Impedance Matching Techniques for Mixers and Detectors

Application Note 963

Introduction

The use of tables for designing impedance matching filters for real loads is well known [1]. Simple complex loads can often be matched by this technique by incorporating the imaginary portion of the load into the first filter element [2]. This technique is rarely useful for matching diodes because the equivalent circuit for the diode must include several real and imaginary elements. A methodical technique for matching such complex loads to a transmission line will be described. Previous references[3] to similar procedures were empirical in nature. No tables are used, but it is necessary to know the admittance of the diode in the frequency band of interest.

Mixer Diode Admittance

As an example, the Agilent Technologies 5082-2709 mixer diode will be matched from 8 GHz to 12 GHz. A common local oscillator power level is one milliwatt, but it is not useful to measure the diode admittance at this level. The admittance is a function of power absorbed, so the diode admittance would change when the matching circuit is added. A matching circuit designed for the diode admittance measured with one milliwatt incident would be incorrect for a diode absorbing one milliwatt. The correct measurement of diode admittance must use more power so that the diode absorbs one milliwatt. A convenient method monitors the rectified current. A level of 1.5 milliamperes is indicative of one milliwatt absorbed.

Figure 1 shows the measured admittance of the 5082-2709 mixer diode. Some computer analysis programs can work with a load characterized in this way. However, in many cases, the equivalent circuit must be defined. The circuit shown in Figure 1 is commonly used for mixer diodes. The values shown were obtained by a computer optimization program. The program changes the values until the calculated admittance at several frequencies is close to the measured admittance. Although the impedance matching will be done at X band, a more accurate equivalent circuit was obtained by using a broader band of frequencies in the computer optimization procedure.
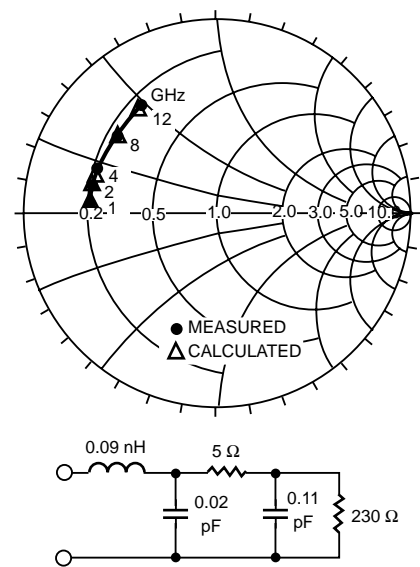

Figure 1. Admittance of 5082-2709 Beam Lead Mixer. 1.5 mA Rectified Current.

Narrow Band Matching

The simplest type of impedance matching would be to match at the center frequency and accept the results at other frequencies. A common technique for single frequency matching is shown in Figure 2. A length of transmission line is used to rotate the immittance to the unit real circle, then the appropriate inductance or capacitance is added to reach the center of the Smith Chart. The equivalent series resistance of the diode at 10 GHz is close to 50 ohms, so it is not necessary to add a length of line to reach the unit resistance circle. A 1.4 nH series inductance will match the diode at 10 GHz (Figure 2A). However, this circuit is incomplete, since a dc return is necessary for successful mixer operation. This could be provided by a large shunt inductance, or the diode could be tuned by a shunt inductance. In this case a length of line is needed to move the susceptance to the unit conductance circle before adding 0.45 nH in shunt (Figure 2B). The VSWR at band edges is 3:1 with shunt tuning, while it is less than 2:1 with series tuning.

