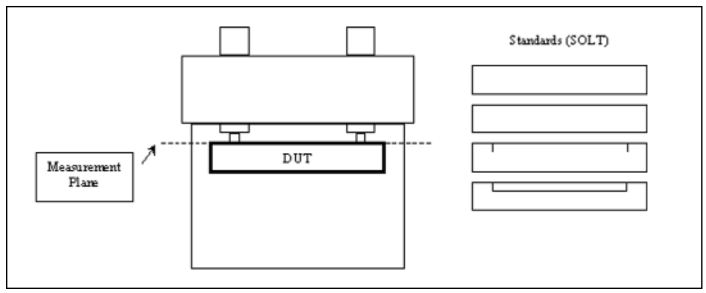
Calibrating Standards for In-Fixture Device Characterization

Accuracy of in-fixture network measurements is directly related to the process used to calibrate the fixture

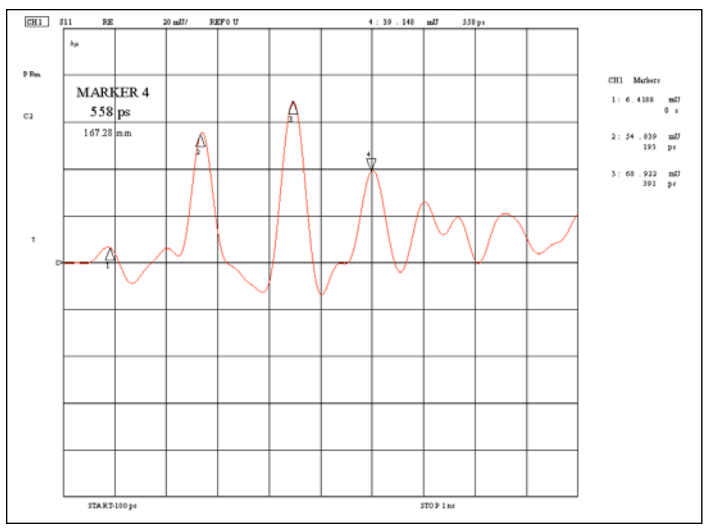
By Loren Betts
Agilent Technologies

In many products, including PCS and cellular phones, the continuing miniaturization of components and subsystems has all but eliminated the use of coaxial connectors as an internal interconnection method. In these products, a bandpass filter may be only a few centimeters long and may be mounted directly to the PC board, without connectors. This presents a problem when using a vector network analyzer to evaluate the characteristics of a component, since there is no longer a well-characterized interface (the connector of the device under test) to which the analyzer can connect.

The test fixture is a good solution to the above problem, as long as it is well constructed, its characteristics are known and its effects can be removed from the measurement results. The fixture must be calibrated, usually by means of the short-open-load-through (SOLT) calibration technique. Calibration of a fixture used to evaluate bandpass filters for mobile phones provides a good example of the details that must be considered and the process itself.

