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Designing Impedance Matching Networks With the HP 8751A

Application Note 1202-1

HP 8751A
Network Analyzer
5Hz to 500 MHz

Summary: The built-in Conjugate Matching function of the HP 8751A makes designing two-element impedance matching networks as easy as using a marker.

Designing two-element impedance matching networks has never been easier. The Conjugate Matching function of the HP 8751A Network Analyzer saves you valuable design time and automates what was once a tedious design chore.

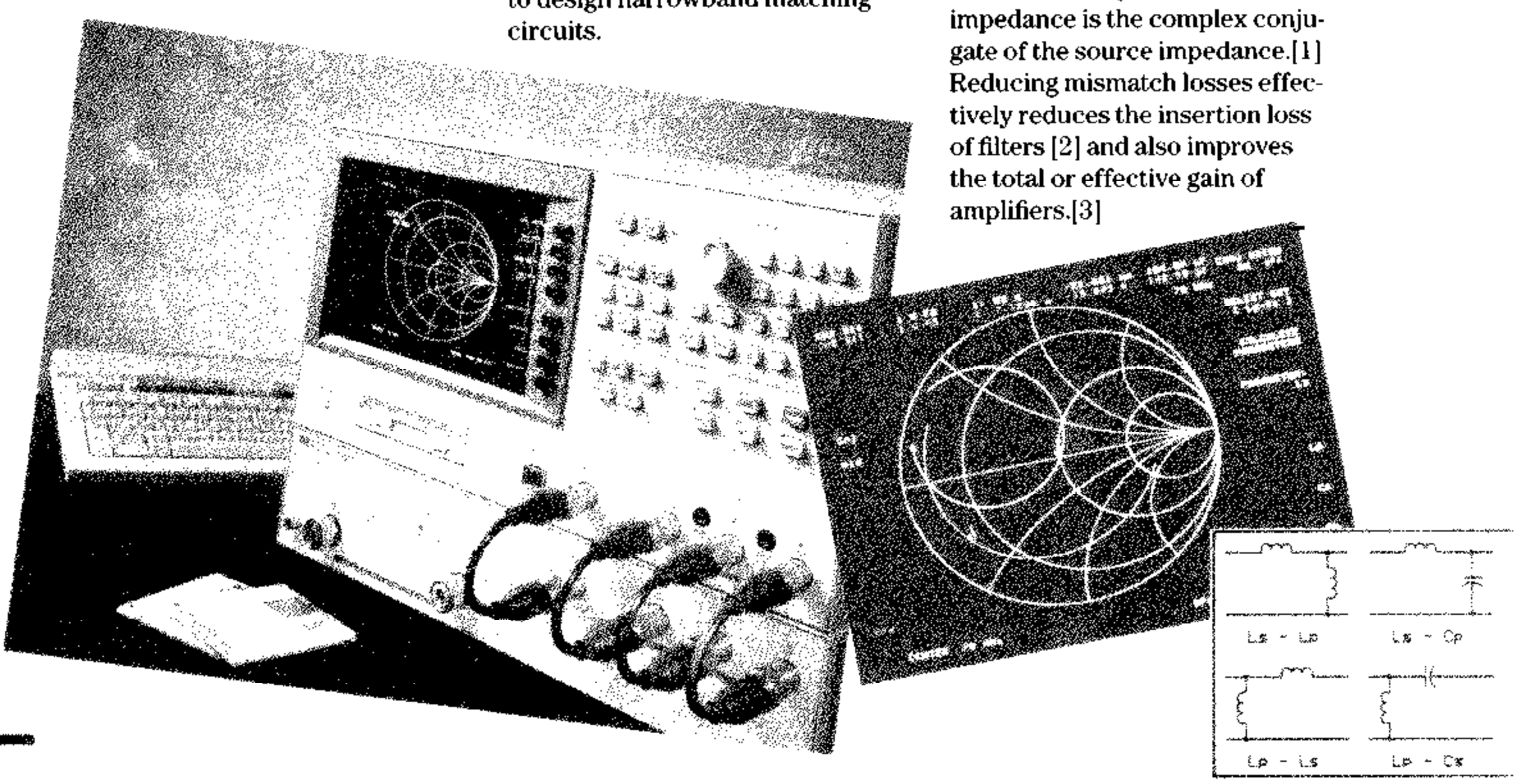
The Conjugate Matching function eliminates the mistakes associated with manual methods and the considerable experience needed for them. It also eliminates the need to transfer data to external software packages used in computer-aided design.