Broadband Matching

Broadband design techniques must consider the entire frequency band in the matching procedure. It is usually sufficient to work with the center and end frequencies. A two-step procedure is shown in Figure 3A. First a length of series transmission line is added to the mixer diode to make the conductance at band edges equal to the inverse of the conductance at resonance (Y_1). The other element in the matching circuit is a shunt resonant transmission line shorted to ground, to bring the band edge admittances together (Y_2). The final admittance curve is shown expanded in Figure 3B. Characteristic impedance and length are best determined by solving the resonance equations at band edge frequencies.
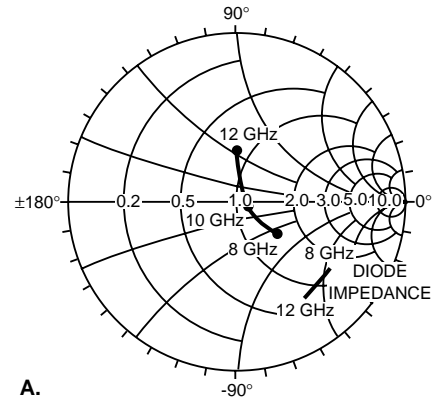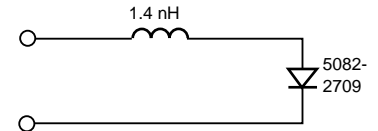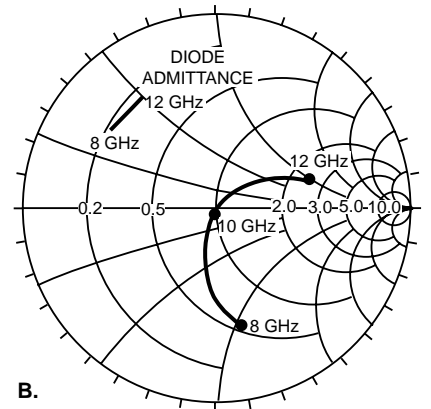

Figure 2A. Single Frequency Series Tuning, Impedance Coordinates.
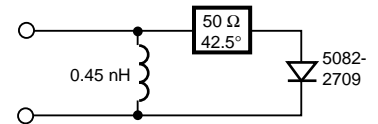

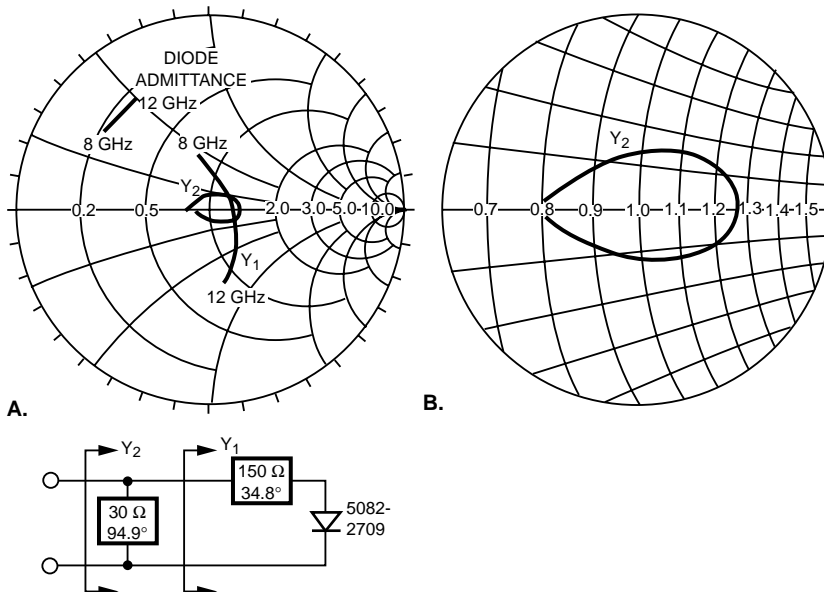**Figure 2B. Single Frequency Shunt Tuning, Admittance Coordinates.**

Figure 3. Two Element Mixer Matching Circuit, Admittance Coordinates.

Let Θ be the electrical length at 8 GHz. From Figure 3A the resonance equations for normalized admittance are:

$$\frac{50}{Z_0 \tan \Theta} + 0.42 = 0$$

$$\frac{50}{Z_0 \tan 1.5\Theta} - 0.75 = 0$$

$$\Theta = 75.9°$$

$$Z_0 = 30 \text{ ohms}$$

Unfortunately, this simple technique does not usually yield realizable values of characteristic impedance. For example, in this case a line impedance of 150 ohms is required. A one mil wide line on 10 mil alumina corresponds to 97 ohms and this is a reasonable limit on microstrip transmission lines.