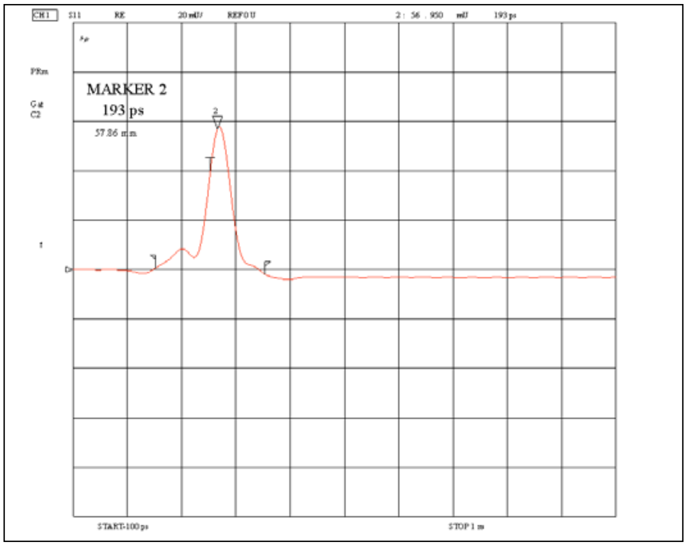


▲ **Figure 1(a). A bandpass filter test fixture.**

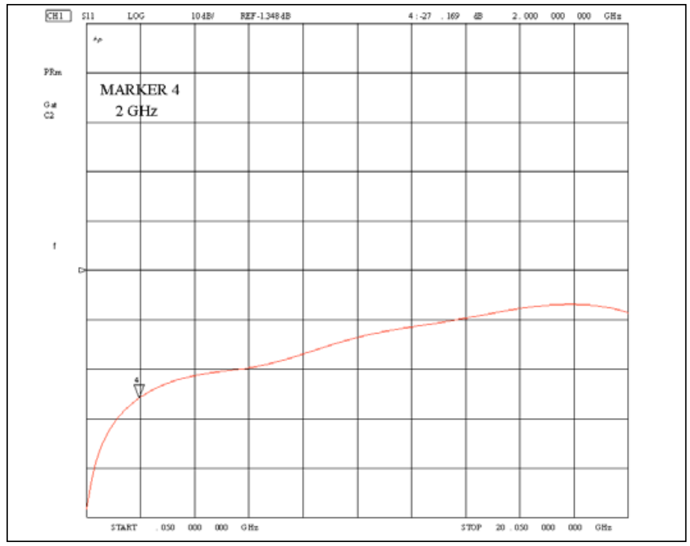


▲ **Figure 1(b). Characteristics in the time domain with the through standard in place of the filter shown in Figure 1(a).**

Figure 1(a) shows an example fixture for testing a bandpass filter. The fixture's SMA connectors are the interface to the network analyzer, and "pogo"-type connectors connect to the filter under test. Its characteristics in the time domain with the through standard in place are shown in Figure 1(b). Transitions in the fixture are readily identifiable; markers 1 and 4 show the transition at the SMA input and output connectors respectively, and markers 2 and 3 show the transition of the input and output "pogo" connectors. Between markers 2 and 3 is the reflection coefficient of the through standard, which can be used to calculate the transmission line impedance.



▲ **Figure 2(a). The match of the fixture viewed in the time domain with gating on.**



▲ **Figure 2(b). Frequency response of the fixture viewed in the time domain with gating on.**

In the time domain, a network analyzer's gating function can be used to remove all data from the measurement except that obtained from the fixture. The match of the fixture may then be analyzed in the frequency domain with gating on, as shown in Figure 2(a). In this case, the gate starts at the SMA transition and stops at the input "pogo" connector.

Figure 2(b) shows the frequency response of the fixture with gating on. The match at 2 GHz is about 25 dB. If the match of the filter is 20 dB, then the measurement uncertainty will be high, often manifesting itself as ripple in the data trace.

In-fixture standards

A set of in-fixture standards consists of short, open, load and through standards and is the same size as the DUT so that they may be inserted into the fixture during calibration. This also allows the "pogo" pins to be compressed the same amount for both the standards and the DUT, which helps define the measurement plane. Defining the measurement plane is a key ingredient in the calibration process, because it is the point at which the analyzer makes its measurement. Consequently, careful determination of this point ensures that undesired electrical characteristics occurring before the measurement plane are not included in the results. Ideally, the measurement plane should be at the RF connections of the DUT.

The short standard is a block of conductive material, and the open standard is a nonconductive dielectric block. The load standard consists of two 100-ohm resistors in parallel, connected to a short microstrip line that ends in a contact pad, which the "pogo" pins contact when inserted into the fixture. In this case, the pins are only in contact with the pad. The use of parallel resistors reduces the series inductance, thereby enhancing the performance of the load element. The through standard is a microstrip transmission line that connects the two "pogo" pins together when inserted into the fixture.

