

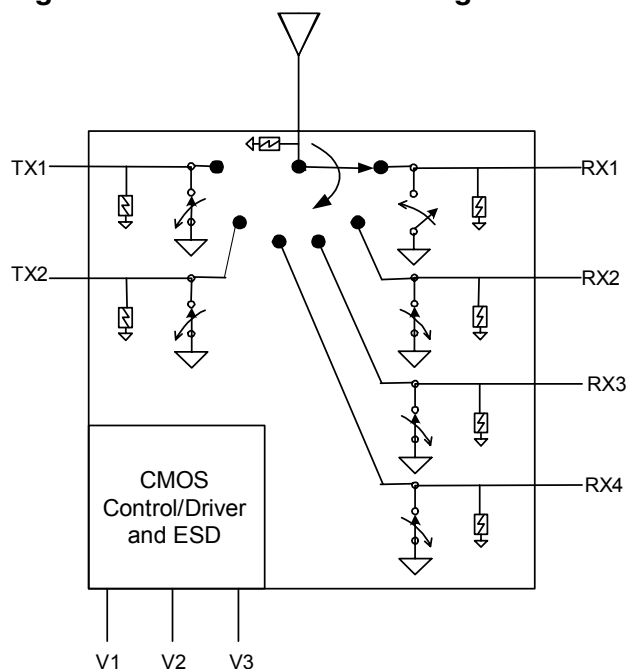
Multi-Port Handset Switch S-Parameters

Introduction

High-power UltraCMOS™ switches are the next-generation solution for wireless handset power amplifiers and antenna switch modules. Most multi-throw switches combine high-power transmit and high-isolation receive functions on one die. Peregrine switches also feature integrated decoders and logic drivers, extremely low power, and low voltage.

Applying any switch requires understanding its impedance and transmission characteristics. S-parameters are common for defining two-port RF networks. Without a multi-port vector network analyzer (VNA), multi-port switches present great calibration, measurement, and design challenges. This application note describes how to calibrate and measure S-parameters for multi-port switches with a common two-port VNA. The procedure is illustrated with the PE4263 SP6T switch.

Figure 1. PE4263 Functional Diagram



Summary:

- Complete seven-port characterization S-parameter matrix for all ON and OFF states
- Step-by-step measurement procedure
- Test fixture and bond wire de-embedding
- Reference plane definition

Seven-Port S-Parameter Definition

S-parameters are widely utilized for analyzing RF circuits. They conveniently and thoroughly describe network impedance and transmission versus frequency. Figure 2 illustrates a two-port network.

Figure 2. Two-Port Scattering Network



a_1 & a_2 are incident waves and b_1 & b_2 are reflected waves described by the following equations:

$$\begin{aligned} b_1 &= a_1 S_{11} + a_2 S_{12} \\ b_2 &= a_1 S_{21} + a_2 S_{22} \end{aligned}$$

where S_{ij} is a complex number with both magnitude and phase. Since PE4263 is passive, the magnitude of all S-parameters lie between zero and one.

Figure 3. Seven-Port Scattering Definition

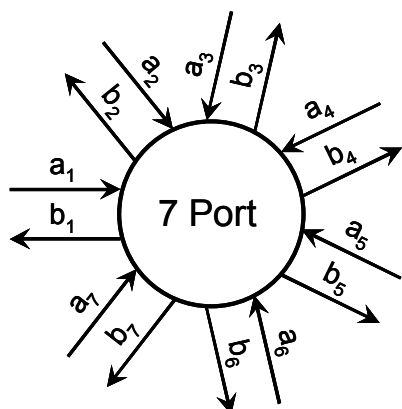


Figure 3 illustrates a seven-port network.

A multiport network is expressed in matrix form:

$$\mathbf{B} = [\mathbf{S}] \mathbf{A}$$

where \mathbf{B} is the reflected wave vector, \mathbf{A} is the incident wave vector, and $[\mathbf{S}]$ is the scattering parameter matrix. A seven-port device is completely described by the 7x7 S-parameter matrix of Figure 4.

Figure 4. Seven-Port Scattering Matrix

S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	S_{27}
S_{31}	S_{32}	S_{33}	S_{34}	S_{35}	S_{36}	S_{37}
S_{41}	S_{42}	S_{43}	S_{44}	S_{45}	S_{46}	S_{47}
S_{51}	S_{52}	S_{53}	S_{54}	S_{55}	S_{56}	S_{57}
S_{61}	S_{62}	S_{63}	S_{64}	S_{65}	S_{66}	S_{67}
S_{71}	S_{72}	S_{73}	S_{74}	S_{75}	S_{76}	S_{77}

S-parameters are normally assigned numerical subscripts. For the example in this document ports have been designated per Table 1.

Table 1. PE4263 Port Assignments

Port	PE4263 Pin Description
1	ANT (Antenna)
2	TX1
3	TX2
4	RX1
5	RX2
6	RX3
7	RX4

Measurement Procedure

PE4263 is a seven-port device with six functional states. Port 1 (ANT) can connect to any of the other six (two TX and four RX). Each state has different seven-port S-parameters. VNAs with up to twelve ports are now available, but they are uncommon, very expensive, and frequently lack polished automation software. Two-port VNAs are common, so an alternative is to measure all port combinations two ports at a time and process the two-port S-parameter files into seven-port S-parameter files.

