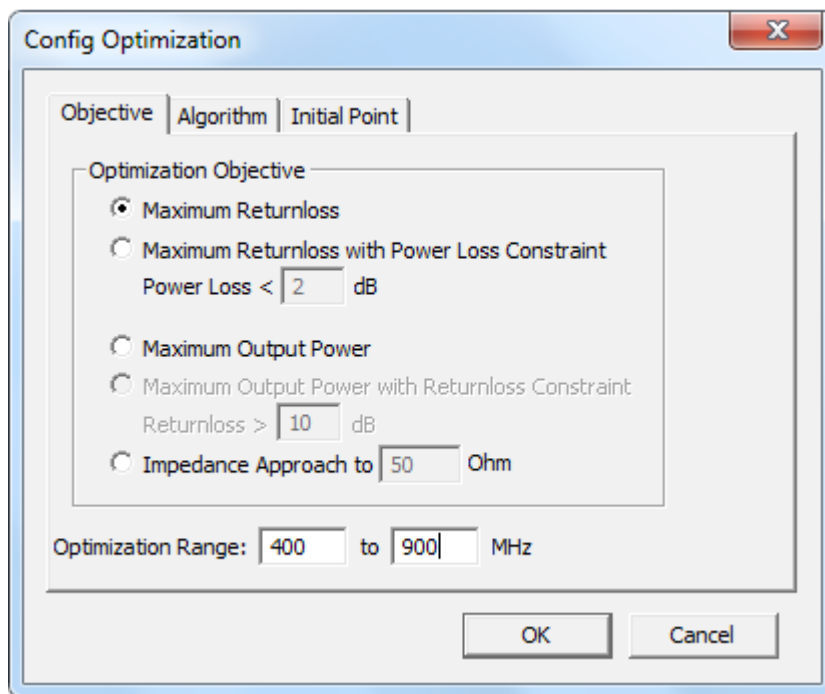


Figure 3.2.2. Interface for configuring optimization parameters: set objective.

The second tab is to select optimization algorithm. There are three optimization algorithms available: BOBYQA, NM Simplex and SBPLX. BOBYQA is quasi-Newton algorithm which converges very fast. It works best for most cases thus is set as the default algorithm. NM Simplex is a first-order algorithm. It converges slower than BOBYQA, while it is more robust for non linear optimization problems. In this example we select the default algorithm BOBYQA.

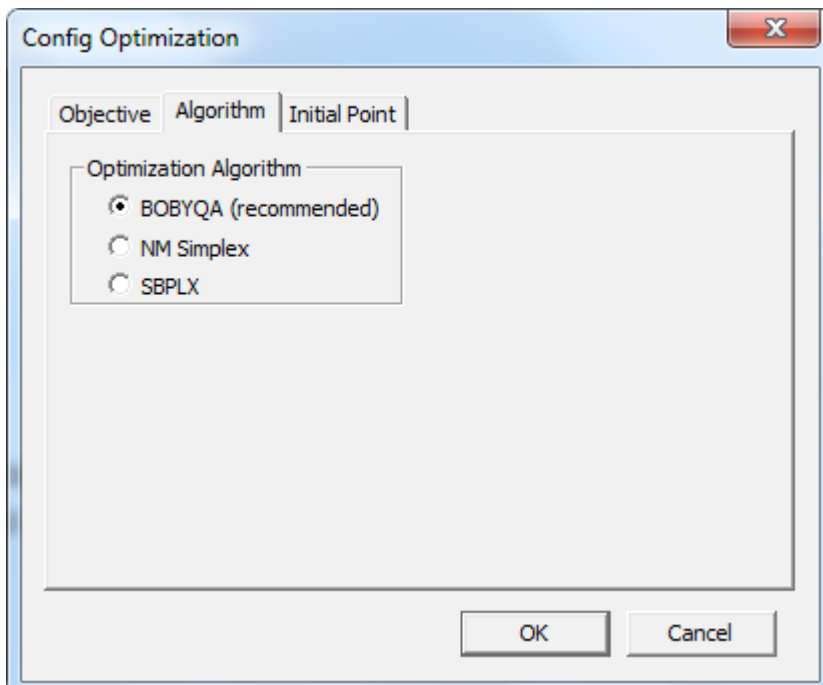


Figure 3.2.3. Interface for configuring optimization parameters: set algorithm.

The third tab is used to choose initial point. Returnloss optimization is a high-order nonlinear numerical problem and there may exist many local minima. Therefore many initial points are needed to avoid local minima. In this example 10000 random initial points is chosen. The “Previous optimal point” is used for fine tuning around an “almost” optimal point.

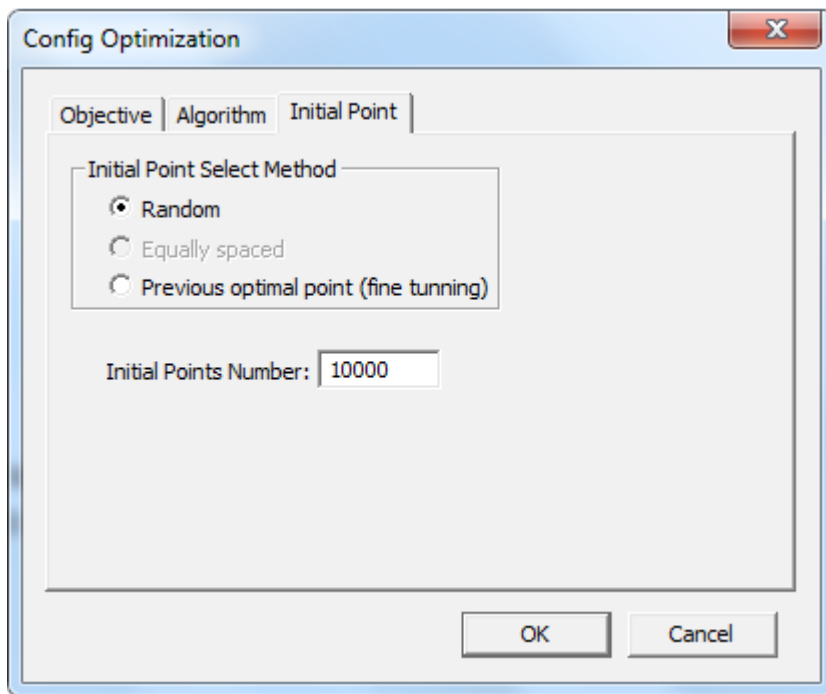



Figure 3.2.4. Interface for configuring optimization parameters: set initial point.

3.3 Start Impedance Match Network Optimization

After finishing the configuration of network and optimization parameters, the user can initialize the optimization procedure. Choose **Optimize – Start Optimization**, or click the icon  on the tool bar, the optimization procedure is started and a status window is pop-up:

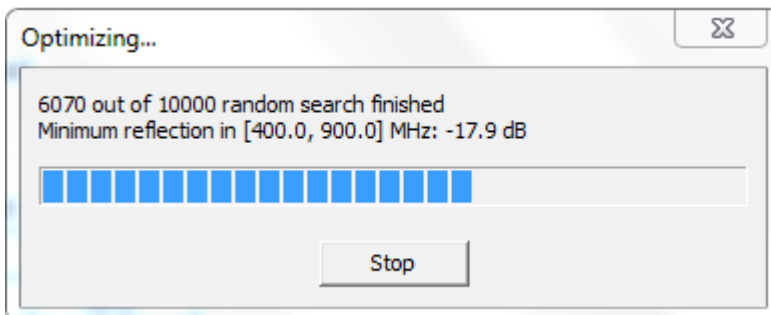


Figure 3.3.1. Optimization progress.

The optimization progress dialog shows how many searches have been pursued. The best result is shown as well. The user may terminate the optimization procedure by clicking the “Stop” button at any time. In this example, we let IMNLab to finish all 10000 random searches. The optimization results are recorded in the document window, as shown in Figure 3.3.2. Note that the results may be different from time to time, especially when the random searching number is small.

