Matching Network Design for Power Amplifiers

Discrete, general purpose microwave transistors are usually accompanied with an extensive set of data supplied by a manufacturer to support versatile designs of many active circuits such as linear and low noise amplifiers, oscillators, frequency multipliers and mixers. A basic data set typically includes an I-V curve and a list of small signal S parameters and noise parameters vs. frequency for several biasing points. These data are sufficient to carry out linear and low noise amplifier design using linear circuit simulator. In relation to amplifiers, transistor data sheets usually contain some additional nonlinear parameters such as level of third order intermodulation products (IP3) and gain compression (P1dB) only to indicate operational boundaries for a device.

For accurate design of strongly nonlinear microwave circuits, such as oscillators or frequency multipliers, use of nonlinear time domain or harmonic balance simulators is required. Modeling a device for use in nonlinear simulators is significantly more complex than providing a list of linear S parameters. This kind of model is usually a result of comprehensive procedures of advanced experimental characterization followed by nonlinear model parameter extraction. Sometimes a nonlinear model suitable for direct implementation in nonlinear circuit simulators is additionally provided in the transistor datasheets.

A class of strongly nonlinear circuits that are, in spite of a high level of maturity of nonlinear modeling and simulation tools, still designed using linear techniques, are power amplifiers. The reason for this approach can be found in a fact that requirements for modern power amplifiers are numerous, stringent and usually conflicting each other. Conditions of operation providing maximum output power, power gain, and power added efficiency (PAE), acceptable level of nonlinear distortion and memory effects for an input signal with prescribed modulation, peak-to-average power ratio (PAPR), and envelope statistics, are still too demanding for state of the art nonlinear modeling and simulation methodologies. Furthermore, a set of requirements for a power amplifier has resulted in a situation that a power transistor itself is designed for a particular application only. In other words, in contrast to general purpose transistors, a number of application scenarios for a typical power transistor is usually only one. For the scenario, in most of the cases, the optimum operating conditions are best determined experimentally using very complex and expensive setup that is beyond the reach of a typical designer. Data describing the optimum operating condition for a device is usually provided by a manufacturer. Sometimes a transistor manufacturer even discloses the design of an amplifier circuit including printed circuit board (PCB) layout and a bill of material (BOM) for the components used.

It seems like a designer can only choose a device which suits the application scenario and strictly follow the manufacturer's recommendations. However, there is still some flexibility for a power amplifier designer to verify a recommended design before prototyping and make changes if necessary, or to adapt it to some specific circumstances, for example when a different substrate material is preferred. This application note describes how to carry out a reliable power amplifier design using WIPL-D Microwave.

Example of Typical Power Transistor Data

Data supplied by power transistor manufacturers include a list of optimal impedances vs. frequency that should be presented at transistor input and output electrodes to ensure the specified performance for a targeted application. As pointed out earlier, these impedances are determined using complex procedures and sophisticated measurement equipment.

An example of a data set provided for a transistor suitable for 2.5-2.7 GHz frequency band, thus addressing WiMAX, WiBro, BWA and multicarrier OFDM applications and operating in Class AB or Class C, is presented in Table 1. Impedance Zsource represent an optimum impedance to be presented at the gate of the MOSFET at a given frequency, while Zload represent the impedance to be presented at the drain.

Table 1. Optimal source and load impedances supplied by a manufacturer for a particular RF power transistor.

f [MHz]	Zsource [Ω]	Zload [Ω]
2500	4.059 - j2.284	3.380 - j0.543
2525	3.679 - j2.593	3.265 - j0.546
2550	3.006 - j2.574	3.077 - j0.449
2575	2.355 - j2.190	2.892 - j0.336
2600	2.075 - j1.657	2.727 - j0.182
2625	1.930 - j1.179	2.564 - j0.034
2650	1.973 - j0.771	2.435 + j0.140
2675	2.017 - j0.557	2.286 + j0.340
2700	2.024 - j0.379	2.227 + j0.538

Analizing data listed in Table 1., it can be concluded that values of the impedances are very low, and therefore a design of the matching networks is not a trivial task. The flexibility given to a designer, and in the same time a challenge, is to design adequate matching networks that will transform the reference impedances of the amplifier within a system (50 Ω) to the required optimum values at the transistor terminals.