This process is not as lengthy as it may appear because many port combinations are redundant. For example, after measuring ANT to TX1, it is not necessary to measure TX1 to ANT. Thus, instead of 36 test configurations, only 21 are required (See Table 2).

Table 2. S-Parameter Two-Port Measurements

NA Port 1	Network Analyzer Port 2					
	2	3	4	5	6	7
1	X	X	X	X	X	X
2		X	X	X	X	X
3			X	X	X	X
4				X	X	X
5					X	X
6						X

Figure 5 depicts the measurement process. Note that calibration need only be implemented once.

Figure 5. Measurement Process

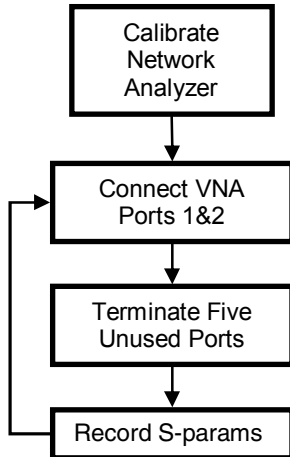
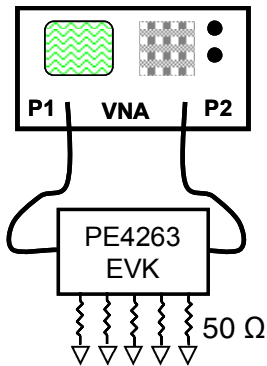


Figure 6. Measurement Setup



Connect VNA port 1 to PE4263 port 1 (ANT) and VNA port 2 to PE4263 port 2 (TX1). Terminate PE4263's unused ports (3 to 7 - TX2, RX1, RX2, RX3, and RX4) with 50 ohms. Power PE4263 and enable state "ANT to TX1".

The test set-up is now ready to measure the first set of two-port S-parameters. Since TX1 is enabled, the data will show low insertion loss and good return loss. Now, referring to Table 2, swap the 50-ohm termination on port 3 (TX2) and VNA port 2 and record another set of two-port S-parameters. Since TX1 remains enabled the data will show high insertion loss and poor return loss; i.e., high isolation between ANT and TX2. Continue through the rest of Table 2.

Select the remaining switch states in turn: ANT to TX2, RX1, RX2, RX3, and RX4; and move and reattach loads and cables as necessary, recording 21 two-port s-parameter files for each switch state.

This yields 6 data files for 21 test configurations - 126 total. To avoid confusion use consistent filenames. For example,

TX1_TX2_RX4.txt

where

- Switch State is ANT to **TX1**
- VNA port 1 is connected to **TX2**
- VNA port 2 is connected to **RX4**

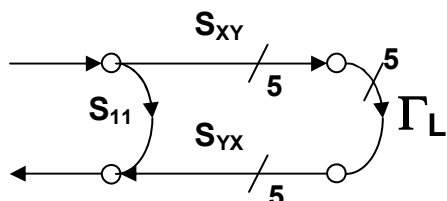
A spreadsheet or script language such as PERL will transcribe data from each two-port file to the appropriate column of a new file. Table 3 maps the 21 two-port measurements to the 7x7 S-parameter matrix.

Table 3. Two-Port to Seven-Port Mapping

VNA Port1	VNA Port 2	S-Parameter Measured
ANT	TX1	S11, S21, S12, S22
	TX2	S31, S13, S33
	RX1	S41, S14, S44
	RX2	S51, S15, S55
	RX3	S61, S16, S66
	RX4	S71, S17, S77
TX1	TX2	S32, S23
	RX1	S42, S24
	RX2	S52, S25
	RX3	S62, S26
TX2	RX4	S72, S27
	RX1	S43, S34
	RX2	S53, S35
	RX3	S63, S36
RX1	RX4	S73, S37
	RX2	S54, S45
	RX3	S64, S46
RX2	RX4	S74, S47
	RX3	S65, S56
RX3	RX4	S75, S57
	RX4	S76, S67

Although an error is created when interchanging the calibrated test ports and uncalibrated loads, these errors may be neglected (see Figure 7).

Figure 7. Worst Case Error Model



Γ_L is the reflection coefficient of a board trace with an external load, and S_{XY} is isolation to unused ports. In the worst case the five paths include two transmit paths (which have less isolation) and three receive paths. The datasheet gives the following minimum return loss values at 2 GHz:

- $\Gamma_L < 25 \text{ dB} \sim .056$ (estimated load + PC trace)
- $|S_{XMT}| < 23 \text{ dB} \sim 0.07$
- $|S_{RCV}| < 37 \text{ dB} \sim 0.014$

Assuming phase addition, the maximum is:

$$ERR_{MAX} = \Gamma_L (2S_{XMT}^2 + 3S_{RCV}^2) = .0006 \text{ or } -65 \text{ dB}$$

-65 dB is orders of magnitude smaller than the actual S_{11} at any port. Derivations for other S-parameters give similar results. Therefore, terminated ports are well-isolated from the selected path and the effect on the measurement may be neglected.

De-embedding Procedure

At this point, the data represents the S-parameters of the EVK with the reference plane at the SMA connector interface. The next step will remove the effects of the EVK circuit board traces and push the reference plane up to the bond wire launch point.

Note that the PE4263 EVK is uniformly symmetric. The connectors, traces, and bond wire pads of every RF interface are identical.

The open calibration trace on the back of the board provides for removal of all board effects by a process called de-embedding.