As the first instrument from Hewlett-Packard to integrate this productivity tool with vector network analysis, the HP 8751A redefines the capabilities of network analyzers by giving you a better way to design narrowband matching circuits.

Why Conjugate Match?

Unmatched circuit elements in a system result in mismatch losses. These mismatch losses decrease the total system gain. A direct result of this is a degraded signal-to-noise ratio in analog systems. In digital circuits, mismatches result in pulse degradation and can cause an increased bit-error rate.

Conjugate matching improves system gain by eliminating unwanted reflections, since maximum power is available only when the load impedance is the complex conjugate of the source impedance.[1] Reducing mismatch losses effectively reduces the insertion loss of filters [2] and also improves the total or effective gain of amplifiers.[3]



Using Conjugate Matching to Design Matching Networks

Design Matching Networks with a Network Analyzer

Vector network analysis is essential for measuring the magnitude and phase reflection characteristics of devices and circuits. But until now, analyzers could not use this information to design matching circuits. With the Conjugate Matching function, the HP 8751A both measures and helps you design.

Simple and Easy Matching

Save design time with Conjugate Matching. These features greatly simplify the task of designing two-element matching networks:

- Automatic evaluation of 8 circuit models with valid models indicated.
- Automatic parameter extraction. The HP 8751A calculates matching element values for you.
- Simulation of reflection characteristics with the derived matching circuit inserted. This displays the input (or output) reflection characteristics of the test device *together* with the matching circuit.
- Real-time simulation of reflection coefficient as the element values are altered.
- System impedance, Z_0, is adjustable on the HP 8751A. Using this feature, Conjugate Matching can match to 50 Ohms, 75 Ohms or other system impedances.

4 Steps to Matched Circuits

Using Conjugate Matching is easy. The needed softkeys {} are found under the DISPLAY hardkey [ ]. To use Conjugate Matching simply follow these steps:

1. Press [MKR] and move a marker to the frequency to be matched.
2. Press [DISPLAY], {CONJUGATE MATCHING}, {CALCULATE PARAMETERS}. The HP 8751A automatically selects the proper circuit model(s) and calculates the matching element values for the first valid model.
3. Press {CONJ MATCH on OFF} to ON. The status notation "Cnj" appears on the left side of the display.
4. To see the eight matching circuit models press {SELECT CKT}, the "*" notation indicates the other valid matching networks (see Fig. 3). Choose another model and press {CALCULATE PARAMETERS} to recalculate the element values for that model.

The result of using Conjugate Matching is seen in Fig. 1. The marker on the upper trace has moved to the center of the Smith chart, the point of perfect match.

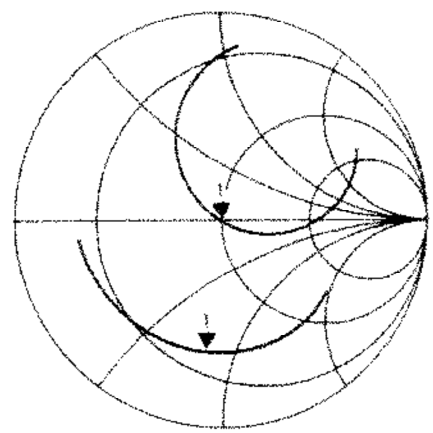


Figure 1.
S_{11} before and after Conjugate Matching on the HP 8751A

8 Models Offer Design Flexibility

Eight matching circuit models, as seen in Fig. 2, offer the designer flexibility in implementing the matching network. Depending on individual design considerations, the designer can select a particular model or let the HP 8751A choose the model and calculate the parameter values.

All the models are automatically analyzed each time Conjugate Matching is invoked. The HP 8751A usually finds several suitable models, indicated by "*" as shown in Fig. 3.

The designer may want to select a given model based on other design criteria [4], such as dc isolation, biasing, parasitics or device size. For example, inductance values may need to be minimized because discrete inductors are often large. By choosing the most appropriate model the designer can reduce the value and thus the size of a particular component. Another important attribute of the two-element models is that all eight of them are easily realized in discrete component form up to microwave frequencies [5].

Better Designs Through Simulation

'he simulation capability of Conıgate Matching improves your esigns by allowing you to better nderstand the affects of tolerance ariations and parasitics on reflec-.on. By varying component values nd then simulating the resulting ıatch, you see the effect of these ariations, *before* building a rototype.