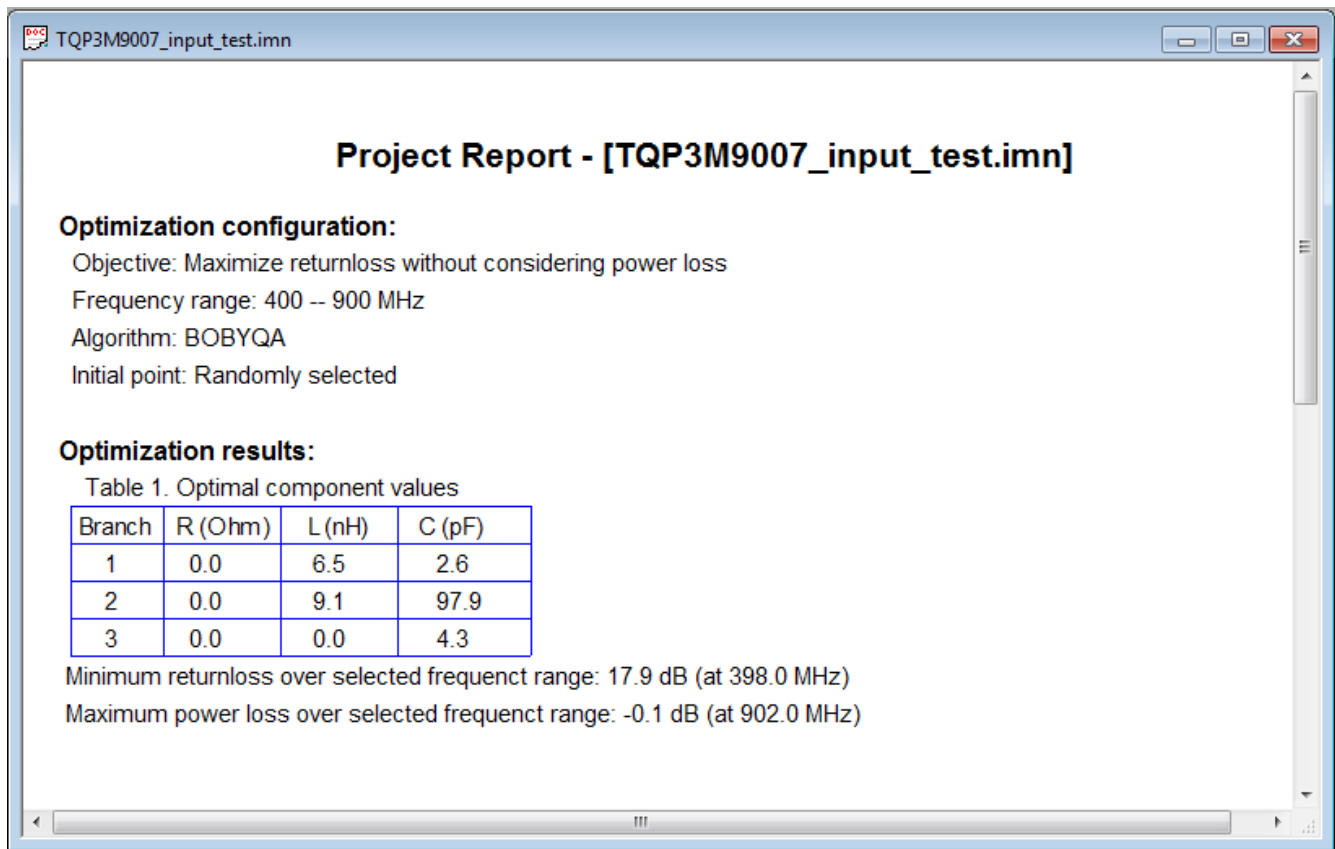


Figure 3.3.2. Optimization results after 10000 random searches.

Have a closer look at the optimization results, one see that C2 is very close to the upper bound of 100 pF. The reactance of an ideal 100 pF capacitor is only 4 Ω , this implies that C2 may be better disabled by setting a very high fixed capacitance. Modify the component bounds as Table 3.3.1 shown:

Table 3.3.1. Modified component lower/upper bounds

Branch	R (Ω)		L (nH)		C (pF)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	0	0	0	30	0.1	10
2	0	0	0	20	10000	10000
3	0	0	0	30	0.1	10

Keep other settings untouched and run the optimization again. The results are shown in Figure 3.3.3.

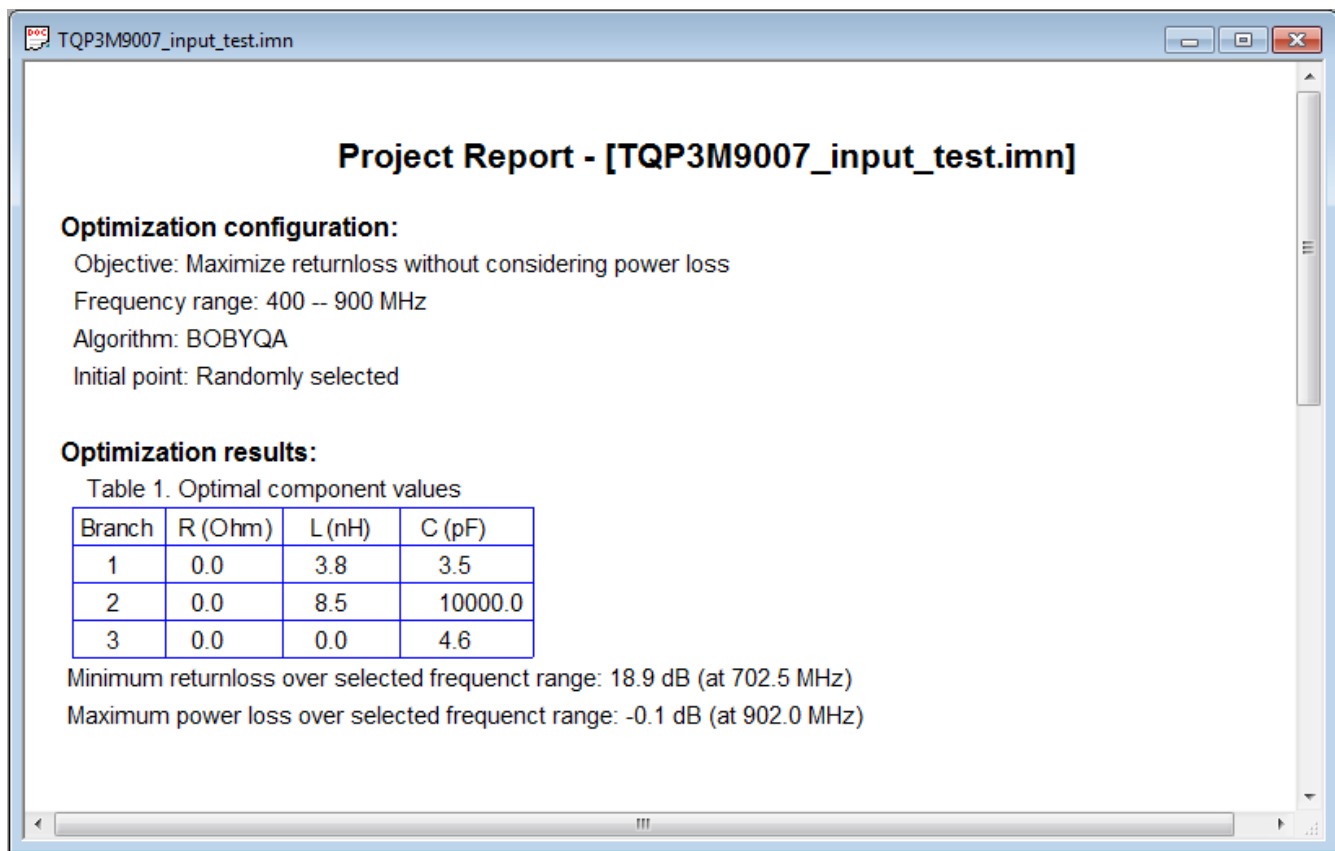


Figure 3.3.3. Optimization results after disabling C2 (set C2=10000 pF).

Now 18.9 dB returnloss has been achieved. Use the previous optimal point as start point for fine tuning:

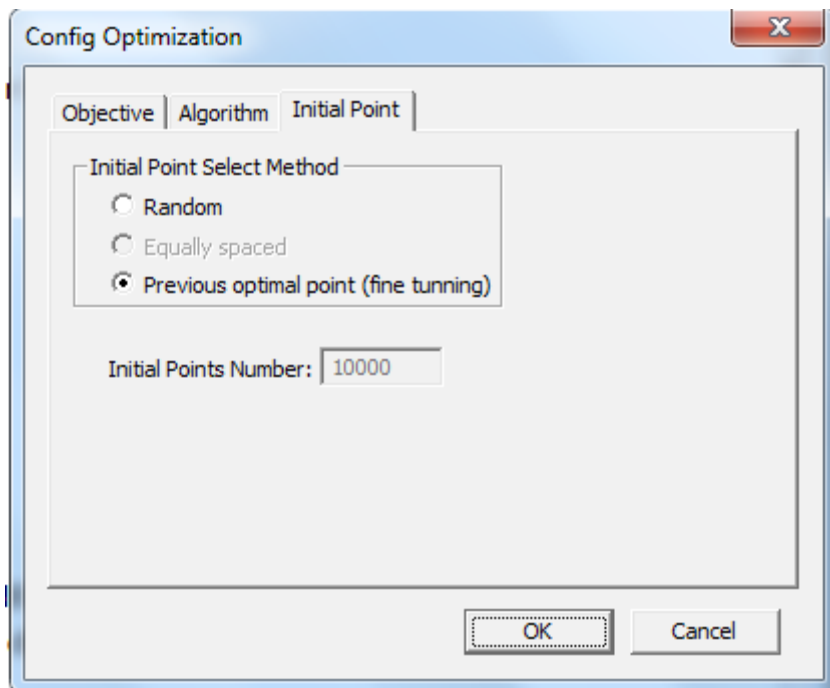


Figure 3.3.4. Fine tuning by using previous optimal point as start point.

Apply optimization several times until the results converge to the same values, as shown in Figure 3.3.5.

