Calibration Substrate
CS-8

INTRODUCTION:

The Model CS-8 calibration substrate contains high precision elements for calibrating out the unavoidable errors and losses in a microwave network analyzer, its associated cabling and the probe for on-wafer testing. This instruction guide consists of two parts. The first part describes the calibration structures and serves as a cookbook style instruction how to use the structures to calibrate a network analyzer. The second part deals with the sources of residual errors, methods of minimizing the errors and methods of correlating the differing types of information from test results. The bibliography at the end of this instruction lists sources of detailed information about the theory of network analyzer operation and the details of various calibration methods.

The basic principle underlying the calibration of a measurement system is to provide accurate, known standards to which the measurement system can be connected. The GGB Industries, Inc. CS-8 calibration circuit is such a standard. Whenever the measurement system (network analyzer+cabling+probe) produces a reading different than the standard, a correction is entered into the measurement system to give a result in agreement with the standard. Naturally, the accuracy of the calibration is limited by the accuracy of the standard and by the care exercised in the calibration routine. Happily, modern network analyzers contain preprogrammed semiautomatic calibration routines that produce accurate calibration with a minimum of work.

This instruction guide assumes that the reader is familiar with the operation of a network analyzer and its various features.

PART 1:

THE CALIBRATION SUBSTRATE:

Figure 1 shows the overall circuit layout of the model CS-8 calibration substrate and Table 1 lists the elements. The circuits have been designed for probes with ground-signal and signal-ground tip configurations, and most structures accommodate probe tip spacing ranging from 50 to 200 micrometers. Other circuits near the corners accommodate probe spacing from 250 to 1000 micrometers (um).

Standard elements for calibrating a microwave measurement system consist of opens, shorts, matched loads, and throughs. These four elements have electrical characteristics that are very different from one another so that each one by itself contributes an important part to the calibration. In principle any set of standards could be employed, but the more identical they are the less accurate the calibration.

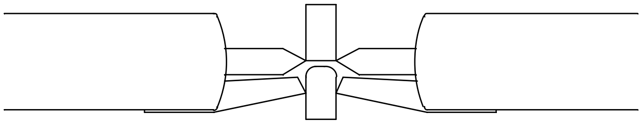
The most convenient standards are those listed 51 to 86 and are arranged in columns so that only one direction of motion is required to move the probes from one element to the next during the calibration routine. Elements 51 through 56 are opens and 61 through 66 are shorts. Elements 71 through 76 are matched 50 ohm loads and 81 through 86 are 400 um long throughs. Elements 30, 31, 33, 34, 40, 42, 44, and 45 are for use with right angle probe configurations. Elements 90, 91, 110, and 111 are for use with

250 to 500 micron pitch probes and elements and 00, 01, 20, 21 are for use with 500 to 1000 micron pitch probes. The long lines 10 and 100 are intended for measurements of line impedance, propagation velocity, loss per unit length, and other parameters such as phase distortion and source match. The remaining elements 50, 60, 70, and 80 are for non-mirror image probe pairs.

Probe Tip Positioning:

For accurate calibration, it is essential to place the probe tips accurately on the calibration structures. Special alignment structures 41 and 43 have been included to facilitate probe alignment. As shown in Figure 2, the center conductor is placed to just contact the corner of the square after 50 to 75 microns (2-3 mils) of over-drive and then the substrate or preferably the probe is rotated so the single ground contact just touches one or the other edge as shown. This gives the probe the coordinates of the structure. For automatic calibration, the coordinates supplied with Figure 1/Table 1 can then be entered into the prober to accurately contact the required structures in sequence. The through line will then be probed exactly 25 microns in from the ends and the short, load, and open pads will be probed exactly in the middle. This is depicted to scale for a GS & SG 150 micron pitch probe in Figure 3.