First measure OPEN, SHORT, and LOAD standards. For the OPEN, measure S_{11} of the spare trace. For the SHORT, use solder or a wire bond to connect the bond pad directly to the adjacent ground area and again measure S_{11} . For the LOAD, ground an RF-precision 50Ω resistor at the bond pad and measure S_{11} a third time.

Assuming minimal losses, the following simplifications may be made for small geometries and low frequencies:

$$\Gamma_T = \Gamma_i \Big|_{\Gamma_L = 0}$$

$$\Gamma_O = \Gamma_i \Big|_{\Gamma_L = 1}$$

$$\Gamma_S = \Gamma_i \Big|_{\Gamma_L = -1}$$

Γ_T is the return loss terminated, Γ_O is the open, and Γ_S is the short.

Although it was characterized as a one-port, the PCB trace is a two-port network. Since it is passive, it is also reciprocal, so $S_{12} = S_{21}$. Substituting $\Gamma_{TO} = \Gamma_T - \Gamma_O$ and $\Gamma_{TS} = \Gamma_T - \Gamma_S$ leaves three equations and three unknowns:

$$S_{11} = \Gamma_T$$

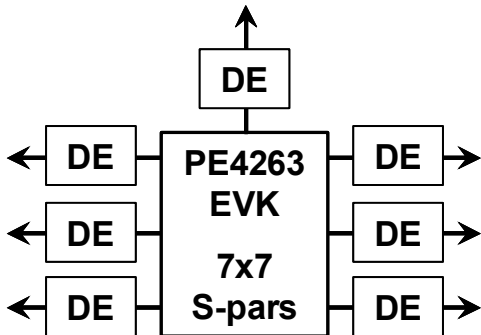
$$S_{22} = \frac{\Gamma_{TO} + \Gamma_{TS}}{\Gamma_{TO} - \Gamma_{TS}}$$

$$S_{21}^2 = S_{12}^2 = \frac{2 \times \Gamma_{TO} \times \Gamma_{TS}}{\Gamma_{TO} - \Gamma_{TS}}$$

Solve for the S-Parameters.

Now, plug these derived S-parameters into a de-embedding element found in most RF simulation software and attach to each port as shown in Figure 8.

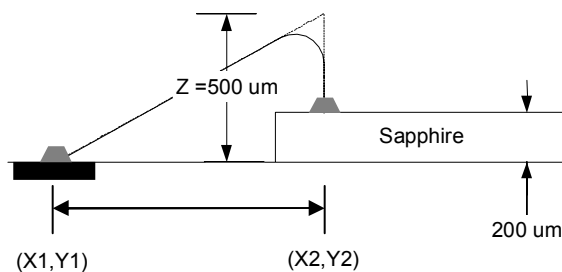
Figure 8. CAD De-embedding



This yields a new 7x7 S-parameter matrix with the PC board trace effects mathematically removed. The reference plane is now where the bond wire leaves the EVK pad.

One step remains: de-embedding the bond wires. The electrical characteristics of a bond wire are defined primarily by its length. Figure 9 shows the vertical cross-section of PE4263 mounted on the EVK board.

Figure 9. Bond wire Geometry



The Z-axis dimensions of each bond wire on the EVK board are made as much alike as possible. X and Y dimensions are measured using a microscope. Neglecting the bend at the apex, total length is approximated from the resulting triangle.

Table 4 gives total length and inductance of the seven RF bond wires.

Table 4. Bond Wire Inductance

Port	Pad	Length X-Y	Total Length	L (nH)
1	RFC	1.35mm	1.74 mm	1.69
2	TX1	1.28 mm	1.67 mm	1.62
3	TX2	1.07 mm	1.48 mm	1.40
4	RX1	1.13 mm	1.54 mm	1.46
5	RX2	1.35 mm	1.74 mm	1.69
6	RX3	1.35 mm	1.74 mm	1.70
7	RX4	1.49 mm	1.88 mm	1.86

Inductance is then calculated by the following formula:

$$L \approx \left[\frac{\mu_o l}{2\pi} \right] \left[\ln \left(\frac{2l}{r} \right) - 0.75 \right]$$

Note inductance is approximately proportional to length. Using the same procedure given earlier, the inductances can be removed to give the S-parameters of the die alone - everything else has now been de-embedded.

Data Overview

Figures 10 through 15 provide a visual summary for each switch position. On the left side are six log magnitude plots of loss between ANT and the six ports. The top right Smith Chart plots S_{11} and S_{22} of the selected channel. The bottom right chart plots the reflection coefficients of the five OFF ports. As before, port numbers follow the Table 1 assignments.