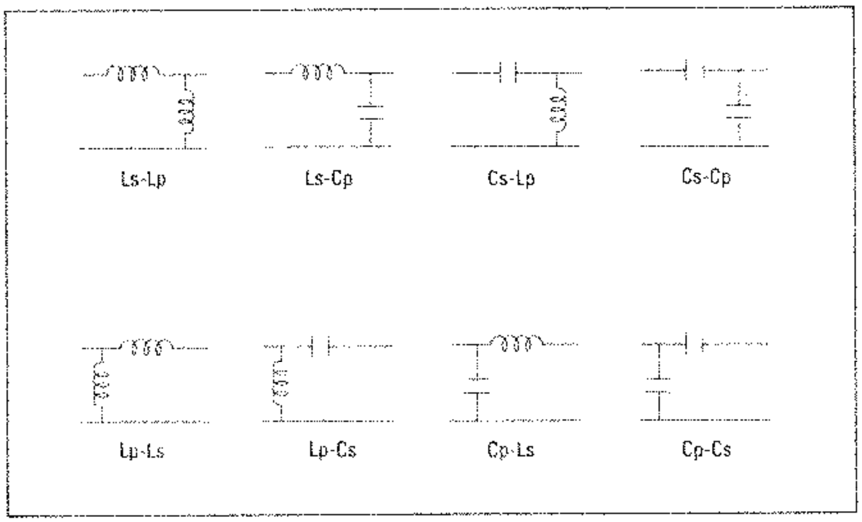


Figure 2. The HP 8751A decides which of these 8 models can be realized and calculates the element values.

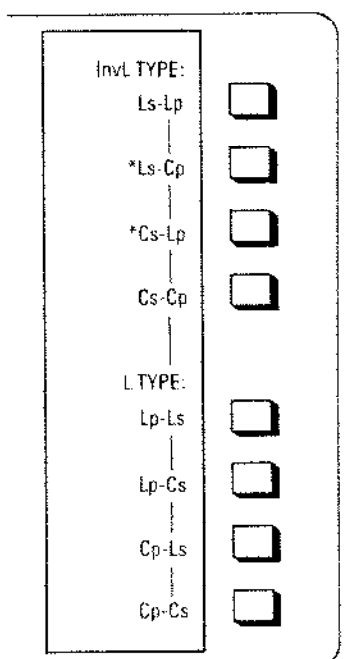


Figure 3. The Select Circuit menu shows which matching models are valid for a given device or circuit.

A Design Example

A 70 MHz crystal filter found in the IF strip of a communications transceiver will be examined and matched with Conjugate Matching. The system Z_0 is 50 Ohms. The input reflection coefficient, S_{11}, of the filter, before matching, is shown in Fig. 4.

The marker at 70 MHz is clearly not at the center of the Smith chart, indicating that impedance matching is necessary. This is also indicated by the fact that the resistive and reactive parts of impedance, R + jX, (read directly from the HP 8751A) is not 50 + j0 Ohms.

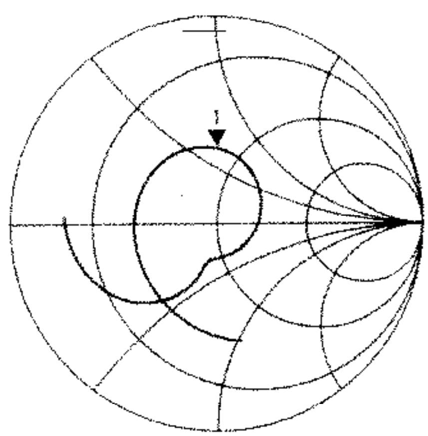
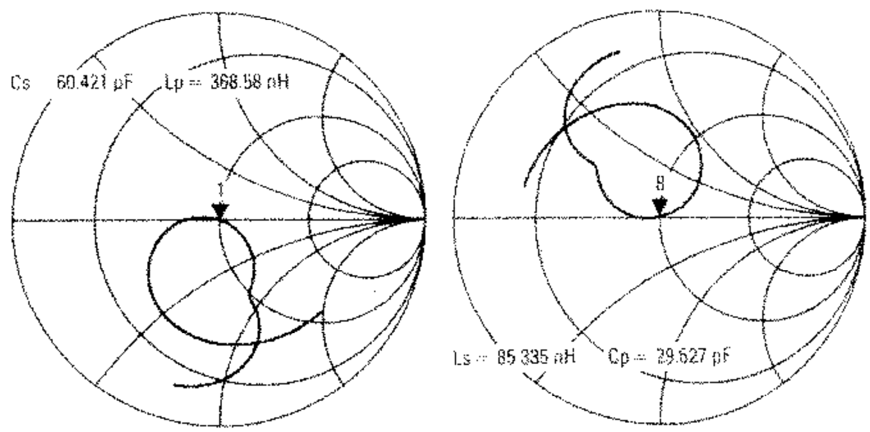


Figure 4. Conjugate Matching will be necessary for this filter since its match is poor at the 70 MHz center frequency.