The characteristics of the calibration standards must be determined, and the resulting electrical data (which forms the calibration kit definition) must be input to the network analyzer to perform the required error correction. This calibration data includes values of impedance, frequency, loss, delay, fringing capacitance and inductance. For example, the open standard may be offset from the point where it interfaces to the fixture, in which case this information is entered as offset delay, offset impedance and offset loss. An open standard may also have "fringing" capacitance at the open connection, which must be included as well. The other standards have similar characteristics that must be measured and input to the analyzer.

Characterizing the standards

The first step is to perform a calibration at the point where low-loss flexible microwave cables terminate in the connectors that will mate to the test fixture. The calibration must be performed with the proper calibration kit and associated calibration kit definition in the analyzer. For this calibration, the Agilent 8720ES vector network analyzer and 85052D calibration kit and definition file are used. The fixture is then connected to the analyzer and a marker is placed at 1 GHz. Since the offset delay equation requires that insertion loss of the through standard be measured at 1 GHz, the remaining measurements were also made at this frequency for consistency. The terms of the open standard (C_0 through C_3) have negligible impact at this frequency.

The analyzer setup is as follows:

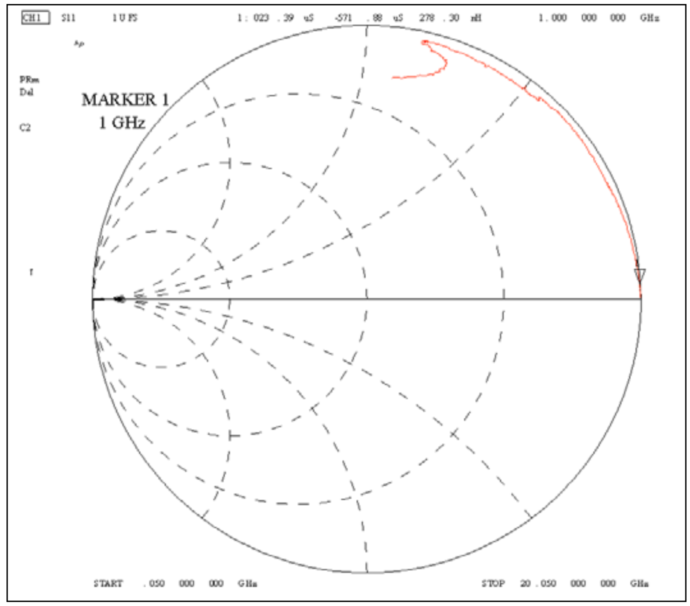
- Start frequency: 50 MHz
- Stop frequency: 20.05 GHz
- Number of points: 401
- Time domain mode: Low-pass step
- Calibration: 2-port SOLT

A short standard is defined as having unity reflection and a 180 degree phase shift, and the short standard defines where the measurement plane resides. The short standard is inserted into the fixture; the analyzer is set to measure S_{11}; and the format is set to phase.

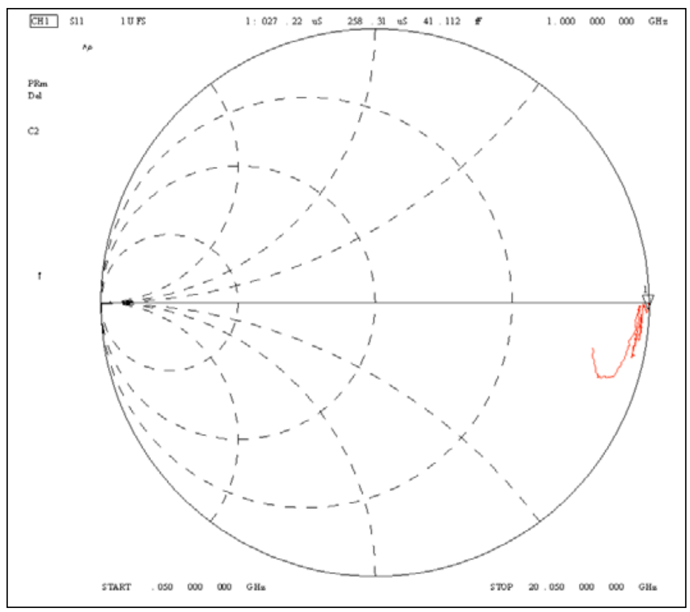
The port extensions for port 1 are then adjusted until the phase reads 180 degrees at the marker. (It may be helpful to set the reference value of the display to 180 degrees to avoid jumps from ±180 degrees while adjusting the port extensions.) The resulting value represents the offset to the measurement plane and should be stored for later use, since it is the basis for definition of the remaining standards. For the short standard, the offset is zero length from the measurement plane, which means that offset loss and impedance are irrelevant.