Introducing realizability into the problem requires a third element in the matching circuit. Limiting the first transmission line to 100 ohms introduces asymmetry into the Smith Chart plot, as shown in Y_1, Figure 4.

It is not possible to make the conductance at band edges equal the inverse of the band center conductance. The criterion for determining the length of the 100 ohm transformer is the equality of the band edge conductances. When the shunt resonant circuit is added, the center frequency mismatch is much worse than the end frequency mismatch (Y_2, Figure 4A). The extra circuit element needed is a transformer with characteristic impedance and length chosen to center the admittance plot on the Smith Chart (Figure 4B). The value of this characteristic impedance is found by the designer interacting with the time shared
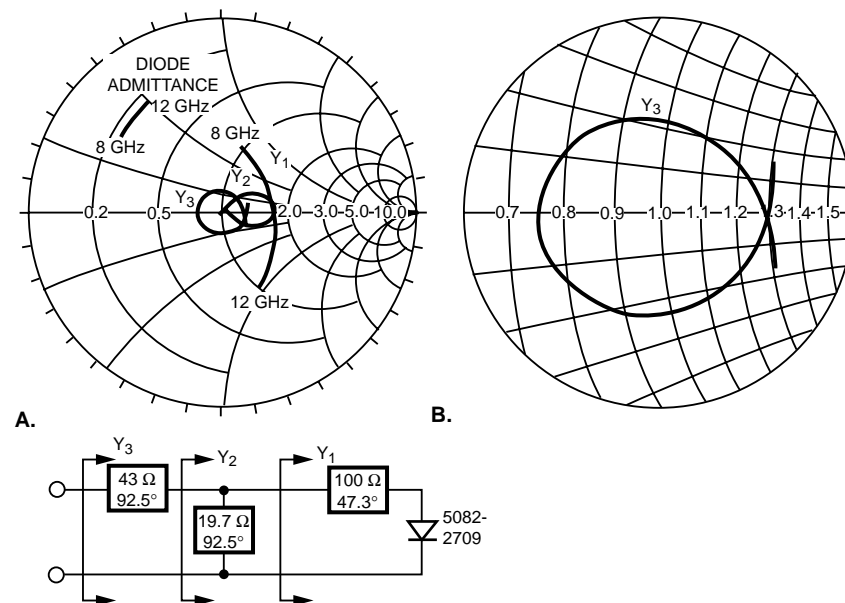

Figure 4. Three Element Mixer Matching Circuit, Admittance Coordinates.

computer analysis program until the maximum standing wave ratio is minimized.

A good starting value for the transformer characteristic admittance is found by estimating the final value of center frequency conductance and calculating the geometric mean of this value and the value at Y_2, 1.7 x 0.02 (Figure 4A). The final value may be estimated by assuming the final admittance plot will have the same diameter on the Smith Chart as Y_2. Attempts to improve the performance with a computer optimization program produced no significant change in the circuit shown in Figure 4.

Detector Diode

With a small amount of dc bias, the 5082-2709 beam lead diode makes an excellent detector diode. The matching procedure will not be so successful in this application, because the admittance is farther from the center of the Smith Chart and is more dispersive. Figure 5 shows the measured admittance of the diode with 50 microamperes bias current and the equivalent circuit obtained with the computer optimization program. The circuit elements representing package parasitics were assumed to be the same for this application as for the mixer application.

Figure 6 shows the three steps in the matching procedure for the detector diode. The 8.2 ohm characteristic impedance required for the shunt resonant transmission line would be difficult to realize. By using two lines in shunt, the characteristic impedance of each is doubled to a more practical value of 16.4 ohms. This technique also reduces parasitics by maintaining symmetry.