Using Conjugate Matching yields two valid models, shown in Fig. 5a and 5b along with their element values and the predicted matches. Effective matching can be realized with either circuit, Cs-Lp or Ls-Cp. The two different models reflect the different ways matching can be performed on the Smith chart as discussed in the Appendix, Impedance Matching Theory.

Notice that the calculated element values in Fig. 5 are not off-the-shelf values. Clearly, standard values are preferred. Here the power of the simulation capability of the HP 8751A becomes apparent. We select the Ls-Cp model as seen in Fig. 5b. We change the extracted elements to the closest standard values, Ls = 82 nH and Cp = 33 pF from the keypad. Simulating the matched



a

b

Figure 5a & 5b. Conjugate Matching has found two matching networks to match the input of the filter: Cs-Lp or Ls-Cp.

response yields the results shown in Fig. 6. The marker position is virtually unmoved, so we conclude that this matching circuit composed of these off-the-shelf components can be used. By changing the [DISPLAY] format from {SMITH CHART} to {LOG-MAG}, the return loss can be compared before and after matching.

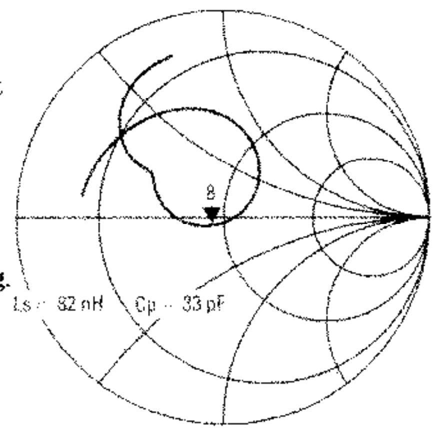


Figure 6. Using the Ls-Cp model from Fig. 5b with standard values yields this match.

Element values can be entered before or after extraction. They can also be changed continuously with the front panel rotary knob. This gives us the ability to see in *real-time* the matching variation based on component tolerances. Fig. 7 shows the resulting match when the L and C values vary by ±5% and ∓5% respectively, a worst-case condition.

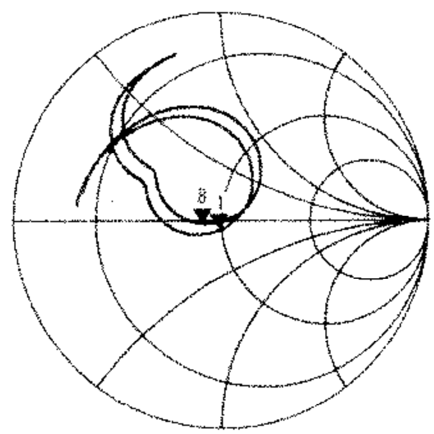


Figure 7. Predicted change in matching characteristics when both L and C vary by ±5 % and ∓5 %.

The bandwidth of two-element matching networks is adequate for most crystal, SAW (surface acoustic wave) and other high-Q devices with fractional bandwidths.

Conclusion

The HP 8751A simplifies and improves the design of two-element impedance matching networks with its built-in Conjugate Matching function. The automatic modeling and parameter extraction capabilities saves significant design time. The simulation capability offers designers insight into circuit behavior before the breadboard or prototype stage.

Appendix

Impedance Matching Theory

A mismatch exists if a device or circuit has input or output impedance different from the characteristic impedance, Z_0, of the source or the transmission line.

In an effort to avoid misunderstandings when analyzing mismatches and their effects on power measurements R.W. Beatty defined a complete set of specific terms. Included in this set is his definition of conjugate matching:

The condition for maximum power absorption by a load in which the impedance seen looking toward the load, at a point in a transmission line, is the complex conjugate of that seen looking toward a source. [6,7]

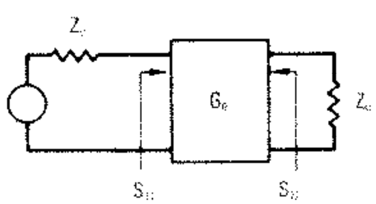


Figure 8. Mismatches will result if S_{11} and S_{22} are not equal to zero.