Figure 10. Reflection Coefficients: ANT and TX1 ports, TX1 selected

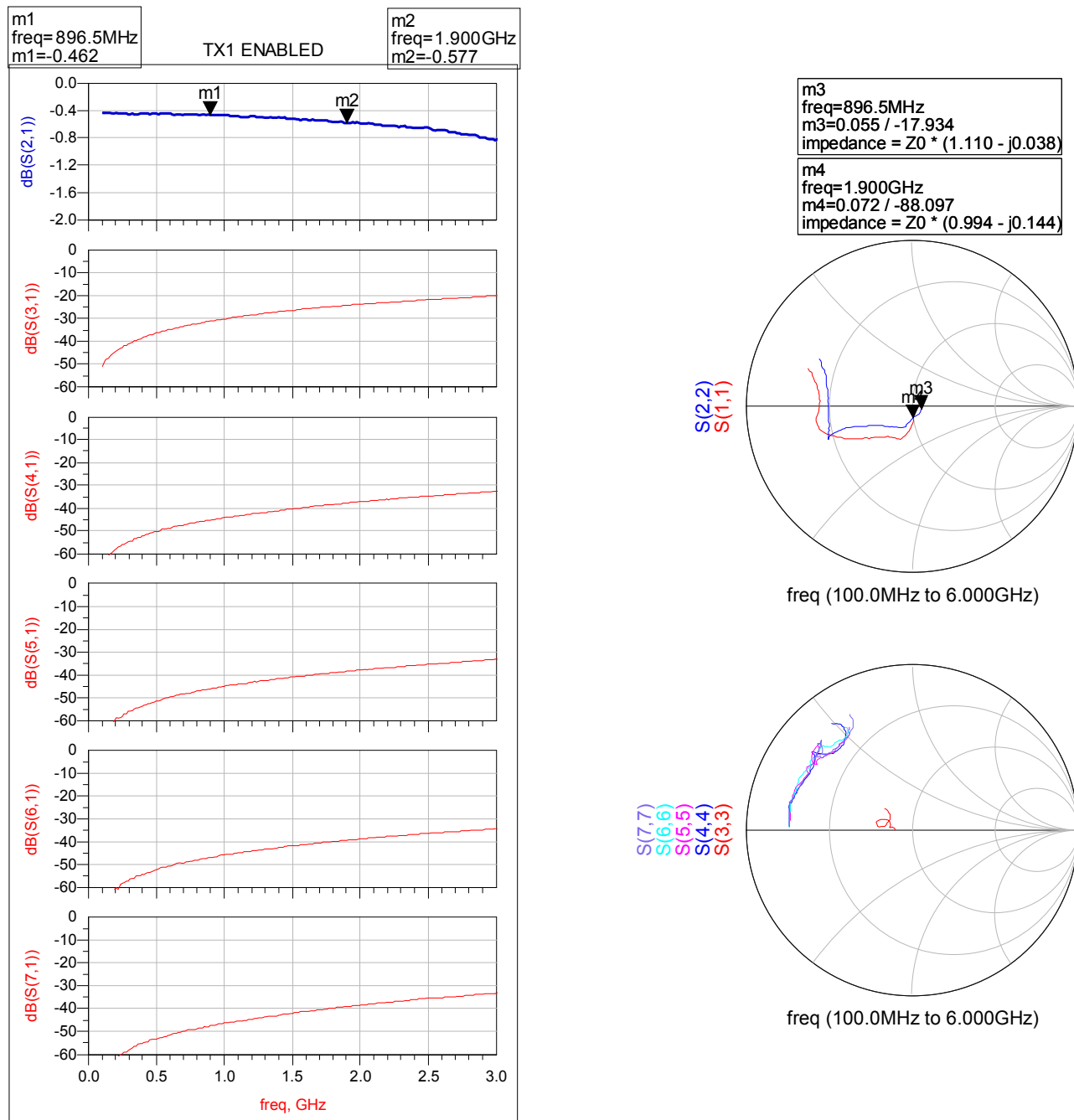


Figure 11. Reflection Coefficients: ANT and TX2 ports, TX2 selected

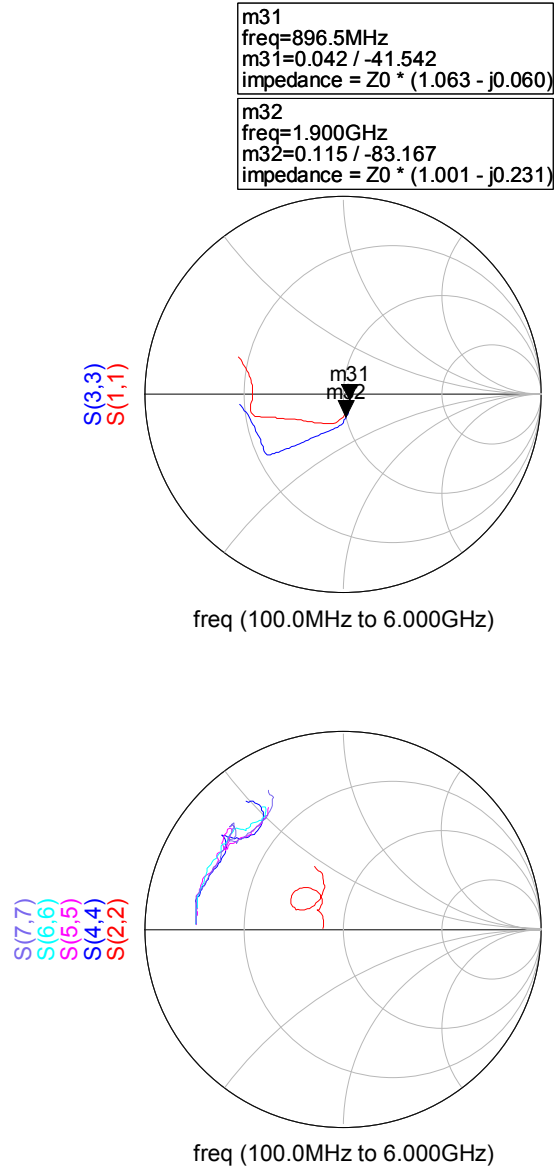
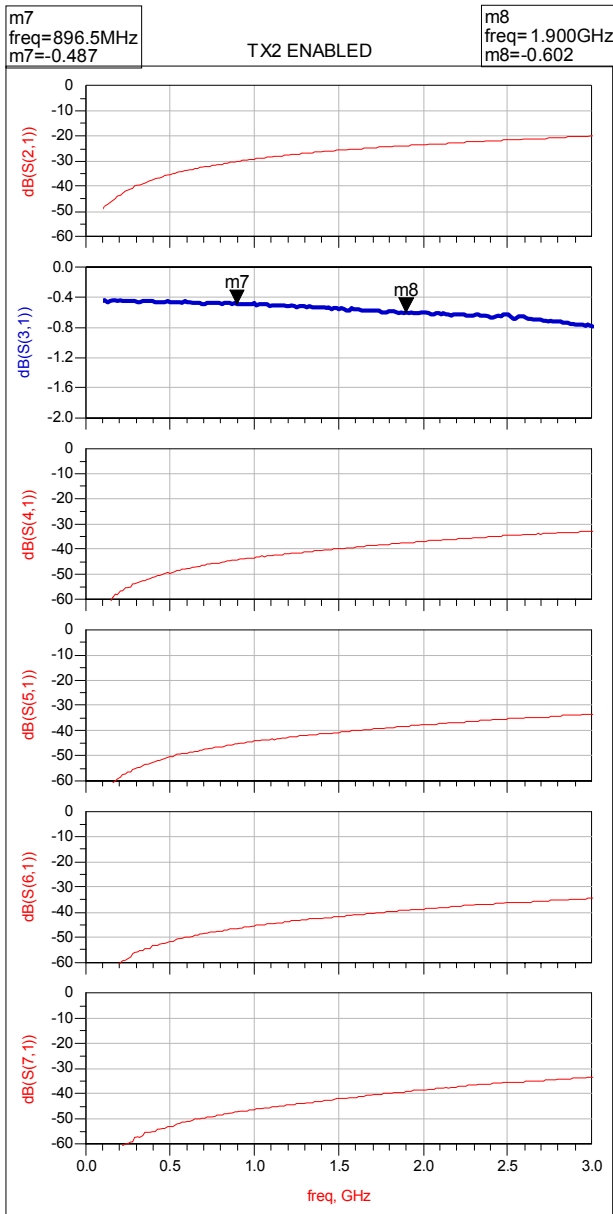