Although the maximum VSWR of 3.6 obtained in this example is adequate for many detector applications, a smaller reflection coefficient is required in some cases in order to avoid deterioration of performance of adjacent circuits. It is possible to improve the design by using both series and shunt resonant circuits to make a double loop on the Smith Chart. However, such a complicated circuit would be difficult to realize. It is often permissible to sacrifice some sensitivity in order to improve the VSWR. In this case the technique shown in Figure 7 is suggested. Here the maximum VSWR is reduced below 1.7 by first moving the diode admittance closer to the center of the Smith Chart by adding a 300 ohm shunt resistor across the diode. The three matching elements are then added.
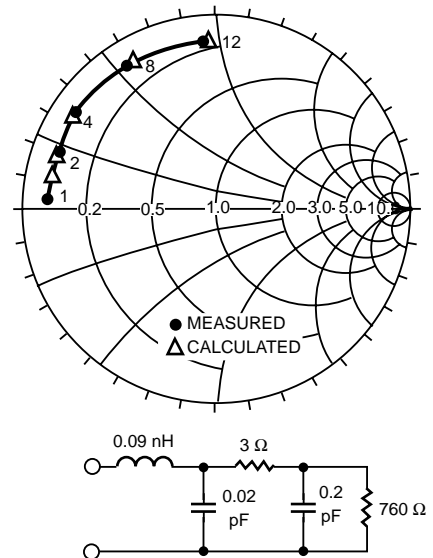

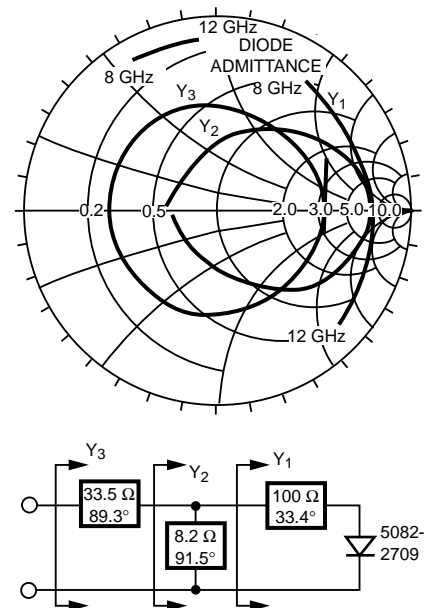**Figure 5. 5082-2709 Beam Lead Diode Admittance, 50 μA Bias.**

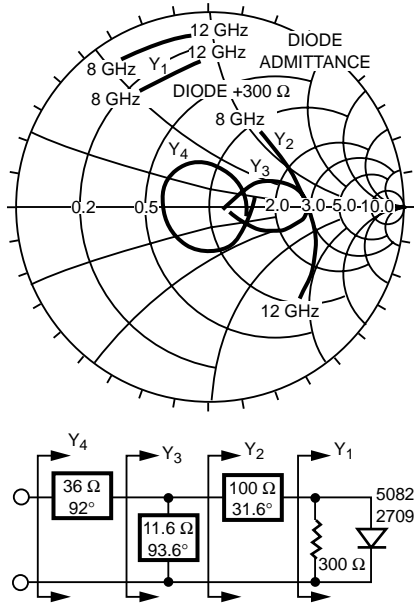**Figure 6. Matching the Detector Diode, 50 μA Bias, Admittance Coordinates.**

Figure 7. Resistive Matching of Detector Diode, 50 μA Bias, Admittance Coordinates.

Sensitivity may be traded for VSWR by adjusting the value of the shunt resistor. Figure 8 illustrates this tradeoff. An unmatched detector diode has a sensitivity of 1.5 millivolts per microwatt. A broadband reactive matching circuit (Figure 6) causes about 1 dB loss due to reflection. Improving the match with a shunt resistor of 1000 and 300 ohms causes more loss due to power absorbed by the resistors. However, sensitivity loss due to reflections from an unmatched diode is one or two dB worse than that due to the matching network using a 300 ohm resistor.
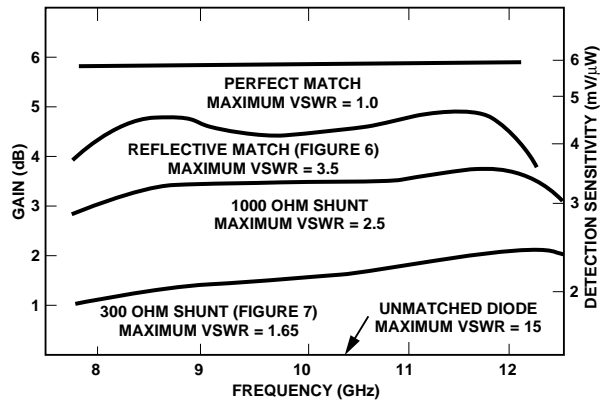

Figure 8. Gain of Detector Matching Networks.