The open standard has unity reflection and no phase shift. The actual open standard will likely have some phase shift because of fringing capacitance. This capacitance as well as the offset parameters must be measured. The open standard is inserted into the fixture, and the port extensions remain on for port 1 using the value determined for the short standard. The analyzer is set to measure S_{11}, and the format is changed to the Smith chart.

If the short standard is electrically longer than the open standard, the analyzer will measure inductance instead of capacitance. The open standard will appear to have positive phase, which infers that the capacitance looks negative (that is, the trace on the Smith chart will rotate backward, or counter-clockwise, as shown in Figure 3). If this occurs, the offset length must be adjusted using the port extensions for port 1, as was done for the short standard, until the phase response is monotonically negative. The difference between the value of the port extension for the short and open standards will be a negative value, since the port extension was reduced for the open standard. This negative value will be entered into the calibration kit definition as an offset length in picoseconds. With this new offset in place, the Smith chart now displays capacitance instead of inductance (Figure 4).



▲ **Figure 3. The Smith chart when the short standard is electrically shorter than the open. The trace rotates backward.**



▲ **Figure 4. The Smith chart, now displaying capacitance rather than inductance, when the offset is in place.**

The fringing capacitance is modeled as a "shunt" element in the calibration kit definition, so the Smith chart marker should be changed to read admittance ($G + jB$). With the marker at 1 GHz, the fringing capacitance (C_0) should be recorded. The higher-order fringing capacitance terms C_1 through C_3 will be negligible at frequencies up to about 3 GHz. The fringing capacitance is entered into the calibration kit definition.

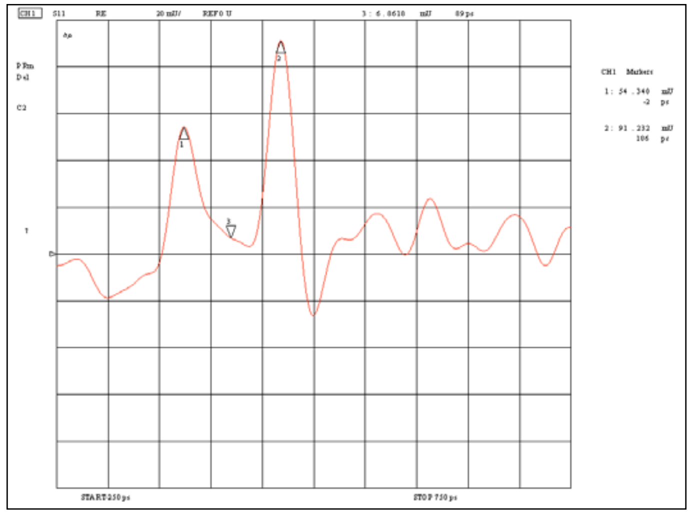
The offset parameters of the through standard must also be characterized; these include offset delay, offset impedance and offset loss. Offset delay is measured by placing the through standard into the fixture with a small piece of copper tape on the output "pogo" pin side of the through standard. The port extensions should be set to the value determined from the short standard. The S_{11} parameter is now measured, and the format is changed to phase. As with the short standard, the port extensions for port 1 should be adjusted until the phase reads 180 degrees at the marker. (It may be helpful in this case also to make the reference value of the display 180 degrees to avoid the jumps from ±180 degrees while adjusting the port extensions.) The value is recorded with the marker at 1 GHz, and the difference between this value and the value measured for the short standard is the offset delay. This delay is also entered into the calibration kit definition.