Project Report - [TQP3M9007_input_test.imn]

Optimization configuration:

Objective: Maximize returnloss without considering power loss
 Frequency range: 400 -- 900 MHz
 Algorithm: BOBYQA
 Initial point: Previous optimal point

Optimization results:

Table 1. Optimal component values

Branch	R (Ohm)	L (nH)	C (pF)
1	0.0	3.7	3.6
2	0.0	8.5	10000.0
3	0.0	0.0	4.6

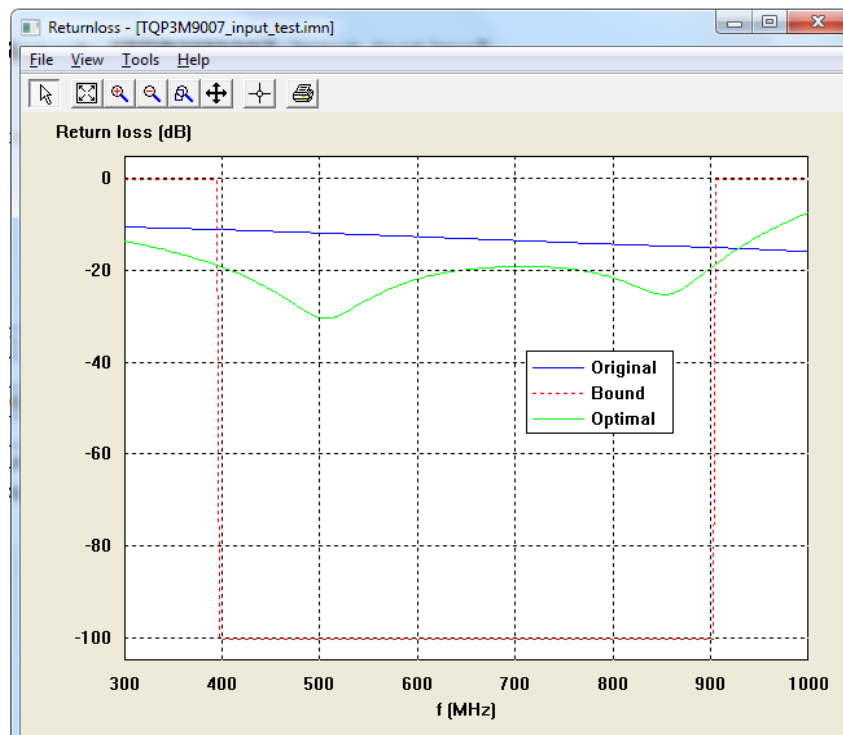
Minimum returnloss over selected frequenc range: 18.9 dB (at 398.0 MHz)

Maximum power loss over selected frequenc range: -0.1 dB (at 902.0 MHz)

Figure 3.3.5. Finalized optimization results.

3.4 View Optimization Results

Choose **View – View Returnloss**, or click the icon on the tool bar, the returnloss curves are displayed as Figure 3.4.1 shown. Note the legend has been dragged down to not cover the curves. We see that the returnloss in the desired band 400 – 900 MHz is several dB better.



de Figure 3.4.1 Returnloss with optimal IMN.

The optimal results are shown in the impedance curve as well. We see in Figure 3.4.2, the total load impedance is closer to the ideal impedance in the desired frequency band 400 – 900 MHz.

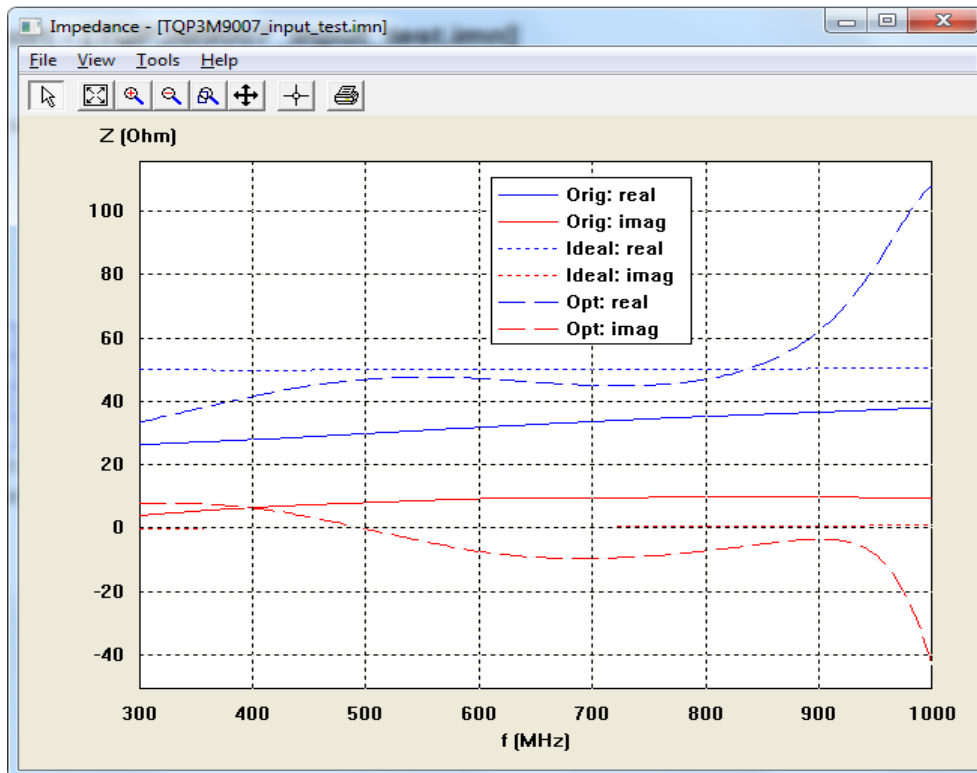


Figure 3.4.2 Load impedance with optimal impedance match network.

Since the impedance match network is lossless, better returnloss implies higher transducer power gain, because less power is reflected back. This is confirmed in Figure 3.4.3, the gain is about 0.2 – 0.4 dB higher in the band 400 – 900 MHz.

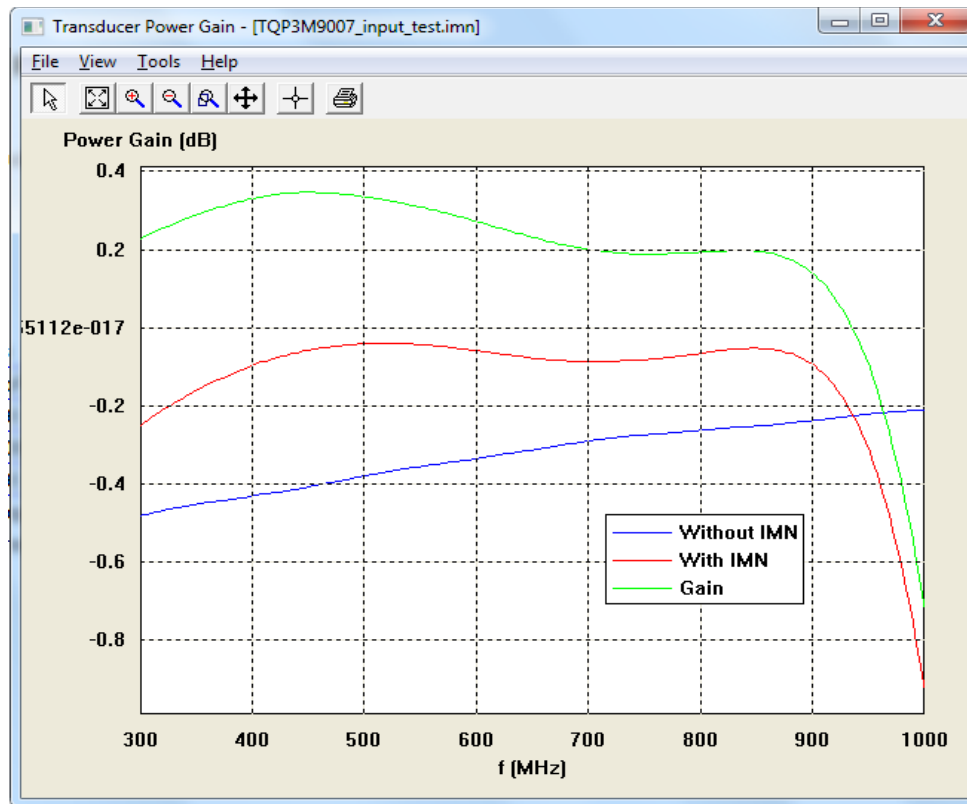


Figure 3.4.3 Transducer power gain with optimal impedance match network.

4. Statistical Analysis of Impedance Match Network

The optimal component values for impedance match network have been found. Statistical analysis may help the selection of real components.

Statistical analysis helps to find out the sensitivity of returnloss versus component tolerance. This sensitivity test helps to select components with appropriate tolerance, neither too loose nor too tight. The component price increases dramatically with tighter tolerance.

The second thing is that a real component is always not ideal. Parasite parameters can not neglected when the frequency is not significantly lower than the resonance frequency. IMNLab provides the functionality of integrating a real component parameters into the analysis. The lumped components are usually characterized by two-port S-parameter. Usually component manufacturers provide S-parameter database for downloading.