Another technique for reducing mismatch loss in detector diodes is the use of increased bias current. This reduces the junction resistance so the diode is a better match to the 50 ohm transmission line. Unfortunately the reduction of junction resistance increases the loss in the diode series resistance. The net loss is always more than the loss in the shunt resistance required to achieve the same VSWR without increasing bias current. Figure 9 shows how tangential sensitivity deteriorates as VSWR improves for the two techniques. In every case, the shunt resistance provides a more sensitive detector for the same VSWR.

Another way of adding the third reactive element in the matching circuit is the use of a shunt inductance or a shunt inductive line at the diode terminals. This allows the admittance to be rotated counter-clockwise on the Smith Chart to a location where a realizable high impedance transformer or a lumped inductance can satisfy the dual requirement of equal band edge conductances equal to the inverse of the center frequency conductance.
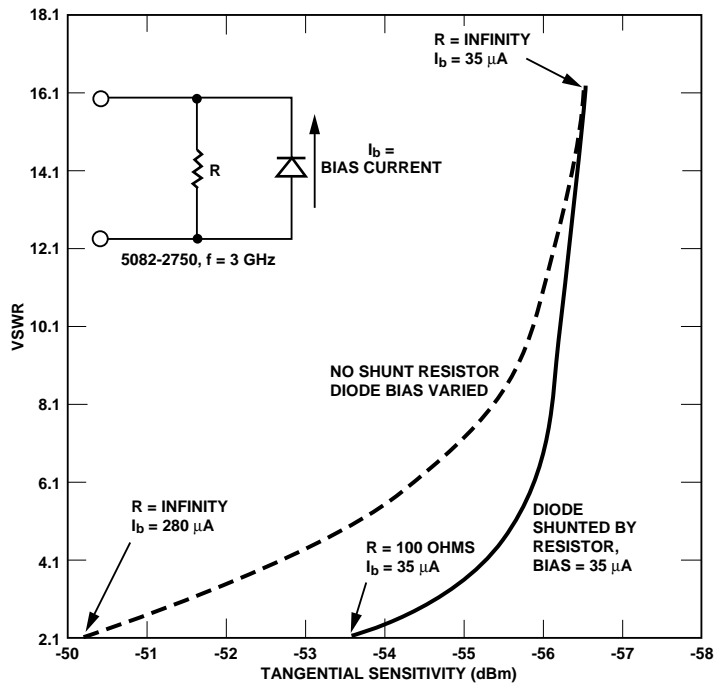

Figure 9. Comparison of VSWR using either Shunt Resistor or Increased Bias.

A combination admittance-impedance Smith Chart is useful for finding the value of this shunt inductance. Point A (Figure 10) is the immittance of the diode-300 ohm shunt resistor combination at 10 GHz. We'll assume the final 10 GHz normalized admittance to be ˜G = 1.5. This point will be reached along the ˜R = 1/1.5 circle by adding a series inductance. The initial shunt inductance then must move point A along the ˜G = 0.27 circle to the ˜R = 1/1.5 circle. To reach the intersection, point B, requires shunt inductance corresponding to the difference between the susceptance at these two points.