In order to carry out a design of matching networks using WIPL-D Microwave, the optimum impedances can be introduced in the simualtor environment through Touchstone Z parameter data block, as presented in Fig. 1.

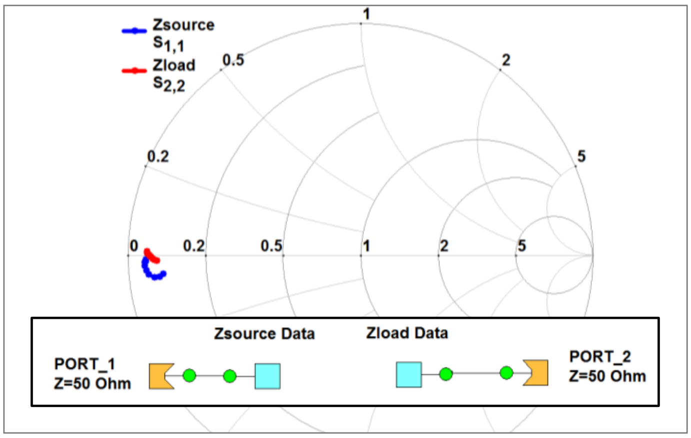

Figure 1. Optimum source and load impedances added as schematic entities through Touchstone Z parameter Data block and graphed on a Smith chart in WIPL-D Microwave.

Matching Network Consideration

There are many ways to match an impedance in a given frequency band. Different topologies utilizing lumped elements, transmission lines or both are possible. The selection of a topology utilized for a particular application depends on many factors.

For amplifiers in general, matching networks must provide DC paths for biasing an active element. Furthermore, a topology chosen should include elements to decouple the amplifier terminating lines from a flow of DC biasing currents, and DC biasing terminals from flow of RF currents. The former is typically realized as a pair of parallel coupled transmission lines which are quarter wavelength long at the operating frequency, or a series capacitor. The latter is especially important to keep the amplifier stable. It is usually realized as a shunt short circuited stub which is quarter wavelength long at the operating frequency, or a shunt inductor. Shunt short stub at the operating frequency represents an open circuit, and therefore doesn't load the rest of the matching network. For the same reason, a properly dimensioned inductor should have sufficiently high impedance at the operating frequency.

In the case of a power amplifier, a subtle detail could prevail in the choice of a suitable matching network topology. For an example, harmonic content of a signal coming out from a power amplifier is very important for a number of applications. In that sense, it becomes important if the output biasing network contains a shunt short circuited stub or an inductor. In principle, at second harmonic of the operating frequency, the stub will ideally act as a short circuit, therefore preventing the signal to flow to the output of an amplifier. The impedance of an inductor will be two times higher than the one at the operating frequency, which could be insufficient to completely block the second harmonic signal. Furthermore, practical inductors with high inductance values required at operating frequency typically have low self-resonant frequency, which may easily fall below the second harmonic, making the behavior of an inductor at the second harmonic frequency unpredictable.

For the particular case of the power transistor described, the schematics of both matching networks as recommended from a manufacturer are presented in Fig. 1. Only the elements critical for high frequency operation are considered. Both networks consist of a combination of lumped and transmission line elements. In input network resistor R1 is used as a matching element together with a quarter wavelength, high impedance biasing line effectively short circuited at the other end by a capacitor C2. The purpose of the capacitor C1 is to isolate the input port for DC currents.