The analyzer is now switched to time domain low-pass step mode and S_{11} is measured. In time domain measurements, the format of the measurement must be set to *Real*. The analyzer will display the linear reflection coefficient, and the offset impedance of the through standard can be determined by placing a marker between the two "pogo" transitions (Figure 5). The reflection coefficient is defined by Equation (1), from which Z (the characteristic impedance of the through standard) can be calculated.

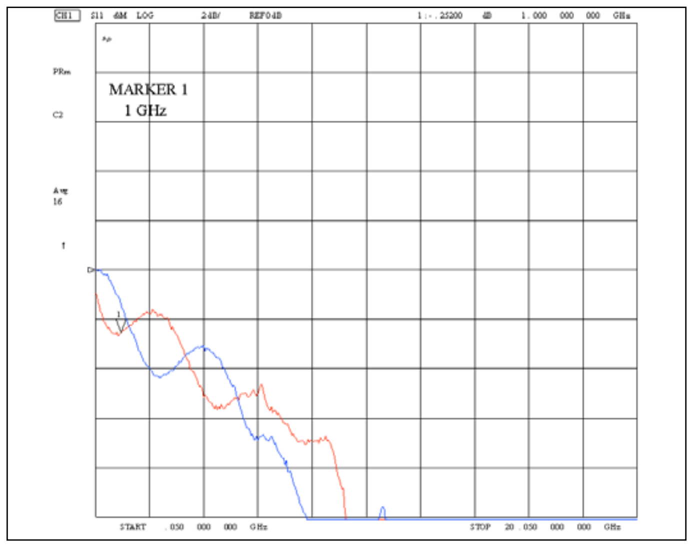
$$\rho = \frac{Z - Z_0}{Z + Z_0} \qquad Z_0 = 50 \tag{1}$$

Offset loss is measured by changing the format back to log magnitude and measuring S_{11} with the copper tape in place. The port extensions for port 1 are adjusted to the value measured for the short standard, and a marker is placed at 1 GHz. A single sweep is made and the resulting data saved to memory. If the response varies, an averaging factor of 8 can be used. The copper tape is then replaced with a small piece of nonconductive dielectric material (paper works well). A single sweep is made, and the data trace and memory trace values are recorded. The traces would ideally be identical, but source match and directivity errors introduce some differences as the error signals interact with the measured signal.

The average of the two traces is the two-way insertion loss of the through standard and port 1 side of the fixture (Figure 6). The two-way loss through the port 1 side of the fixture can be measured using the same technique. Subtracting the fixture loss gives the two-way insertion loss of the through standard. Dividing this number by two gives the insertion loss of the through in dB. The offset loss for the calibration kit definition is



▲ **Figure 5. Offset impedance, identified with markers between the two pogo-connector transitions.**



▲ **Figure 6. Two-way insertion loss of the through standard.**

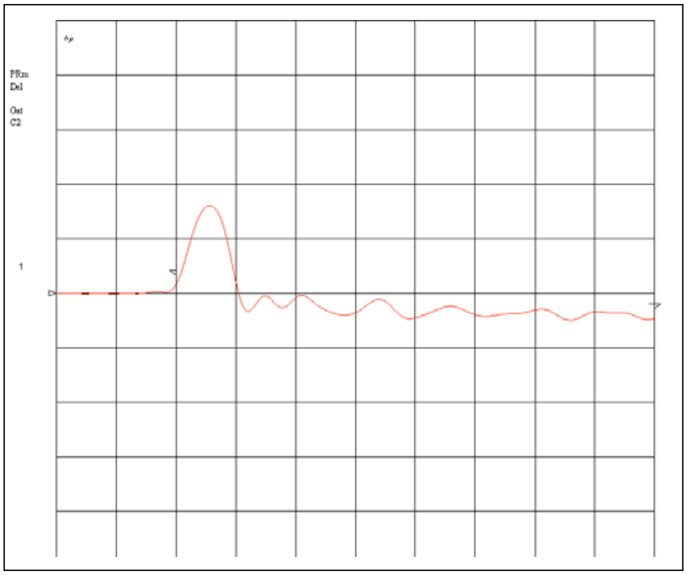
given in units of Gohm/s. Equation (2) is used to calculate this value, where Z_0 is in ohms (the Z value calculated for the through standard), loss is in dB and delay is in seconds.