$$\frac{1}{2\pi\,10\,L} = 0.0148 - 0.0117 = 0.0031$$

$$L = 5.1 \text{ nH}$$

The series inductance to reach point C, 1.2 nH, is chosen to make the band edge conductances equal.
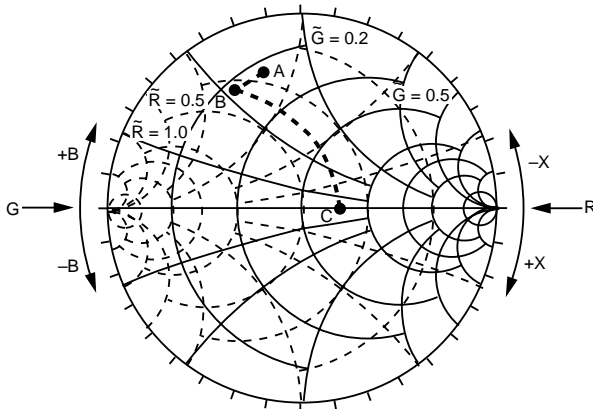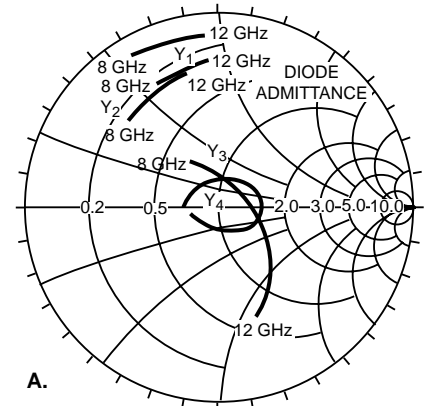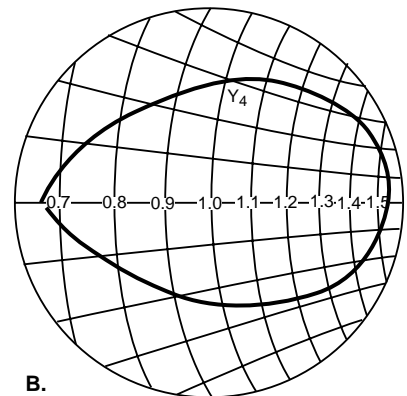

Figure 10. Detector Matching on Immittance Chart.

Figure 11 shows the admittance from 8 GHz to 12 GHz at each stage of the design – shunt inductance at A, series inductance at B, and finally the resonating shunt shorted line at C. The final admittance is expanded in Figure 11 B. The maximum VSWR is 1.55, slightly better than the 1.66 value of Figure 7.

Although the calculations show improved performance with lumped elements, the question of realizability must be considered. Spiral coils on microstrip make excellent inductors [4] [5] until the distributed capacity between turns becomes excessive. Figure 12 shows the empirical limits on inductance for these coils.
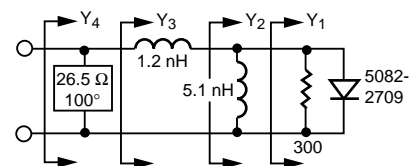

Figure 11. Detector Matching with Shunt Inductance, 50 μA Bias, Admittance Coordinates.
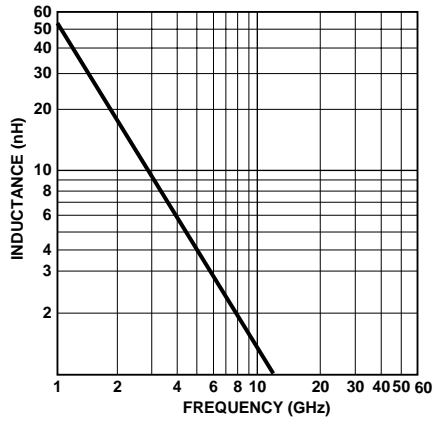
Figure 12. Maximum Inductance of Microstrip Coils.

The proposed shunt inductance of 5.1 nH is clearly too large. The equivalent shunt shorted line is approximated by equating reactance at 10 GHz. Characteristic impedance is set at 100 ohms to best approximate the lumped inductance.