4.1 Configure Component Value and Tolerance

Choose **Analyze – Monte-Carlo Analysis**, or click the icon on the tool bar, the analysis configuration window is pop-up as:

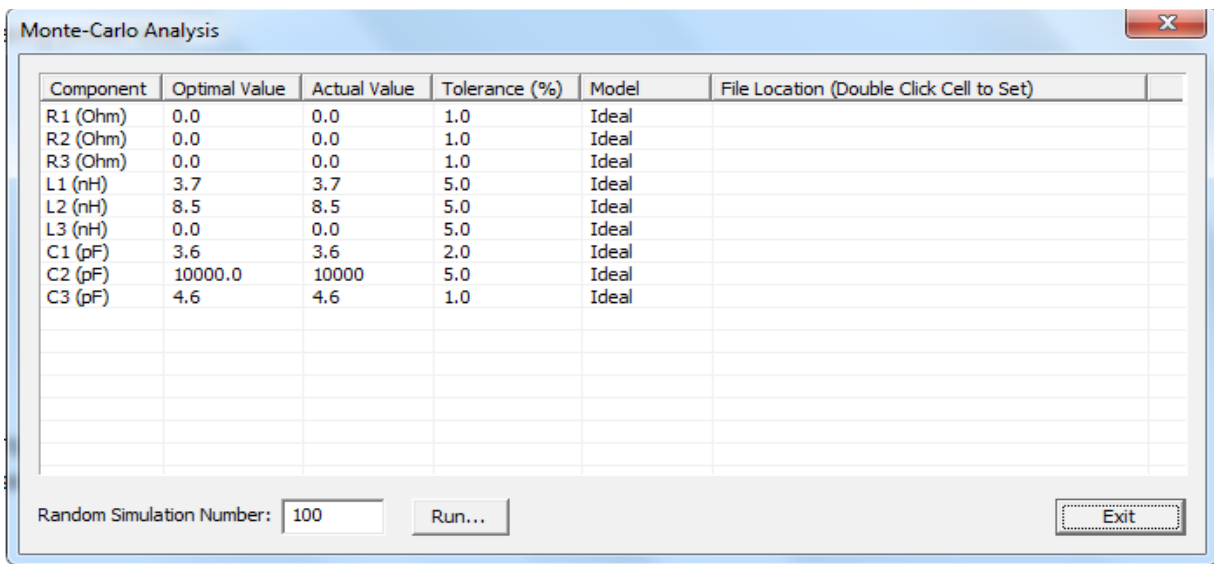


Figure 4.1.1 Statistical analysis configuration dialog.

In the configuration dialog, the user can edit the actual value and tolerance of any component. We change the inductors L1 to 3.9 nH 2%, L2 to 8.2 nH 2%. The capacitors C1 and C3 are kept with the same value, but changed to 1.5% and 1% tolerance. RF capacitors from 0.1 to 10pF with tight tolerance ± 0.05 pF are available. The final configuration is shown in Figure 4.1.2.

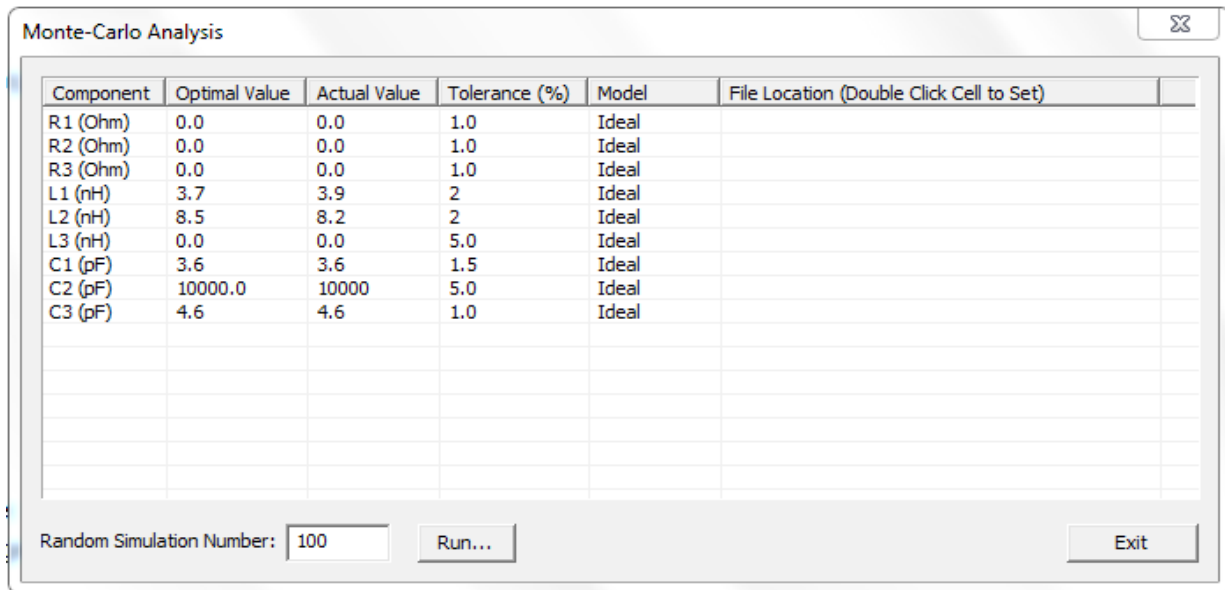


Figure 4.1.2 Component value/tolerance configuration with ideal model.

Keeping the random simulation number to be the default 100, the statistical analysis window for returnloss is shown by press the "Run" button. Also the analysis results are added to the project report as Figure 4.1.4 shown. We see that the minimum returnloss is changed from 18.9 dB to 18.2 dB. This is about 0.7 dB worse than the ideal case.

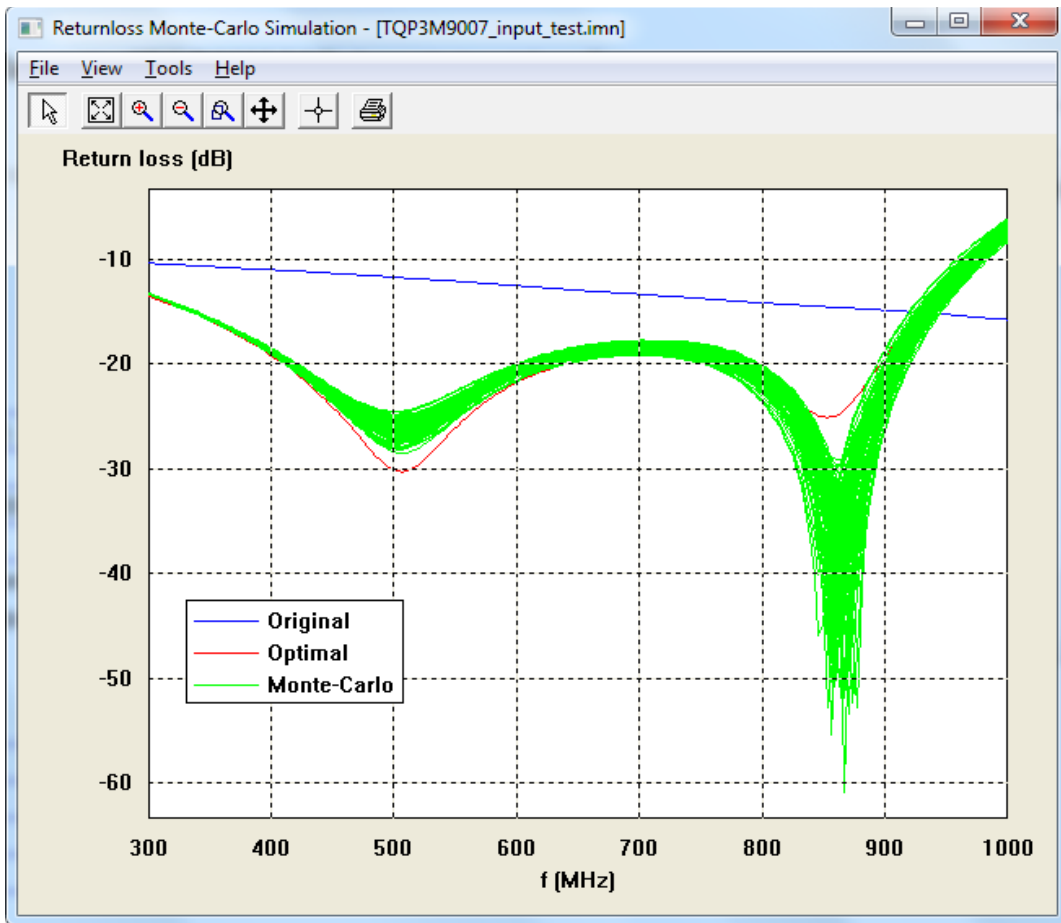


Figure 4.1.3 Statistical analysis of returnloss with ideal components.

Project Report - [TQP3M9007_input_test.imn]

Optimization configuration:

Objective: Maximize returnloss without considering power loss

Frequency range: 400 -- 900 MHz

Algorithm: BOBYQA

Initial point: Previous optimal point

Optimization results:

Table 1. Optimal component values

Branch	R (Ohm)	L (nH)	C (pF)
1	0.0	3.7	3.6
2	0.0	8.5	10000.0
3	0.0	0.0	4.6

Minimum returnloss over selected frequenct range: 18.9 dB (at 398.0 MHz)

Maximum power loss over selected frequenct range: -0.1 dB (at 902.0 MHz)

Monte-Carlo simulation:

Table 2. Actual component values

Branch	R (Ohm)	L (nH)	C (pF)
1	0.0 (1.0%)	3.9 (2.0%)	3.6 (1.5%)
2	0.0 (1.0%)	8.2 (2.0%)	10000.0 (5.0%)
3	0.0 (1.0%)	0.0 (5.0%)	4.6 (1.0%)

Number of random curves: 100

Minimum returnloss over selected frequenct range: 18.2 dB (at 398.0 MHz)

Maximum power loss over selected frequenct range: -0.1 dB (at 902.0 MHz)

Figure 4.1.4 Statistical analysis report.