Figure 12. Reflection Coefficients: ANT and RX1 ports, RX1 selected

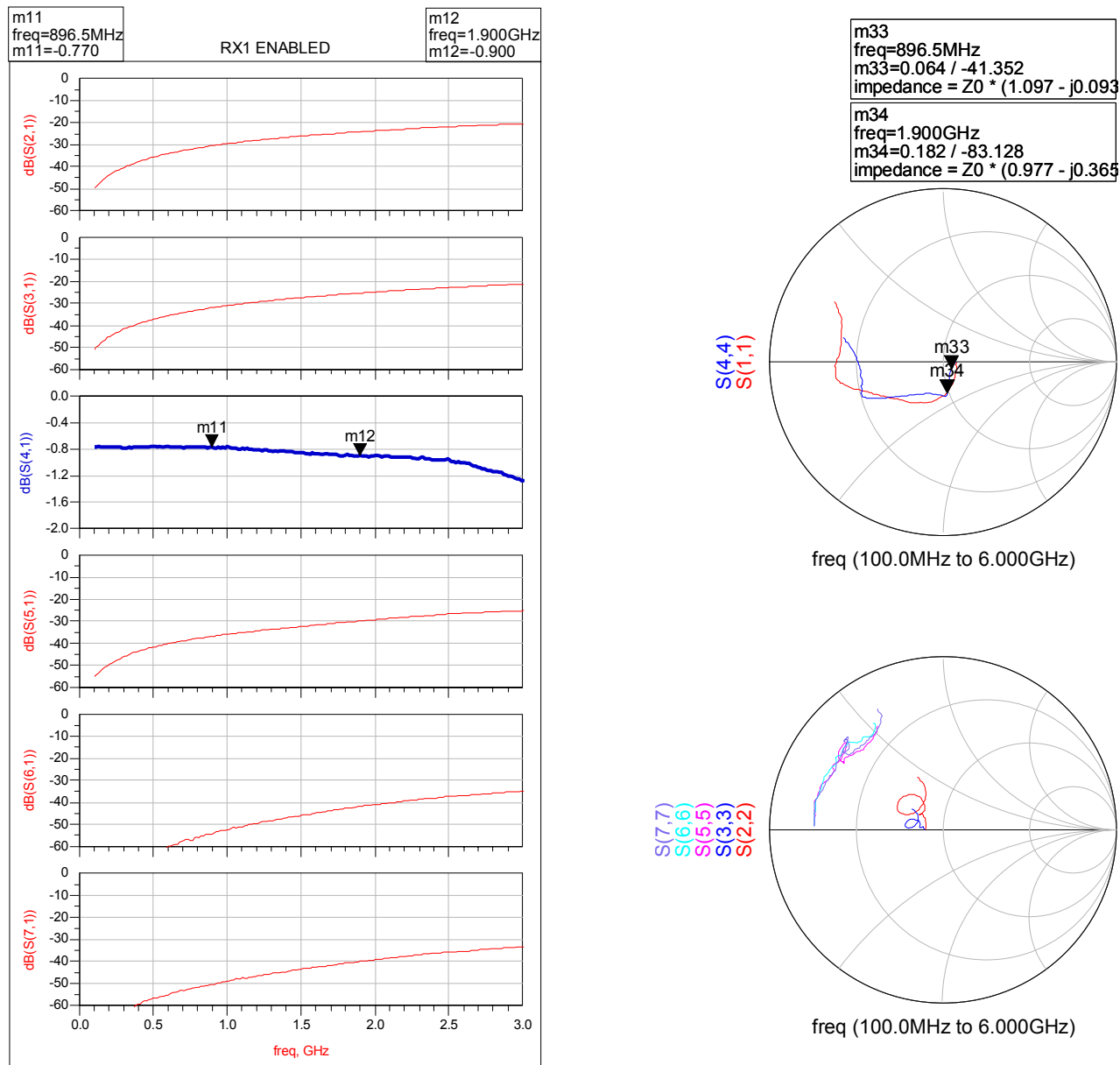


Figure 13. Reflection