Matching circuits are introduced to eliminate these mismatches as illustrated in Fig. 9. By choosing impedance matching networks such that $\Gamma_S = S_{11}^*$ and $\Gamma_L = S_{22}^*$ maximum gain can be realized. [8]

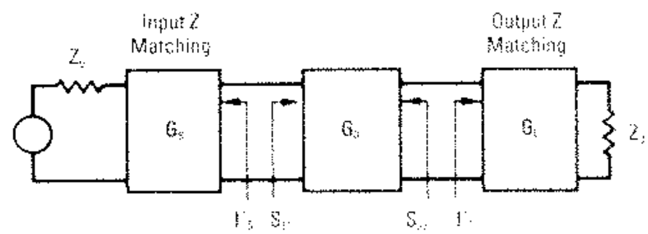


Figure 9. Mismatches are eliminated with matching circuits.

Matching on the Smith Chart

Impedance matching on the Smith chart is a well established technique. The introduction of the Smith chart [9] greatly simplified the time-consuming complex number calculations required for impedance transformations and provides a convenient graphical method of designing matching circuits.

Admittance varies along a constant conductance circle (grey line) from Z_2 to Z_1 by inserting an inductance in parallel with the device. And the impedance varies along a constant resistance circle (solid line) from Z_1 to Z_0 by inserting capacitance in series with the device as shown in Fig. 10.

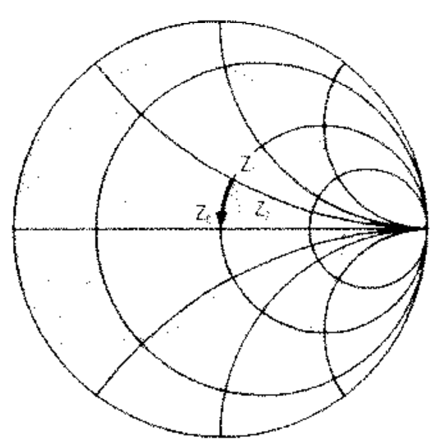


Figure 10. By traveling along constant resistance or constant conductance circles, lossless elements are used to design matching circuits

Impedance transformations on the Smith chart (Fig. 10) can be generalized by the following four rules:

1. Clockwise movement around constant resistance circles (solid circles) indicates increasing series inductance.
2. Counterclockwise movement around constant resistance circles indicates increasing series capacitance.
3. Clockwise movement around constant conductance circles (grey circles) indicates increasing shunt capacitance.
4. Counterclockwise movement around constant conductance circles indicates increasing shunt inductance.

By negotiating around the Smith chart in such a manner, one can transform impedance between any two points.

Translate to Element Values

These impedance transformations are realized by lossless elements, inductors (L) and capacitors (C). The values can be calculated from the change in the reactance or the susceptance of Z_0, Z_1 and Z_2 as shown in Fig. 10. The difference in reactance between Z_2 and Z_1 is realized with a shunt inductor. The move from Z_1 to Z_0 is achieved with a series capacitor.

Multiple Matches Possible

Note that in the above example in Fig. 10, we went counterclockwise twice. One just as easily could have performed the match by traveling clockwise. Because there are usually several ways of moving from any given impedance to the center of the Smith chart, multiple matching circuits are often offered by Conjugate Matching as seen in Fig 3. and in the design example.

References

[1] Adam, Stephen F., *Microwave Theory and Applications*, (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1969). p 231.

[2] Coon, Alan, Capabilities and Applications of SAW Coupled-Resonator Filters, *Proceedings RF Expo West, February 5–7, 1991*, (Copyright 1991, Cardiff Publishing Company) pp 537–542.

[3] Choma, John, Jr., *Electrical Networks, Theory and Analysis*, (Copyright 1985, John Wiley & Sons, Inc.) pp 190–193.

[4] Choma, John, Jr., ibid, pp. 193–197.

[5] Pengelly, R.S., and D.C. Rickard, "Design, Measurement and Application of Lumped Elements up to J-Band," *Proceedings, 7th European Microwave Conference*, (Copenhagen), 1977, pp 460–464.

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[8] Application Note 154, Hewlett-Packard Co.

[9] Smith, P.H., "A Transmission Line Calculator", *Electronics*, 12 (No. 1), 29 (1939). Also Smith, P.H., "An Improved Transmission Line Calculator," *Electronics*, 17 (No. 1), 130 (1944).

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