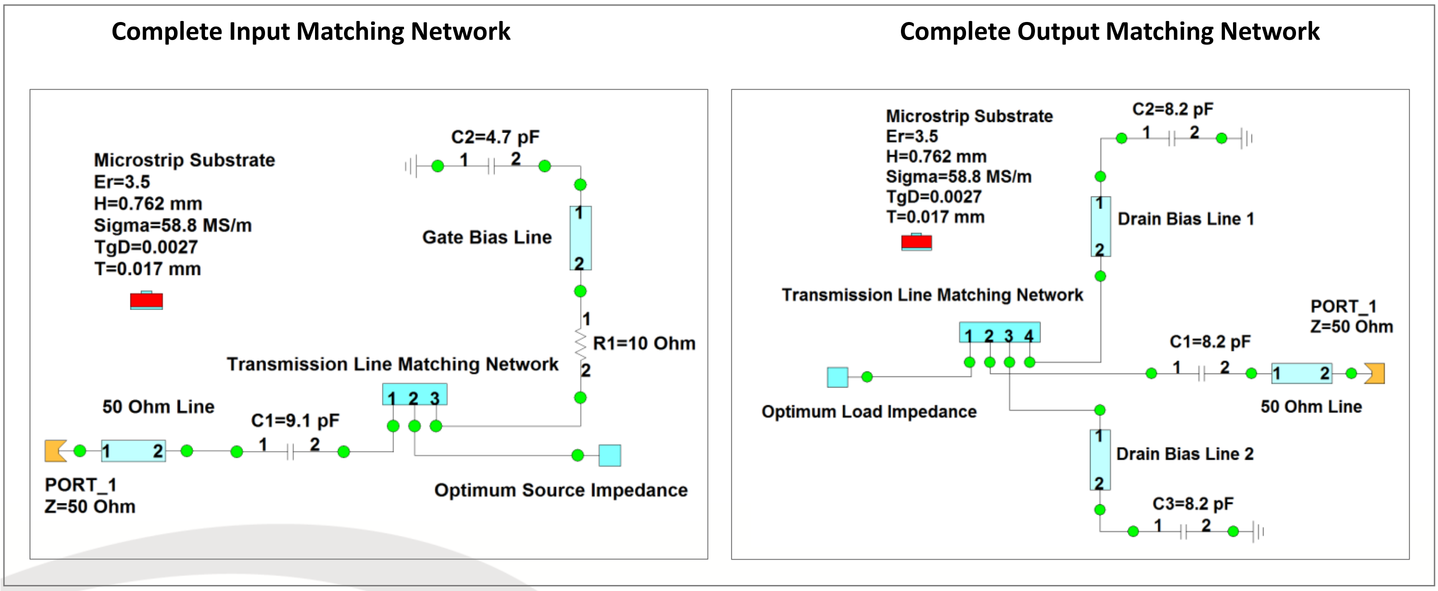

Figure 2. Schematics of input and output matching networks as suggested by a manufacturer in WIPL-D Microwave.

Similarly, capacitor C1 in output matching network prevents the flow of DC currents through the output port. Biasing is again introduced using two shunt high impedance lines that are approximately quarter wavelength long and short circuited for microwave signal through the capacitors C2 and C3. According to the manufacturer's recommendations, two biasing lines with slightly different lengths should be used. The reason for this is to widen a bandwidth of aforementioned second harmonic suppression. If the lengths of both lines were the same, this would result in a sufficiently high value of harmonic suppression occurring at the single frequency.

As shown in Fig. 2, both matching networks have a part comprising transmission line elements, which are illustrated in Fig. 3. Actually, the representation shown in Fig. 3 corresponds to the models of the matching networks implemented in WIPL-D Microwave by using electromagnetic (EM) components. The significance of introducing EM components for most accurate modeling of microstrip matching elements will become apparent in the following text.

The thickness of a microstrip substrate used is dictated by a physical location of transistor leads with respect to the bottom of the transistor capsule. At the place of transistor mounting, a cutout in a substrate must be made to allow the direct attachment of the source electrode, which is electrically connected to the bottom of the transistor housing, to the metal supporting plate acting as a ground and providing thermal path for effective cooling of the device.

The width of the transistor leads on gate and drain side is substantial, approximate ratio to the other elements of matching networks is illustrated in Fig. 3. The substantial lead width determines the minimum transmission line width to be used for a first transmission line matching element in both of the networks. However, wide leads conform well to the low values of the optimum impedances to be presented to the device at both terminals, as low impedance microstrip transmission line sections are required for the first matching element in the networks, which directly translates into substantial line widths.