Coefficients: ANT and RX2 ports, RX2 selected

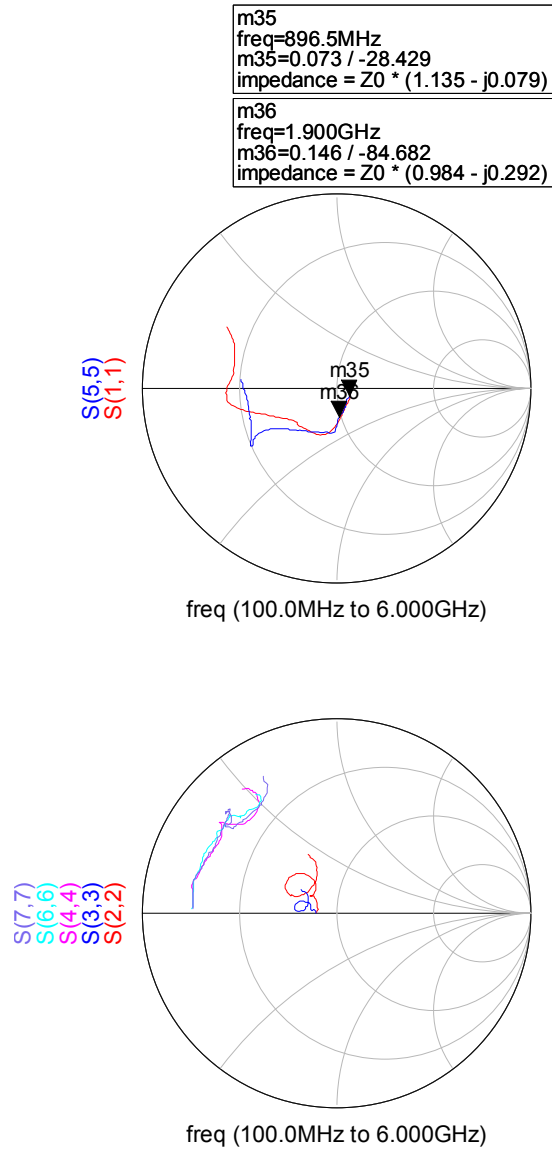
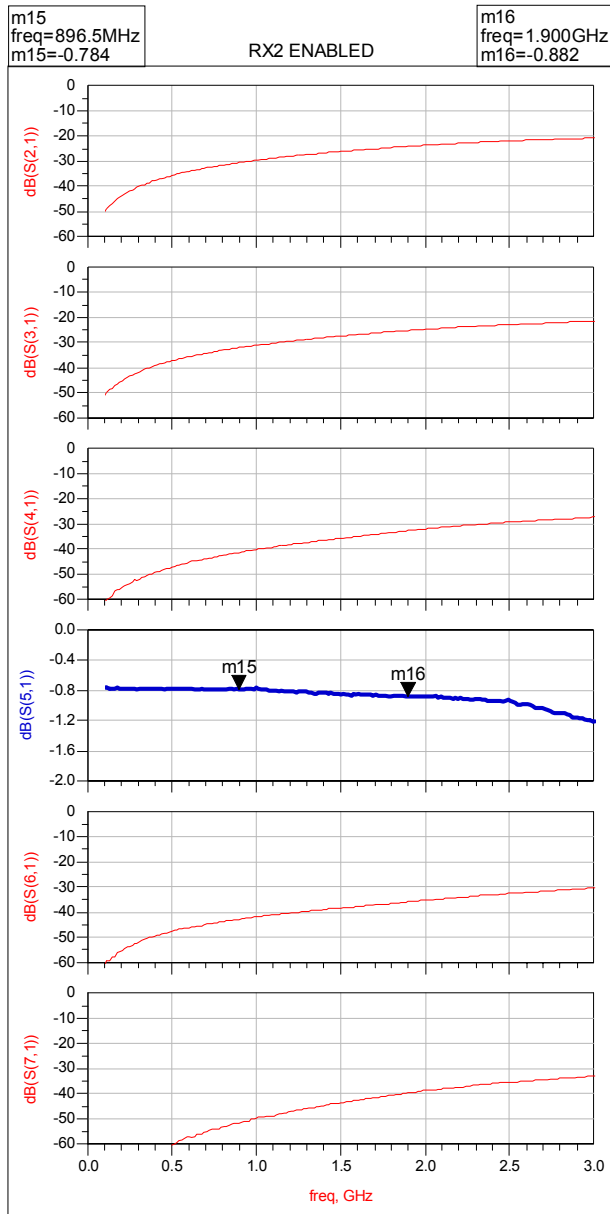