$$2\pi 10 \times 5.1 = Z_O \tan \Theta = \tan \Theta.$$

$$\Theta = 72.7°$$

The same series inductance is used and a shunt shorted line resonates band edges. The result is shown in Figure 13. The more dispersive shunt line replacing the 5.1 nH inductor is responsible for a higher band edge VSWR. The performance is now worse than that of Figure 7.
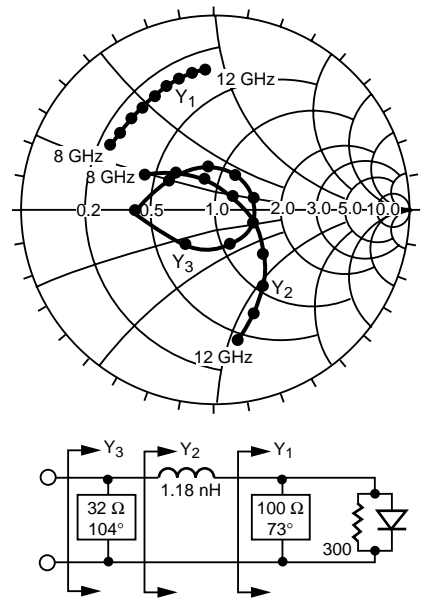

Figure 13. Detector Matched with Shunt Transmission Line, 50 µA Bias, Admittance Coordinates.

An analysis of lumped element matching procedures by Thomas [6] predicts that a series initial element will provide maximum bandwidth. Substituting a lumped inductance for the 100 ohm line in Figure 7 does show slight improvement over Figure 11. This is shown in Figure 14A and B. When the lumped inductance exceeds the limits of Figure 12, best performance is obtained by using the limiting lumped inductance in series with the necessary distributed element needed to provide the proper reactance.
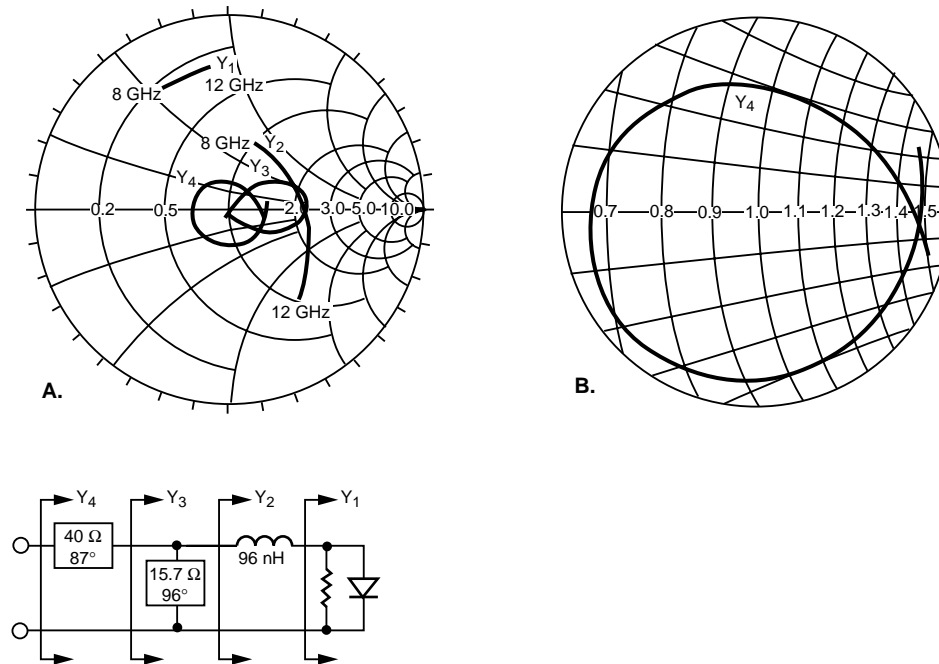

Figure 14. Detector Matched with Initial Series Element, 50 μA Bias, Admittance Cordinates.

Conclusion

An empirical procedure for designing matching circuits for mixers and detectors has been described. Optimum designs are achieved without the use of computer optimization procedures.

References

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3. LaCombe, D., "Thick-Film Limiter-Detector Reduces Receiver Costs", Microwave System News, August, 1973, pp 37-42.

4. Daly, D. et al, "Lumped Elements in Microwave Integrated Circuits" IEEE Trans. MTT Vol. MTT-15, pp 713-721, December 1967.

5. DeBrecht, R., and Caulton, M., "Lumped Elements in Microwave Integrated Circuits in the 1-12 GHz Range", G-MTT Digest, 1970, pp 14-18.

6. Thomas, R., "Broadband Impedance Matching in High-Q-Networks", EDN pp 62-69, Dec. 20, 1973.

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