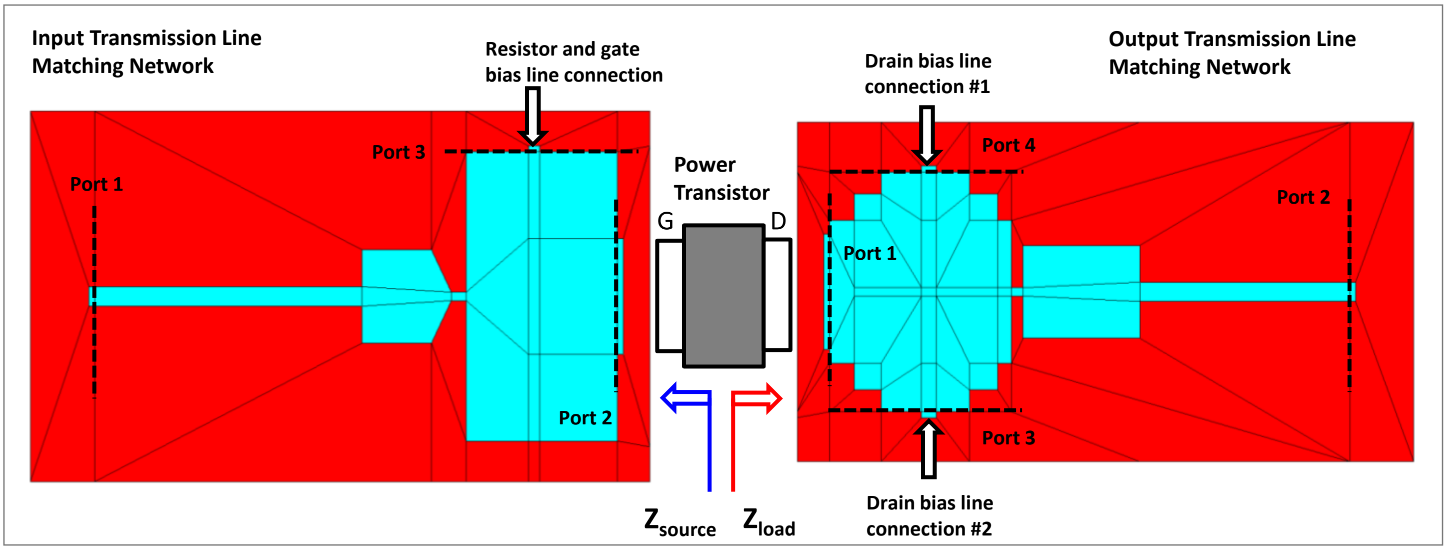

Figure 3. WIPL-D EM component models of transmission line parts of input and output matching networks.

Both of the transmission line networks have similar topology. In input matching network, the first transmission line element is an impedance transformer. It is wider that the lead of the transistor which effectively creates a discontinuity that must be taken into account. On the other hand, the first matching element in drain circuit utilizes a triple step to gradually increase of line width to realize an impedance transformer. The second matching element in both of the networks is very narrow, very short transmission line which is electrically equivalent to an inductance. Extremely high ratio of line width change (approximately 1:20 for the case of gate matching network) significantly contributes to an inductance value and must be accurately taken into account. The third element in the matching networks is a short, low impedance transmission line section acting as an impedance transformer. In the input network a transformer is tapered at one end. Finally, both networks end with a piece of a 50 Ω transmission line. Locations of the connections of distributed and lumped elements from Fig. 2 comprising matching, DC biasing and DC blocking circuits are also indicated in Fig. 3.

WIPL-D Microwave has several built-in technology libraries with circuit element models of commonly encountered transmission line discontinuities. The user can choose whether the calculations of electrical characteristics of a discontinuity will be based on approximate analytical expressions or full wave EM simulations. The accuracy of the analytical expressions is in a practically acceptable range of several percent for the case of mild discontinuities. However, the accuracy becomes unacceptable for connection of two, three or four lines with drastically different widths, such is the case for some of the discontinuities presented in Fig. 3. To obtain accurate results for such extreme case, an electromagnetic simulator must be used. However, as evident from Fig. 3, discontinuities are physically located very close to each other. When this is the case, discontinuities are said to be coupled. The coupling between the discontinuities introduces additional effects comparing with the case where the coupling does not exist. A circuit comprising coupled discontinuities can not be accurately modeled as if the discontinuities were not coupled. Therefore, for the case of matching networks from Fig. 3, neither the analysis with analytic models nor the analysis utilizing EM modeling for each of the individual discontinuity is adequate.

On the other hand, each network includes long and uniform transmission line segments, such as terminating and biasing lines, which can be efficiently modeled using analytic component models. An interface between the “analytic” and “electromagnetic” part of the circuit, and connections between transmission lines and lumped elements can be accurately modeled in WIPL-D Microwave by proper alignment of the reference planes on interconnecting ports, as illustrated in Fig. 3, and the use of de-embedding.