Figure 14. Reflection Coefficients: ANT and RX3 ports, RX3 selected

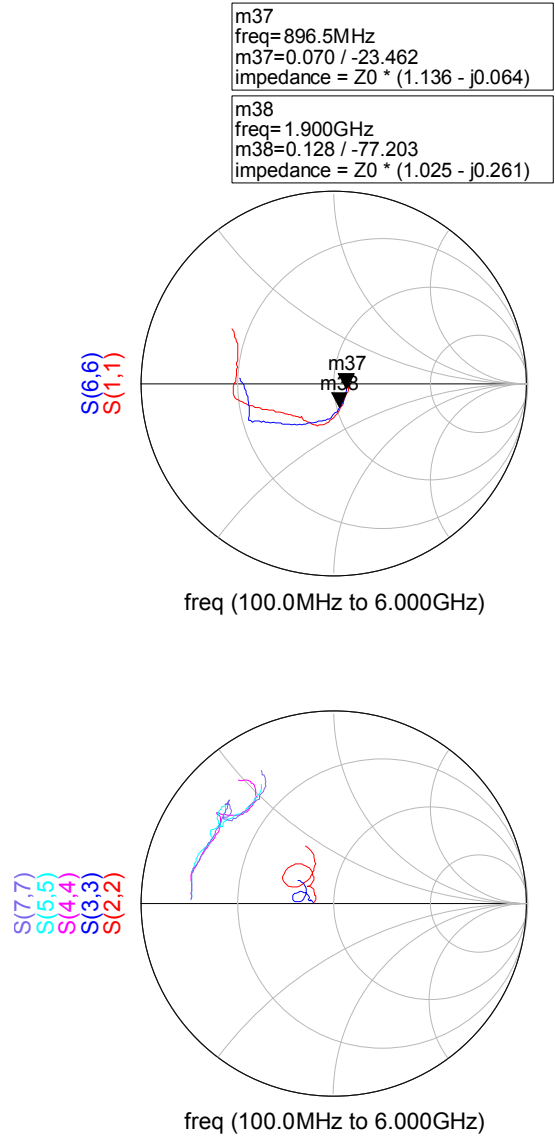
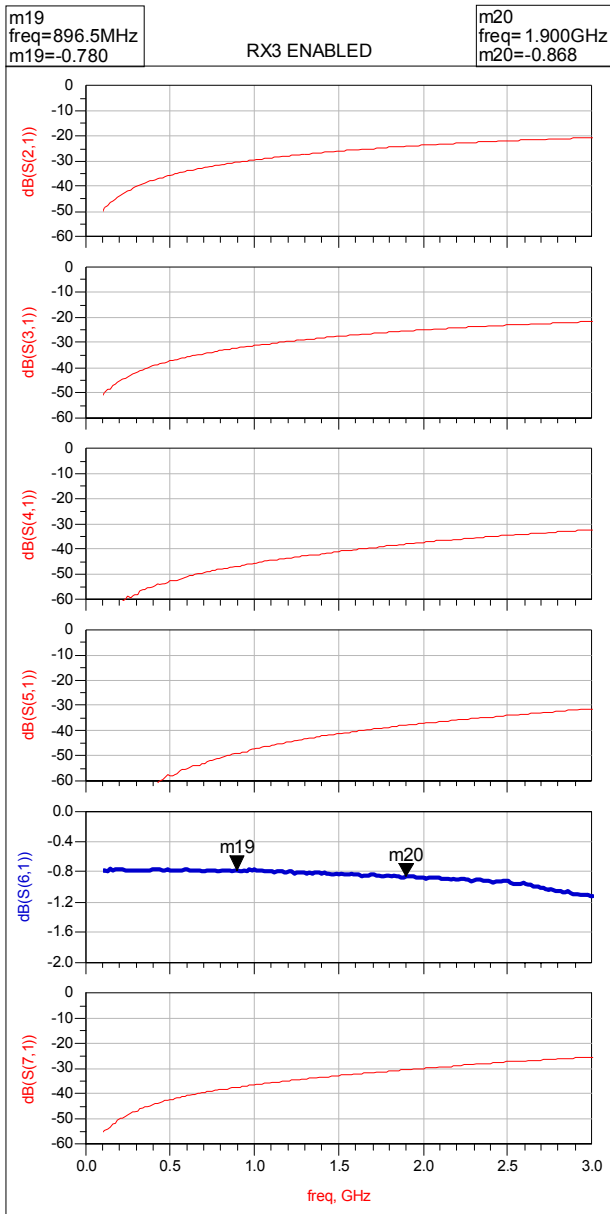
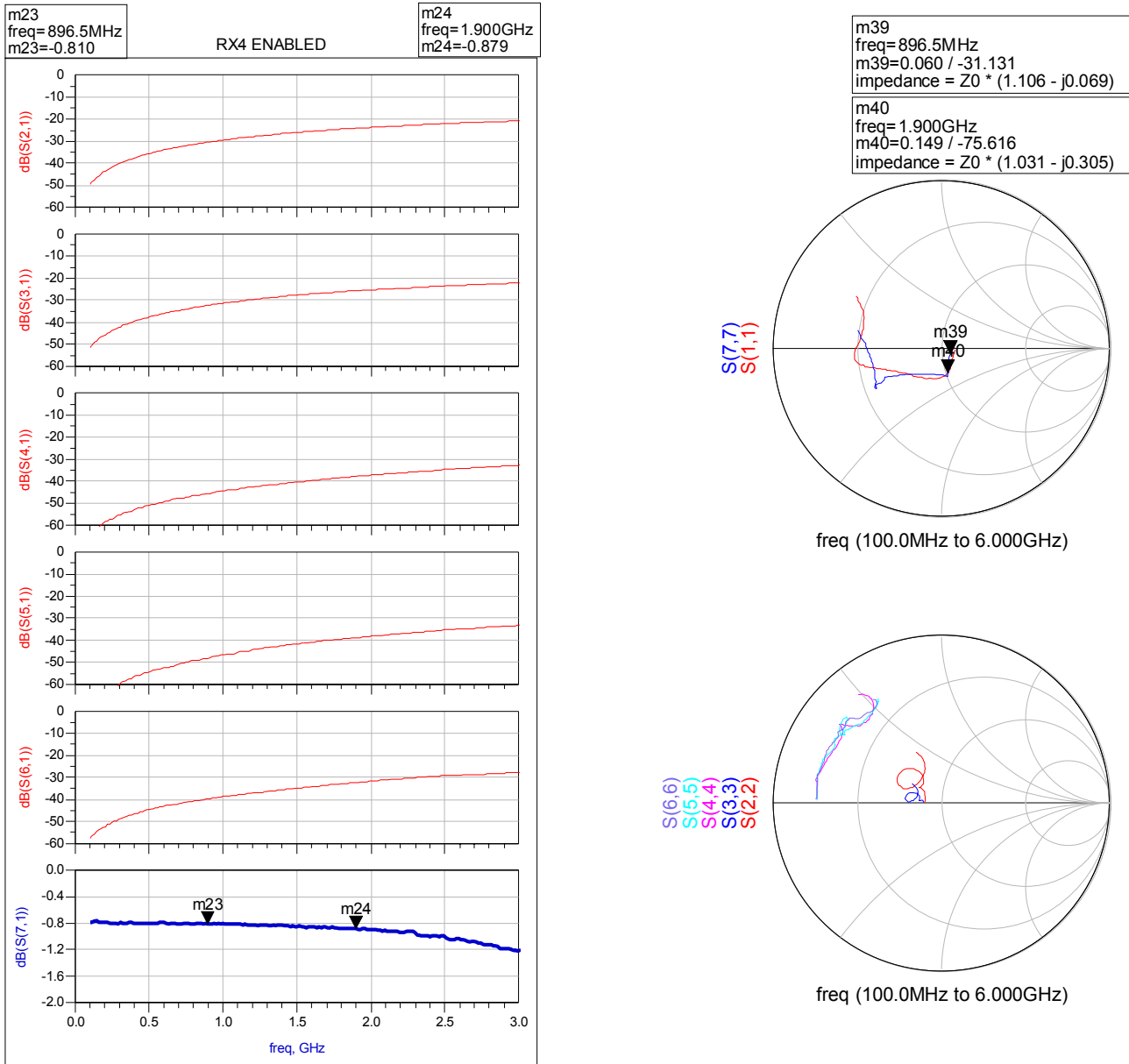