$$Offsetloss = \frac{Z_0 \times loss}{delay \times 10 \times \log(e)} \tag{2}$$

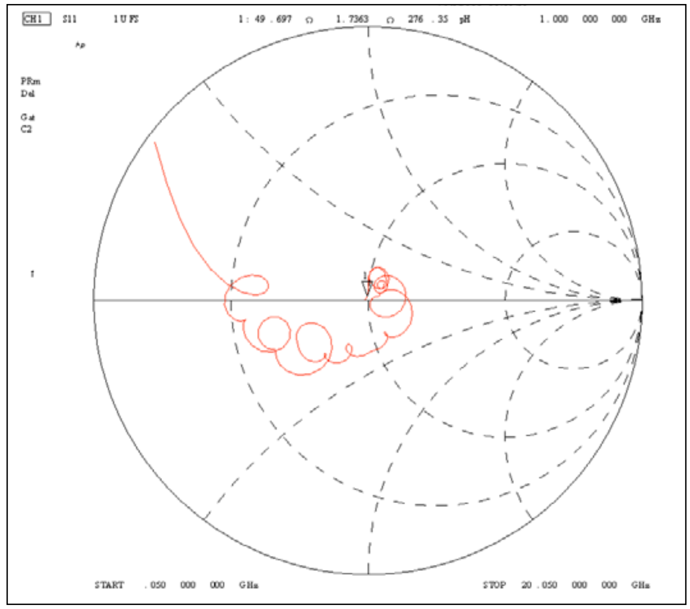
For the load standard, the offset delay and impedance must be adjusted by removing the effects of the fixture with the analyzer's gating function. The load standard is inserted into the fixture and the port extensions remain on for port 1 using the value determined when the short standard was measured. The analyzer is switched to the time domain mode. The stop

Type	C_0 (Z)	C_1	C_2	C_3	Offset delay	Offset Z_0	Offset loss
Short					0	50	0
Open	41.112	0	0	0	–6.62	50	0
Load (fixed)					10	45	0
Through					84.6	50.69	14.4

▲ **Table 1. Final calibration kit definition.**



▲ **Figure 7(a). In the time domain mode, the start and stop points of the gate are placed so that the fixture is removed from the measurement.**



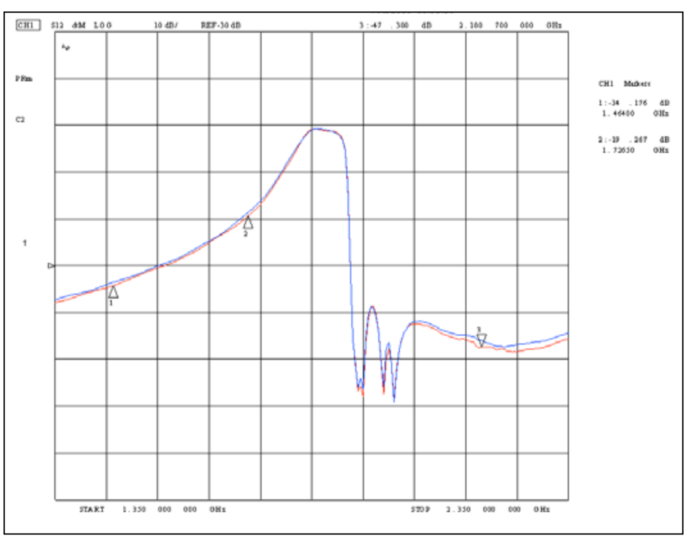
▲ **Figure 7(b). The Smith chart records the resulting inductance value generated by 7(a).**

and start points of the gate are placed so that the fixture is removed from the measurement [Figure 7(a)].