4.2 Integrate Real Component Model

The previous analysis is still assuming ideal component model. IMNLab supports integrating of real component models for analysis. This helps the user to obtain more meaningful simulation results. Double click the first empty cell of the row for component L1, the dialog for component viewing and selecting shows up. Click the "Browse" button to locate the S-parameter file for the component L1. Coilcraft inductor 0402HP-3N6XGL is imported for analysis, this is shown in Figure 4.2.1.

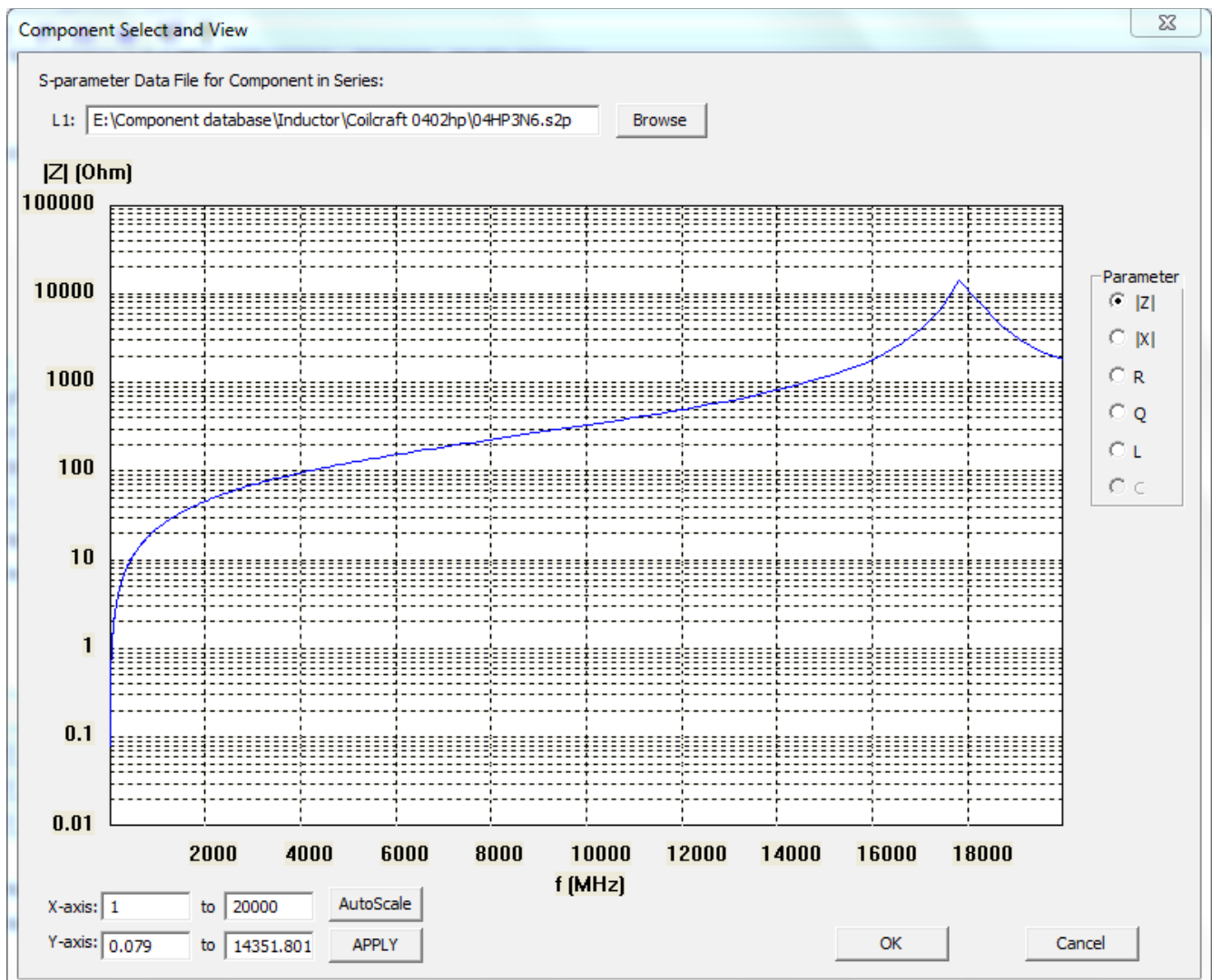


Figure 4.2.1 Component L1 parameter view and select.

The scaling is automatically set and the displayed parameter is magnitude of the total impedance. It may be more interested to view the equivalent inductance over the interested band. The equivalent inductance is defined as $X_L/(2\pi f)$, where X_L is reactance. By changing the parameter to “L”, and setting the frequency to 1-3000MHz and the inductance scale to 3.4 - 3.8 nH, the equivalent inductance of Coicraft 0402HP-3N6XGL is shown in Figure 4.2.2. The nominal inductance is 3.6 nH. The ringing at the low frequency may be caused by the measurement variations. The equivalent inductance is very close to the nominal value of 3.6 nH till 1000MHz. The equivalent inductance increases to about 3.7 nH at 3GHz. This implies this inductor is good enough to use this inductor in the UHF band 470 – 862 MHz.

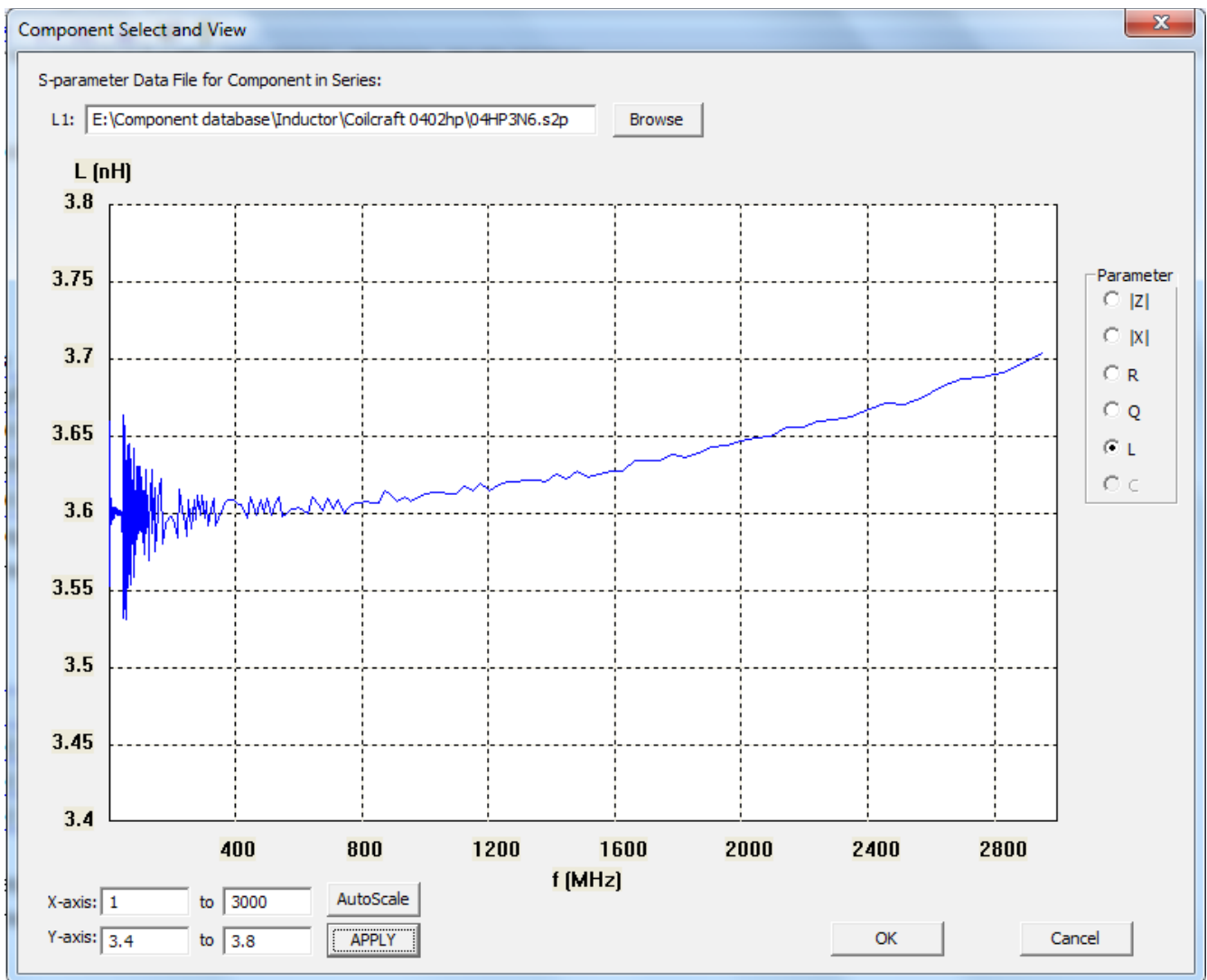


Figure 4.2.2 Equivalent inductance of L1 (Coicraft inductor 0402HP-3N6XGL).

Murata inductor LQW15AN8N7G80 is used for L2. The nominal inductance of this inductor is 8.7 nH. The equivalent inductance is shown in Figure 4.2.3. One see that the equivalent inductance is close to 8.5 nH in 400 – 900 MHz, which is actually the optimal result.