Fig.2



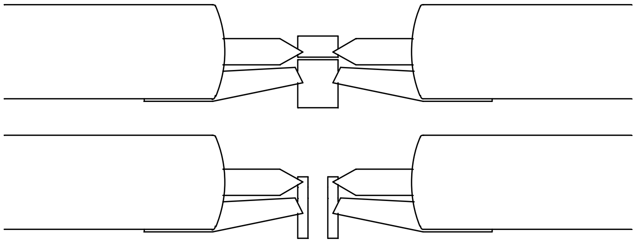


Fig.3

Probe Over-drive:

As the probe is lowered to make contact with the test structures on the substrate, the ground tip will contact the circuit first. Further lowering of the probe will cause the ground to flex and the center tip then makes contact. To ensure reliable contact, 2-3 mils (50-75um) of vertical over-travel is recommended from the point at which the ground first makes contact. Another way to judge the proper amount of over-travel is to watch for about 10 to 15 microns of forward movement of the signal point after it first contacts. The 25 micron space between the two halves of the alignment structure can be used as an aid in visualizing this forward movement.

CALIBRATION METHODS:

Three major calibration methods have been developed to calibrate network analyzer systems:
OSLT (Open, Short, Load, Through)
LRM (Line, Reflect, Match)
LRL (Line, Reflect, Line)

Other methods listed in the references are either extensions or special cases of these three.

OSLT Calibration:

The open required by the OSLT method has been implemented in three different ways by workers in the field. Method #1- The probe can be raised up more than double the probe spacing above a bare spot on the substrate. Method #2- The probe points can be contacted to a bare spot on the ceramic substrate.

Method #3- The probe can contact one of the special open pad structures. The first and second methods are not preferred because the fringing electric fields at the probe tips are very different than the fields when the probes contact the short, load, and through structures. The third method is preferred because the electrical fields at the probe tips are very similar to those of the matched load and the through structures. Documentation with your GGB Industries, Inc. microwave probe will indicate what value of capacitance must be entered into the calibration routine to account for the fringing in Method 3. The short is implemented by contacting one of the shorting bars or offset shorts. The electrical characteristics of the short includes a small inductance which depends on the probe contact spacing (pitch). This inductance is specified as an inductance or as an equivalent electrical length in series with a perfect short. Documentation with your GGB Industries, Inc., microwave probe will indicate the proper inductance value when probing one of the shorting bars.

The matched loads consist of a precision 50 ohm thin film resistor to provide a precise 50 ohm termination, accurate to 0.25% at low frequencies. At high frequencies the load can also exhibit either a small shunt capacitance or a small series inductance, depending on the contact spacing (pitch) of the probe tips. These parameters, also supplied with your probe documentation can be entered into the calibration routine of a Keysight/Agilent/HP network analyzer by means of a fictitious short length of transmission line. To enter an inductance, a short length of high impedance line (Zo=500 ohms) is connected in series with a perfect 50 ohm resistor. The equivalent inductance value, L, is given by L=495dt where dt is the time delay of the 500 ohm line. To enter a shunt capacitor, a short length of low impedance line (Zo=5 ohms) is used. Here the equivalent capacitance is given by C = 0.198dt where dt is the delay of the short section of 5 ohm line. The length of the high or low impedance line required to produce a purely resistive load impedance is also included in the probe documentation.

The through lines 81 through 86 consist of 50 ohm single ground coplanar lines that are 400 um long. The probe tips should contact the line 25 um from the ends so that the length of the line between contacts is 350 um. The high dielectric constant alumina substrate results in a propagation velocity that is 0.435 that of free space so the equivalent free space electrical equivalent length is 804 um and the delay is 2.68 ps. If the alignment structures 41 or 43 are used then the probes will have the proper 350 um spacing.

LRL and LRM Calibrations:

The LRL and LRM methods of calibration are very similar. Neither requires open or short standards but both require identical reflects. Either the shorting bars or open pads can be used as the reflects. We recommend the shorting bars, being very careful to contact them exactly the same way with both probes. The LRL method requires two lines of differing lengths whereas the match in LRM takes the place of the second line of LRL. Line dispersion and radiation limits the accuracy of the LRL method for single ground coplanar lines and it is not recommended for single sided probes. For LRM calibration a matched load, which is equivalent to an infinitely long lossless line, substitutes for the second line in LRL and in that case the matched load sets the calibration impedance. The LRL and LRM methods produce a calibration that is referenced to the center of the 400 um through line. To produce a probe tip calibration, the reference must be offset by half the first line delay.