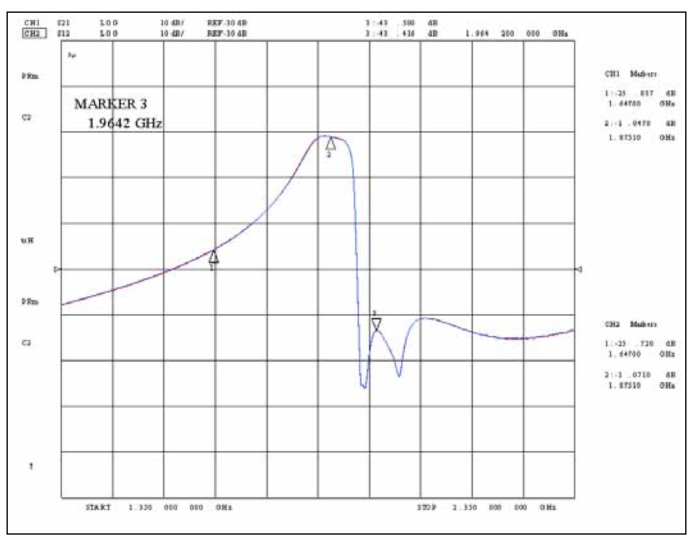
With gating still on, the transform is turned off, and the format is changed to the Smith chart. The values should be considered series inductance, so the marker format must be changed to $R + jX$. The resulting inductance value is recorded, as shown in Figure 7(b). This is the "correct" value, the goal when trying to determine the offset delay and offset impedance through iteration.

The short, open and through calibration kit definitions are entered into the analyzer and a good guess is made of the offset length and impedance of the microstrip line connected to the load element. This value is entered into the analyzer and a one-port calibration is performed with the in-fixture standards. The load element is inserted, and the match (S_{11}) of the load element is measured in the Smith chart format. The resulting inductance value is then compared to the one recorded earlier. The offset delay and offset impedance are adjusted until the inductance value after calibration is nearly the same as the value recorded earlier with gating. The value obtained after the iterative process is the offset length and impedance of the load standard. In this case, the offset length is short enough so that offset loss can be ignored.

Table 1 shows the final calibration kit definition for the in-fixture standards. The follwoing values correspond to a definition for an ideal calibration kit:



▲ **Figure 8(a). The initial calibration kit definitions produced the responses in (a).**



▲ **Figure 8(b). The responses in 8(a) were significantly improved using the new calibration kit definition (b).**

- Offset loss and delay = 0
- Offset Z_0 = 50
- Minimum frequency = 0
- Maximum frequency = 999
- C_0 through C_3 = 0 for the open standard only

The values obtained through this process show that while calibration standards are precise, they are not perfect and some variance usually occurs.

Results

Accurate calibration will produce S_{21} and S_{12} responses that are identical. In Figure 8(a), the results using the simplistic calibration kit definitions show that at certain frequencies, the traces differ by as much as 3 dB — for example, at marker 3. This difference occurs because the calibration kit definitions do not match the calibration standards. For example, the through standard, which was assumed to have zero length, is different in its physical implementation. The results obtained using the new calibration kit definition in Table 4 are shown in Figure 8(b). The two traces agree within 0.1 dB, which is a significant improvement.

It may be helpful to use the VNACal kit manager, located at www.vnahelp.com, for entering the calibration kit definitions into the network analyzer. ■

Author information

Loren Betts joined Agilent Technologies in 1997 after graduating from the University of Alberta, Canada, with a Bachelor's degree in Computer Engineering. Currently, he works as an Application Specialist for Agilent, focusing on its network analyzer products. He is attending Stanford University and plans to earn a Master's degree in Electrical Engineering. He can be contacted at tel: 707-577-2828; or e-mail: loren_betts@agilent.com