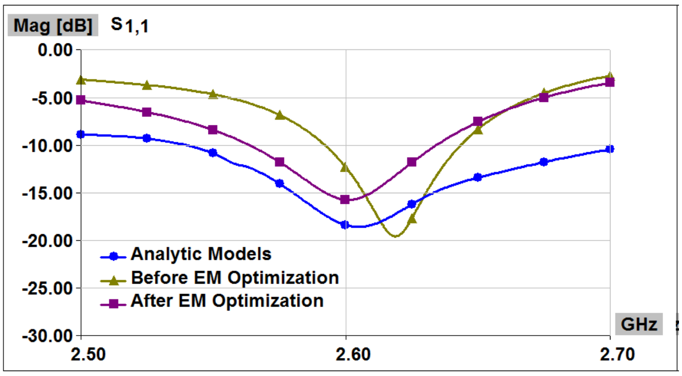

Figure 4. Simulated performance of input matching network using modeling and optimization options available in WIPL-D Microwave.

The possibility to partition the circuit as presented in Fig. 2, i.e. introducing analytical elements where appropriate, and EM components where coupled discontinuities require EM analysis within a single design environment, makes WIPL-D Microwave a tool of choice for power amplifier design. The built-in optimizer can be used for subsequent optimization of all of the elements of a network including EM component elements and optimum dimensions of microstrip circuits can be easily determined.

An outline of the optimum design flow for the previously presented power amplifier is presented next. As a first step, circuit models for each of the matching networks using analytic components only have been assembled in WIPL-D Microwave. Dimensions of the microstrip elements have been optimized to give return loss value better than 15 dB at the central frequency of operation (2.6 GHz). The simulated S parameters of all-analytic models of the networks are shown in Fig. 4-5.

More accurate modeling in the next design step should account for the coupling between all of the discontinuities. The simulation of partitioned matching networks according to Fig. 2 gives substantially different results from all-analytic solutions. While the performance of the input matching network can be considered acceptable as the return loss maximum is only slightly shifted to higher frequencies, the performance of the output matching network is not, as it provides around 3 dB return loss within the band. The difference between the results obtained with two modeling approaches best illustrates the limitations of individual modeling of discontinuities when a typical power amplifier matching networks are concerned.

In order to achieve the acceptable values of the return loss for the matching networks, optimization of the schematics shown in Fig. 2 has been performed as the final design step. During optimization only the dimensions of the transmission line elements presented in Fig. 3 have been varied. As a result of optimization, the values for the return loss better than 15 dB have been obtained at the central operating frequency, as presented in Figs 4-5.

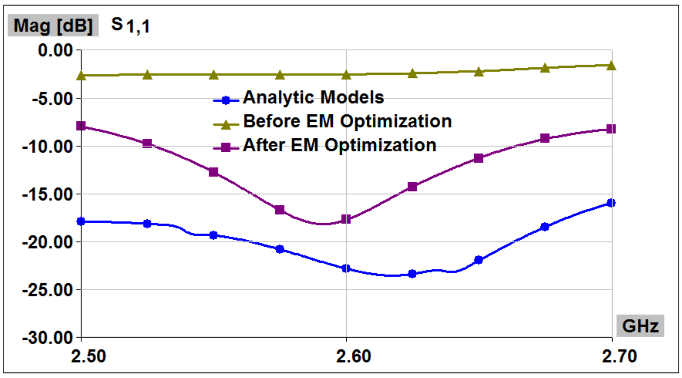

Figure 5. Simulated performance of output matching network using modeling and optimization options available in WIPL-D Microwave.

Conclusion

The adequate modeling of matching networks is crucial for the success of power amplifier design. Due to a set of simulation tools included, WIPL-D Microwave provides a complete environment for accurate and efficient modeling and design of power amplifiers.

Example of a comercially available power transistor has been presented to explain the matching network topologies prefered for the power amplifier application and to demonstrate the outline of the complete design flow. The neccessity to introduce electromagnetic analysis to accurately model typical power amplifier matching networks or otherwise face the significant inaccuracy due to the effects of coupled discontinuities has also been explain.

The design has been carried out for the microstrip substrate recommended by a manufacturer. If necessary, it can be easily adapted to any other substrate prefered providing that the substrate thickness conforms with the height of the transistor lead and the first transmission line element in the networks remains wider than the width of the transistor lead.