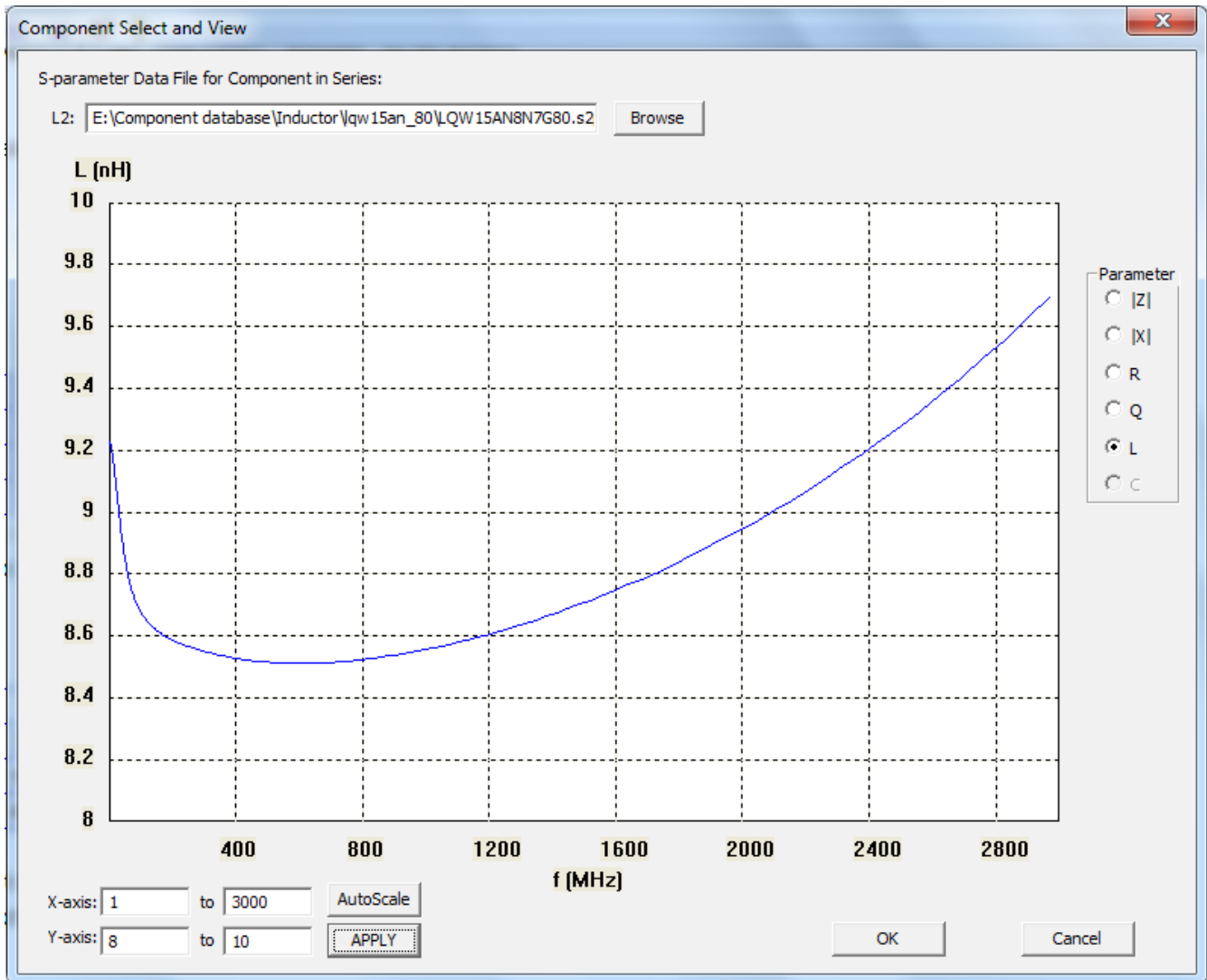


Figure 4.2.3 Equivalent inductance of L2 (Murata inductor LQW15AN8N7G80).

The equivalent capacitance of C1 (Murata GJM1555C1H3R6WB01) is shown in Figure 4.2.4. Due to the parasite serial inductance, the equivalent capacitance increases to about 3.75 pF at 1000MHz, 4.4 pF at 2000MHz. Those values are significantly higher than the nominal capacitance 3.6 pF.

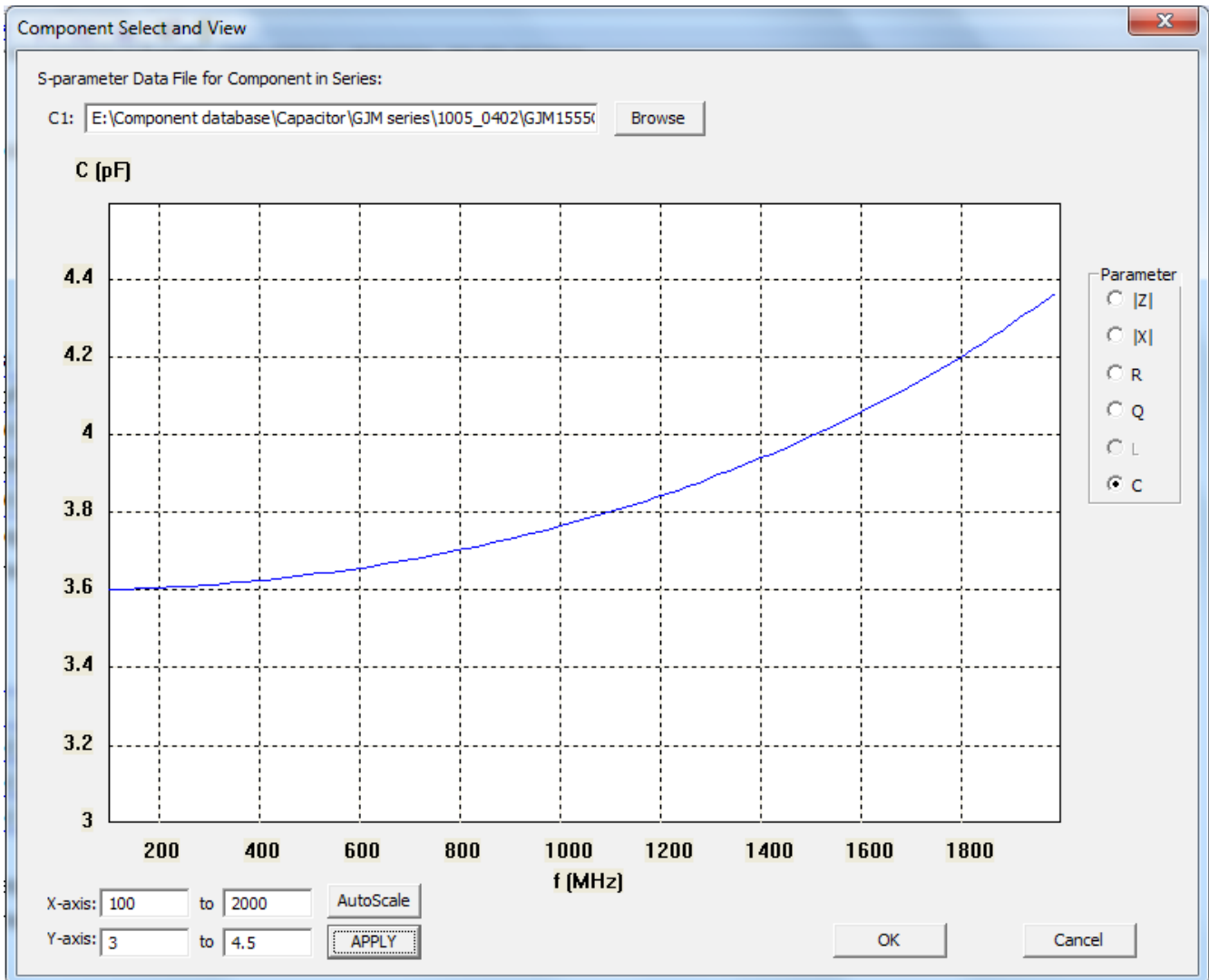


Figure 4.2.4 Equivalent capacitance of C1 (Murata GJM1555C1H3R6WB01).

The equivalent capacitance of C3 (Murata GJM1555C1H3R6WB01) is shown in Figure 4.2.5. The nominal capacitance is 4.3 pF. The equivalent capacitance increases to about 4.6 pF at 1000MHz, 5.6 pF at 2000MHz.