The resistor material at the edges of the line 100, is 25 micrometers shorter than the line, therefore the resistor material can be used as an alignment structure to set the distance between the two probes to achieve the proper 25 micrometers overlap on each end of the line.

PART 2:

CALIBRATION ERRORS:

As indicated in the previous sections, the accuracy of the system calibration is limited mainly by the accuracy of the impedance standards and by the accuracy of the probe placement while contacting the standards. We have already discussed the general problems of accurate probe placement, the capacitance of the opens, the inductance of the shorts, and the inductance or capacitance of the loads. This section discusses in more detail how these parameters affect the overall usefulness and accuracy of the calibrations and how they affect the measurement accuracy of a device under test (DUT).

The Through:

The signal propagation on the through lines is slowed to approximately 0.435 that of light by the presence of the high dielectric constant alumina substrate. Therefore the free space electrical length required by the network analyzer is increased by the reciprocal of this factor.

As noted above, the through lines should be contacted 25 um from the ends. Therefore the microwave signals propagating between the probe tips contacting the 400 um line only travel 350 um which corresponds to a free space electrical length of 804 um or 2.68 ps. Probing the through line 25 um from the ends leaves a 25 um open section of line at each end. This length would be quarter wavelength resonant at about 1,400 GHz, so even at W band the open sections are much below resonance and can be considered as lumped capacitors, C1, measuring 25 by 50 um. These capacitors can be considered as part of the probe tips after calibration.

The calibration algorithms assume that the through line has 50 ohms impedance and that it is non-dispersive. Unfortunately single sided ground coplanar lines are dispersive below about 5 GHz and radiate so that even a line that is only 350 micrometers long has a small but measurable dispersion and this is included as a small error in the calibration.

The Opens:

When we contact a standard open pad with capacitance, C2, the capacitance difference, C2-C1, is the apparent capacitance of the open pad. This difference is the open capacitance specified in the SOLT calibration method. In the LRM routine, no open standard is employed so the capacitors C1 are the only part of the calibration. Careful measurements show that the capacitances C1 and C2 are essentially independent of probe pitch.

The Short:

The inductance of the shorting bar depends on the length of the current path and so depends strongly on probe tip pitch. This inductance is also included in the probe documentation.

The Matched Load:

The resistive elements consist of a high resistance alloy 0.12 um thick and sheet resistance of about 60 ohms. Skin depth for this material is about 12 um at 100 GHz so the resistance differs little from the low frequency value. Special techniques are employed to form electrical contacts between the metal and the resistive layer that do not exhibit resistance-capacitance transmission line effects.
Shunt capacitance and series inductance seriously affect the characteristics of the matched loads. As noted above, the inductance of the load depends upon the pitch of the probe employed, but the capacitance depends little on pitch. The resistor pads are nearly identical to the open pads so the load

capacitance is nearly identical with that of the open. Also, the current path through the load is almost identical with the current path through the short, so the inductance of the load is nearly identical with that of the short. The inductance causes the current to lag the voltage whereas the capacitance causes the current to lead the voltage. These two opposing effects tend to compensate for one another so that the load appears nearly perfectly resistive for some intermediate probe pitch. In the past, workers in the microwave field have ignored the capacitance and inductance effects in the loads. However, our desire for higher accuracy requires their inclusion in the calibration.

Crosstalk:

As discussed previously, during calibration, errors in measured values are corrected so that the measurements agree with those expected from the assumed perfect standards (open, short, load, and through). These corrections include any signals that couple from one probe to the other. For example, if we calibrate one (first) probe on an open while the other (second) probe is touching a nearby open, a small part of the signal on the calibrating probe reaches the other probe. That small crosstalk or leakage signal is included in the calibration of the first probe. If the second probe had been touching a load or a short, the calibration of the first probe would have been slightly different. