Design of a Power Detector with a Zero-Bias Schottky Diode

A power detector is an important part of many microwave systems. For an example, it is frequently used in transmitter systems to monitor a power coming out from a power amplifier. If connected in a loop with a variable attenuator and control logic circuit, the power of the amplifier can be adjusted to a required level. At the receiver side, a power detector can be used in several ways. In channelized receivers, comprising a battery of narrowband filters, a power detector can be placed at each filter output allowing instantaneous monitoring of the spectrum with a resolution of a filter cell in the frequency span of the battery. Furthermore, along with the increased interest in researching the possibilities for simplifying transceivers, implementation of power detectors has reemerged. The most promising solution, the so-called six-port topology, utilizes power detectors at the receiver side to replace classical method of signal down-conversion to baseband using a mixer.

This application note describes some practical aspects of designing a power detector with a zero-bias Schottky diode for various applications using WIPL-D Microwave design environment.

Design of a Non-matched Detector

The simplest way to design a detector is to utilize a zero-bias diode, place it on the 50 Ω transmission line, and provide adequate paths and short circuits for DC and RF currents. A zero bias diode does not require any external bias to operate as a detector, and for number of applications non-matched design is adequate. Example of a non-matched detector will be presented for the center frequency of 24 GHz and span of 250 MHz. A dielectric substrate selected for the design has a relative dielectric constant εr=3.5, and thickness h=0.254 mm.

A schematic representing a non-matched detector is presented in Fig. 1. Lumped elements are used to model a diode. Resistor Rs=10.3 Ω models a series diode resistance. A capacitance Cj=0.13 pF arises from the capacitance of a diode junction, while resistance Rj models junction resistance. For zero-bias diodes, junction resistance has a very high value and can be excluded from the schematic. However, many detector diodes are used with a bias and in that case the influence of Rj must be considered. Diode is grounded on the cathode side for a microwave signal.

Schematic from Fig. 1, where analytical models have been used to model microstrip elements, is very simple as matching is not required. The short taper is used as an interface for adjusting relatively narrow line used to connect the leads of the diode to a terminal 50 Ω microstrip line. Between the taper and the circuit port, a shunt quarter wavelength long transmission line is connected with both, a radial stub and short circuit to ground connected at the other end. A radial stub is basically a wideband capacitance to the microstrip ground. Accordingly, it represents a short circuit for a microwave signal which transforms into open at the connection with the terminal line. Therefore, the terminal line is not loaded by the presence of the short. As indicated, in parallel to the capacitive connection to the ground for a microwave signal, a conductive connection to the ground must be made to allow flow of detected DC current through the diode. This physical connection is conveniently made by using a via (plated through hole). However, at microwave frequencies, the parasitic inductance of via results in a relatively high reactance and performance of via connection to microstrip ground significantly deviates from a short circuit for a microwave signal making pairing with a radial stub necessary.

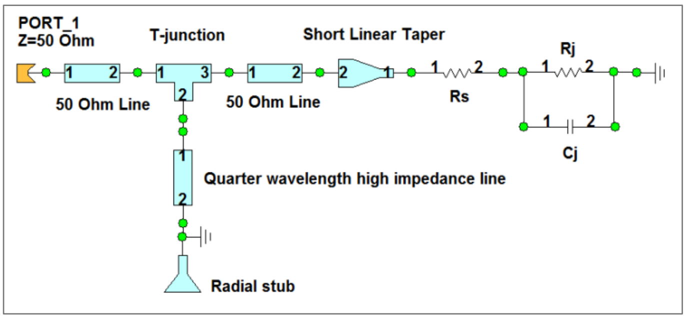

Figure 1. Schematic of the non-matched power detector using analytical microstrip elements from WIPL-D Microwave library.

Microstrip layout of non-matched power detector is shown in Fig. 2. It has been generated as an electromagnetic (EM) component directly from a schematic similar to that from Fig. 1 with a single mouse click using a powerful schematic export to 3D EM Model feature available in WIPL-D Microwave. The only adjustment to the schematic a user has to make involves removing the schematic representation of Rs, Cj, Rj and ideal connections to ground, as these schematic elements do not have adequate layout representation

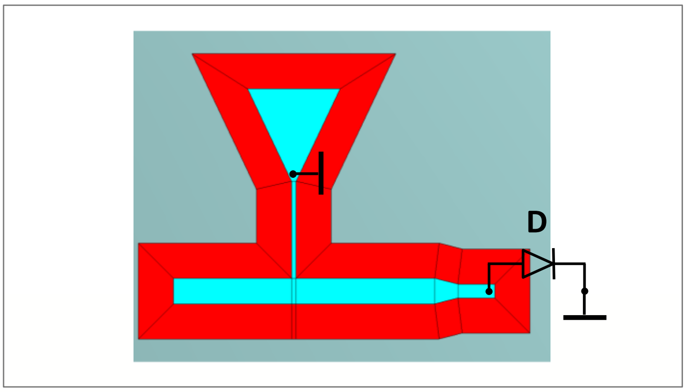

Figure 2. Microstrip layout of non-matched power detector automatically generated from a circuit schematic.

The layout shown in Fig. 2 is for illustration purposes only as it is not necessary to introduce an EM component to accurately model the circuit from Fig. 1. For such a simple circuit calculations using analytical microstrip models are sufficiently accurate. Calculated values of return loss of the non-matched detector circuit are presented in Fig. 3. A value of the return loss is approximately 2 dB in the frequency band 22-26 GHz.

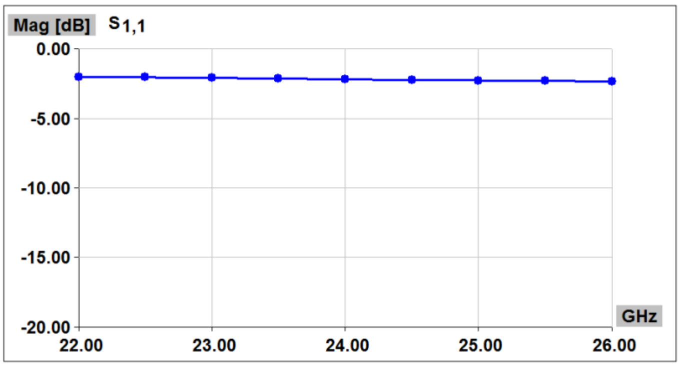

Figure 3. S parameters of the schematic from Fig. 1.

When a detector with such a high return loss value is used in a transmitter power control loop, it is preceded by a directional coupler with a typical coupling coefficient value in the range of -20 dB, or less. Due to the loose coupling, high return loss of a non-matched detector does not affect the performance of the amplifier, or a transmitter chain as a whole.

Design of a Matched Detector

In applications where a detector is used after a filter or connected at the ports of a six-port receiver, a high level of return loss has significant effect, as the performance of these circuits is very sensitive to a value of the impedance presented at the terminals. For such applications, a good match of power detector is essential. The location of diode reflection coefficient in the Smith chart is shown in Fig. 4.

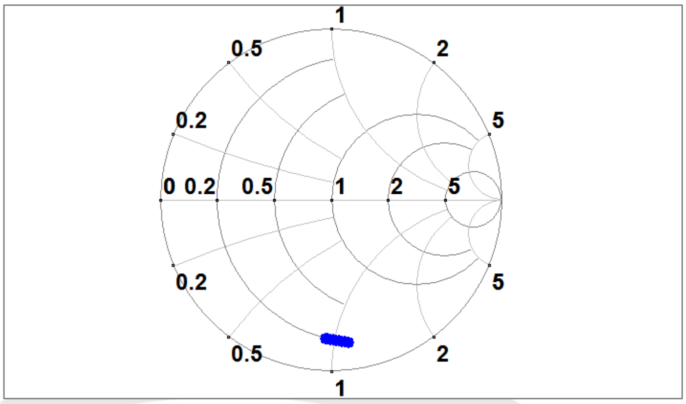

Figure 4. Diode reflection coefficient.

A simple matching network should be used to match the diode or otherwise the insertion loss introduced by the network may affect the sensitivity of the detector. An example of such a network comprising only two lumped elements is presented in Fig. 5. The schematics also contain a transmission line to model the diode pad effect, which is not negligible at the frequency of interest. The recommended pad size is indicated in the figure. The simulated return loss with the lumped elements values optimized is displayed in Fig. 6. Return loss values are significantly improved comparing to the non-matched case reaching a maximum of approximately 15 dB at 24 GHz.

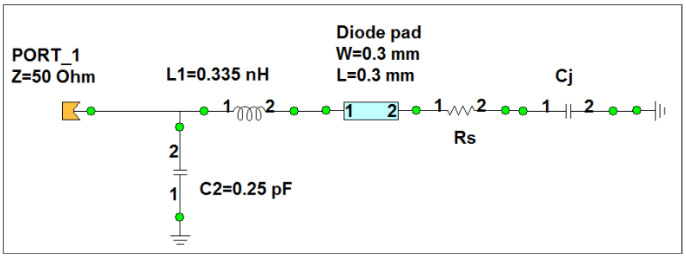

Figure 5. Lumped element matching circuit.

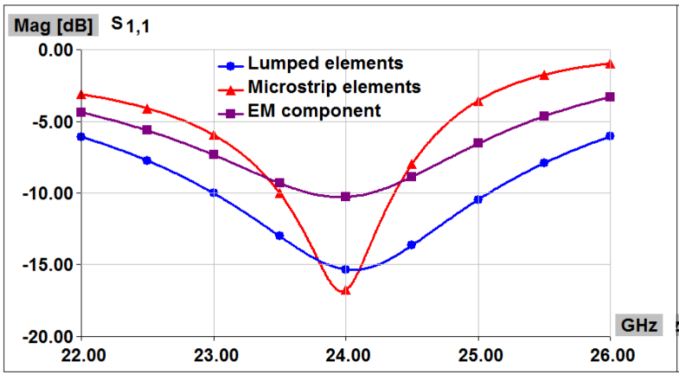

Figure 6. Comparison of simulated S parameters for detector schematics from Fig. 5, Fig7 and Fig 9.

Matching with lumped elements is not adequate at such a high frequency of operation. A network comprising distributed elements should be used instead. One possible solution is to replace L-C matching section from Fig. 5 with a series and a shunt transmission line, as shown in Fig. 7 where a complete microstrip schematic of the matched detector is presented.

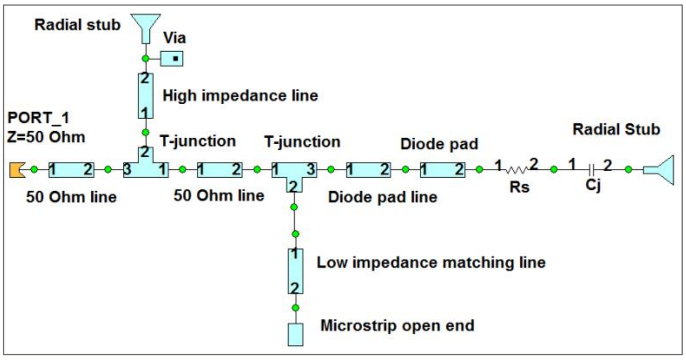

Figure 7. Microstrip element matching circuit.

Looking from the anode, the first matching element is a short transmission line with the line width set to be equal to diode pad width, so that no discontinuity is introduced. The diode pad line has a characteristic impedance of 69 Ω and replaces an inductor from Fig. 5. Next element in the network is a T-junction connecting together diode pad line, a shunt low impedance line replacing the capacitor from Fig. 5, and 50 Ω terminal line. Low impedance line (20 Ω) is open circuited at the opposite end which is adequately modeled by introducing an open end schematic microstrip element. Last element in the network is shunt circuit comprising quarter wavelength high impedance line (106 Ω), radial stub and via to ensure the flow of DC current trough the diode. The only difference from the previously explained case is that a perfect ground connection from Fig. 1 has been replaced with a via model. Similarly, ideal connection to the ground at diode cathode from Fig. 1 has been replaced with a radial stub, as the short circuit to ground is required there at microwave frequencies only.

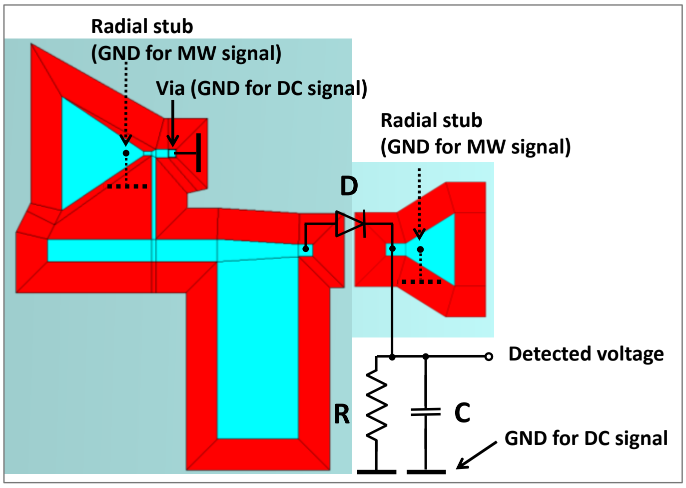

Figure 8. A complete layout of the matched detector.

Results of the simulation of the schematic from Fig. 7 are presented in Fig. 6. Around 24 GHz return loss values are better than 15 dB. However, the return loss curve is very steep around the minimum indicating that an error in circuit dimensions during fabrication or a variation of diode equivalent circuit parameters from one sample to another may cause a shift of the minimum to other frequency.

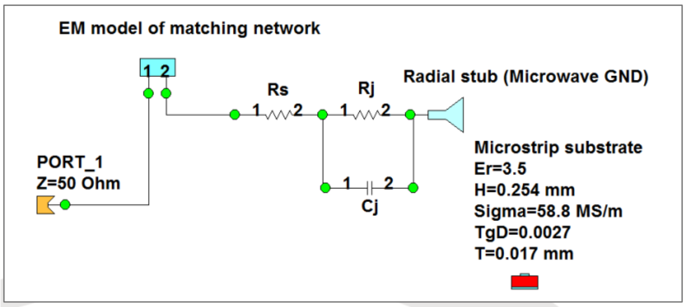

Figure 9. Final WIPL-D Microwave schematic of the matched power detector including all the elements significant at microwave frequencies.

The accuracy of analytical element used to model microstrip T-junction comprising a connection of lines with considerably different widths, such is the case of the one connecting 69 Ω impedance line and 20 Ω line, is poor. Therefore, EM modeling of diode matching circuit is highly recommended. As explained earlier, generation of complete EM component representing the layout of the whole matching network is straightforward in WIPL-D Microwave - the program automatically translates analytical elements into an EM component, as presented in Fig. 8. The figure illustrates the complete matched detector microstrip circuit and indicates the locations of short circuits at DC and microwave frequencies. The layout of a radial stub at diode cathode, which is not a part of designed matching network, is also included. Resistor R and capacitor C are external components which must be added in a real detector circuit, but are not relevant for high frequency simulations. Resistance value should be dimensioned to ensure efficient power transfer of the detected signal to an external circuit. It is usually set equal to the video impedance of the diode (the impedance of the diode as a baseband signal source). Capacitance C is selected according to the required frequency bandwidth of the detected signal and prevents the noise outside the band to affect detector sensitivity.

Optimization of the matching network EM component with the other elements of the detector circuit connected is required to finish power detector design. All of the elements have been assembled in a schematic presented in Fig. 9. The return loss of the optimized circuit is presented in Fig. 6. The values around the frequency of 24 GHz are in the range of 10 dB. The minimum is not as steep as in the case of schematic from Fig. 7 indicating improved sensitivity to fabrication tolerances and the spread of diode characteristics. However, a value of 10 dB may not be sufficient for some applications, e.g. where a filter is connected to detector input.

Conclusion

The design of a power detector can be easily acomplished if the right set of tools is available. WIPL-D Microwave is a one stop design environment providing a microwave circuit designer with several modeling options. The modeling using analytical elements can be smoothly expanded to EM analysis as an automated transfer of any schematic comprising elements with adequate layout representation to a 3D EM component is available whenever more accurate modeling is required.

A choice between non-matched or matched power detectors is driven by the context of a particular application. For the case of a matched detector, the simplest matching network topology is preferred where detector sensitivity is a must. However, the return loss values obtained by a simple network may not be sufficient for some applications. If this is the case, a more complex matching network must be designed trading-off the sensitivity for favorable return loss values. To accurately account for all the effects occurring within the matching network, use of electromagnetic modeling is highly recommended.