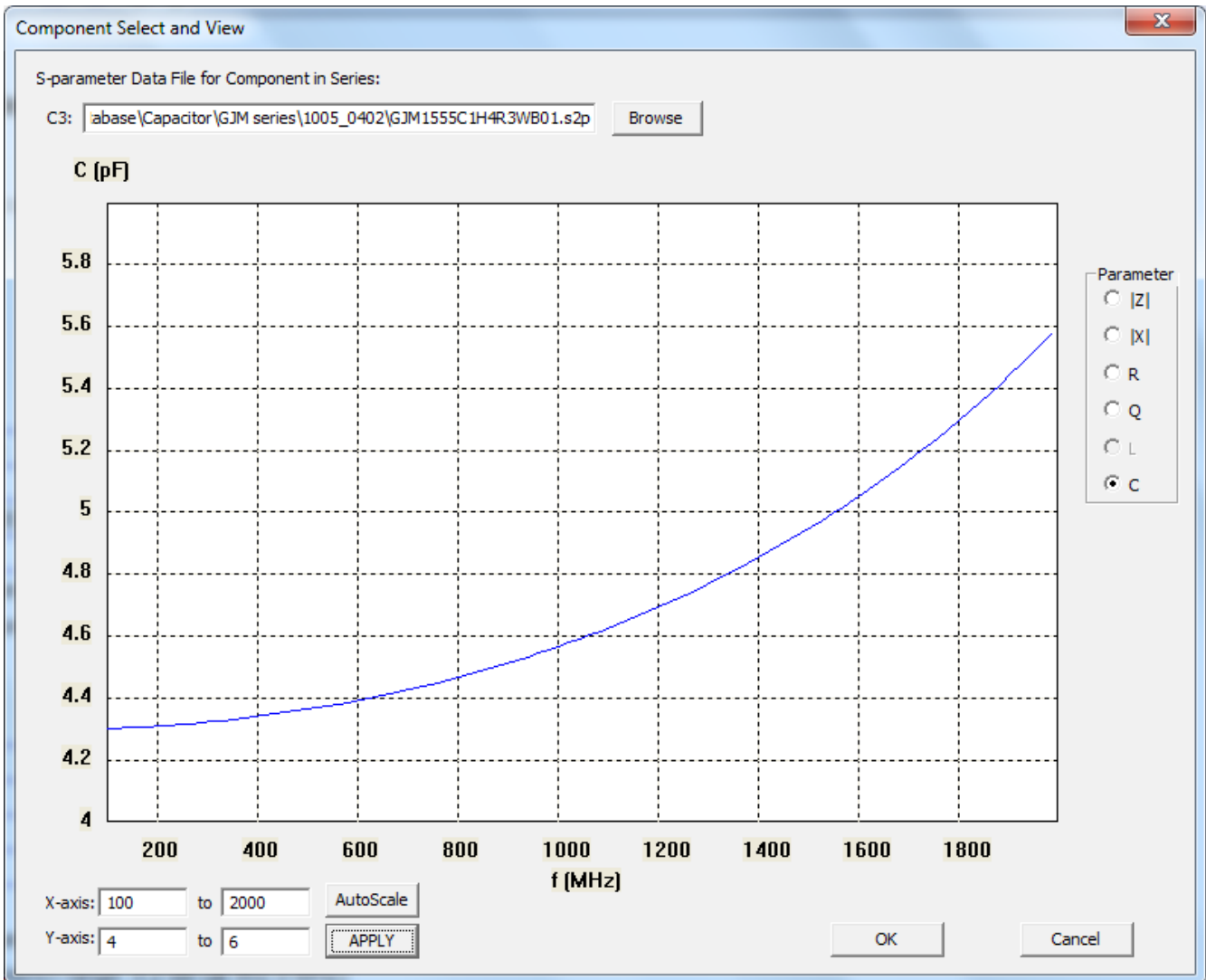


Figure 4.2.5 Equivalent capacitance of C3 (Murata GJM1555C1H4R3WB01).

After selecting the s-parameter files for all components and changing the model from “Ideal” to “S-parameter”, the configuration interface is shown in Figure 4.2.6.

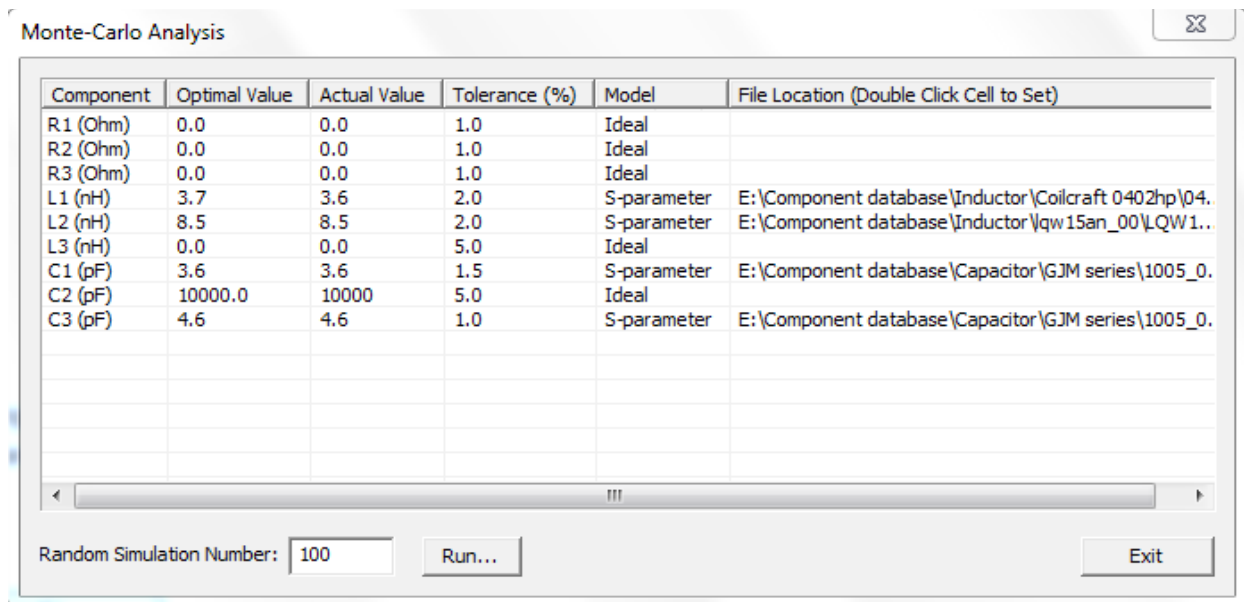


Figure 4.2.6 Component value/tolerance configuration with ideal components.

Click the “Run” button, the Monte-Carlo simulation results are shown in Figure 4.2.7. Compare the returnloss curves to the results in Figure 4.1.3, there exists some difference.

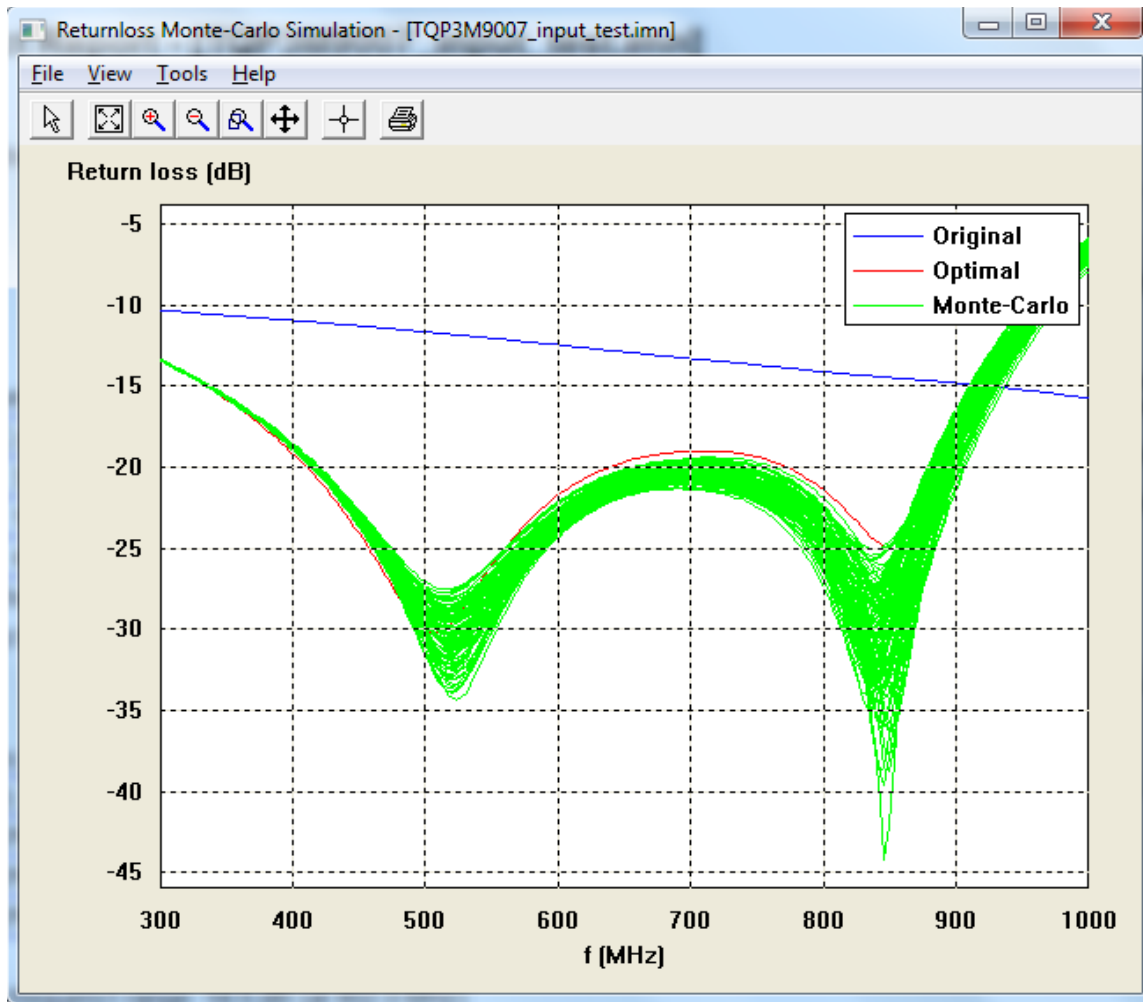


Figure 4.2.7 Statistical analysis of returnloss with real components characterized by s-paramter.