Figure 15. Reflection Coefficients: ANT and RX4 ports, RX4 selected



Conclusion

PE4263 S-parameters with the reference plane at the circuit board bond wire launch are available to selected customers via Peregrine Semiconductor Marketing or Sales. This note describes the procedure used to generate the data and a clear description of the reference plane location. For help or more information about this report, please contact Peregrine Applications at help@psemi.com.

Sales Offices

The Americas

Peregrine Semiconductor Corporation

9380 Carroll Park Drive
San Diego, CA 92121
Tel: 858-731-9400
Fax: 858-731-9499

Europe

Peregrine Semiconductor Europe

Bâtiment Maine
13-15 rue des Quatre Vents
F-92380 Garches, France
Tel: +33-1-4741-9173
Fax : +33-1-4741-9173

Space and Defense Products

Americas:

Tel: 858-731-9453

Europe, Asia Pacific:

180 Rue Jean de Guiramand
13852 Aix-En-Provence Cedex 3, France
Tel: +33-4-4239-3361
Fax: +33-4-4239-7227

Peregrine Semiconductor, Asia Pacific (APAC)

Shanghai, 200040, P.R. China
Tel: +86-21-5836-8276
Fax: +86-21-5836-7652

Peregrine Semiconductor, Korea

#B-2607, Kolon Tripolis, 210
Geumgok-dong, Bundang-gu, Seongnam-si
Gyeonggi-do, 463-943 South Korea
Tel: +82-31-728-3939
Fax: +82-31-728-3940

Peregrine Semiconductor K.K., Japan

Teikoku Hotel Tower 10B-6
1-1-1 Uchisaiwai-cho, Chiyoda-ku
Tokyo 100-0011 Japan
Tel: +81-3-3502-5211
Fax: +81-3-3502-5213

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