5. Test and Tune Impedance Match Network

After obtaining good results from simulation, it is time to test the optimal IMN on real circuit. There exists other parasite effect on the real board. One GND via contributes about 0.5nH serial inductance. One pad of EIA0402 package contributes about 0.1 – 0.5 pF shunt capacitance, depending on the distance to the reference plane. Also there exists mutual inductance between inductors if they are not placed orthogonal to each other. The ground bounce effects will decrease the inductance of a inductor as well.

Experienced RF engineers may optimize the PCB layout to reduce the parasite effect, but it is impossible to avoid it completely. Usually some tuning work is still needed to obtain optimal results on a real board.

Starting from the optimal IMN obtained from the simulation, then trim the component values gently based on the measured results on network analyzer. Usually the returnloss will have several ripples inside the interested band. The trick of manual tuning is to make the ripples have about the same height. After some tuning work, the real IMN ends with:

- L1: 3.3nH (Coilcraft 0402HP-3N3XGL 2%)
- C1: 3.6pF (Murata GJM1555C1H3R6WB01 +/-0.05pF)
- L2: 8.7nH (Murata LQW15AN8N7G80 2%)
- C2: 1nF (any C0G 0402 capacitor)
- C3: 4.3pF (Murata GJM1555C1H4R3WB01 +/-0.05pF)

The real circuit with input IMN is shown in Figure 5.1. Note that the first branch, composed by L1 and C1 in series, is closer to the amplifier input load. Branch 3, composed by C3 alone, is close to front connector and furthest from load. One see that L1 and L2 is mounted vertically to each other to avoid mutual coupling. Capacitor C2 is used to block DC bias voltage for amplifier.

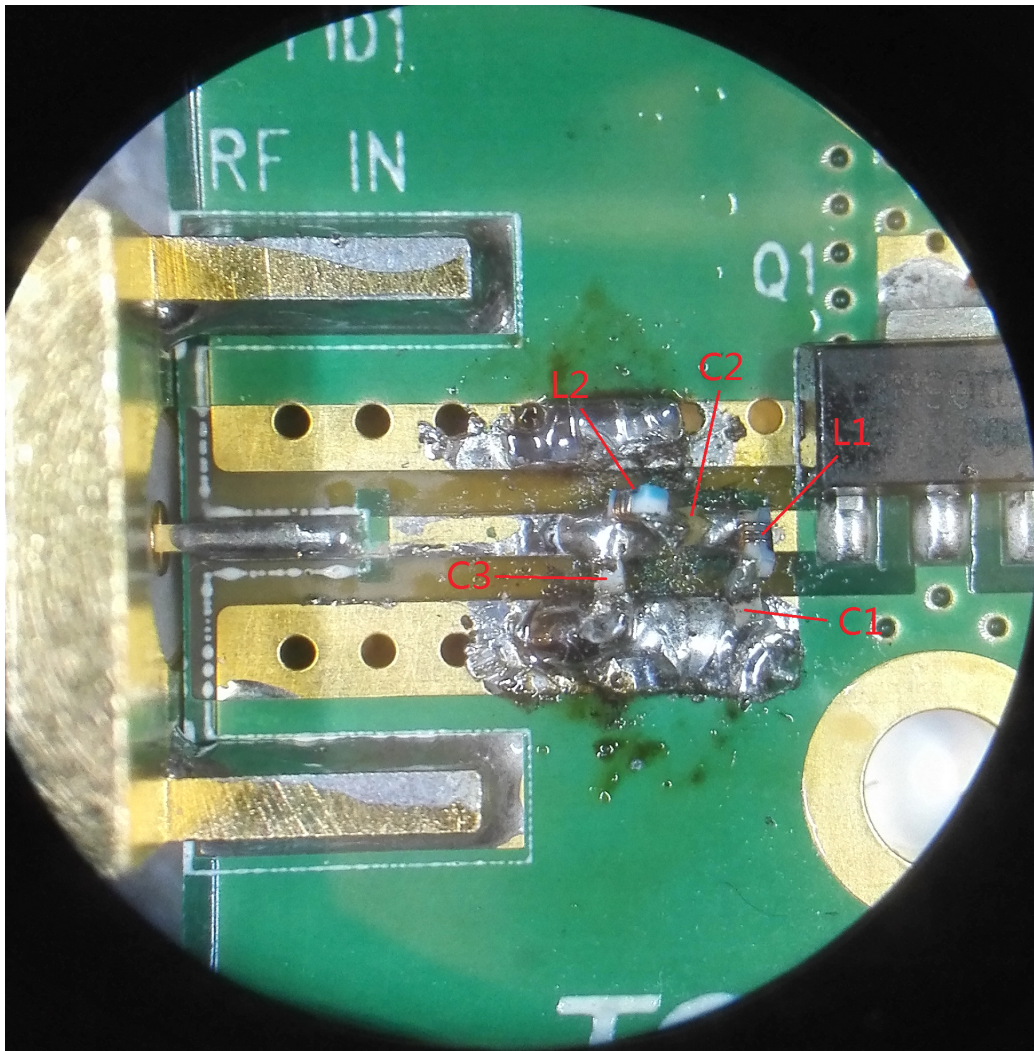


Figure 5.1 Optimal IMN for input port of TQP3M9007 evaluation kit.

The measured returnloss is compared to the simulation results in Figure 5.2. The simulation curve is obtained by using the s-parameters model provided by manufacturers. The measured curve matches well with the simulation results except at the two resonance points 510MHz and 850MHz. At the resonance points the returnloss is very low, a little deviation will cause significant difference in terms of dB.

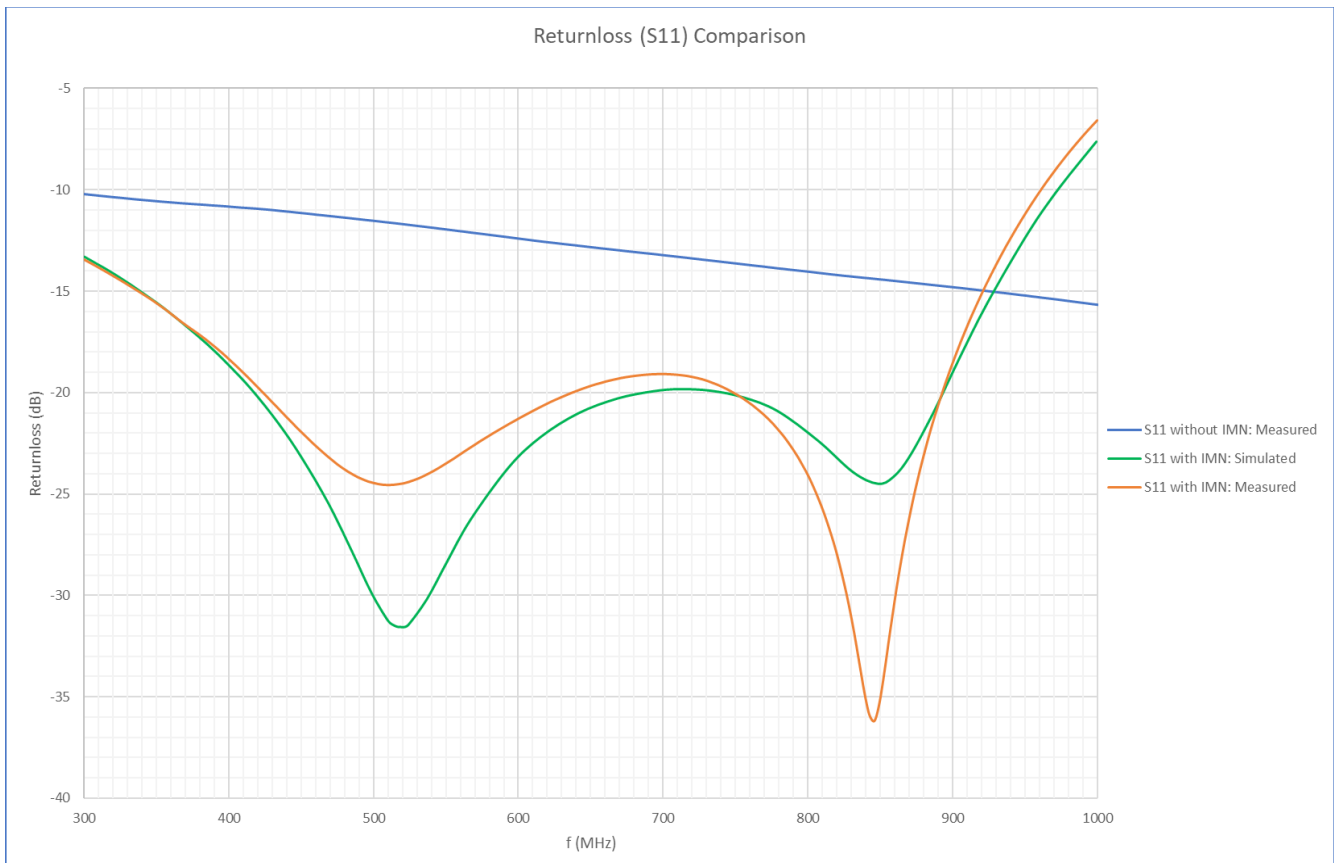


Figure 5.2 Returnloss comparison of simulation and measurement results.

5. Conclusion

In this tutorial the users are guided to design a wideband impedance match network for a real circuit by using IMNLab software. The simulated impedance match network is tested on the real circuit and the measurement results match well with the simulated results.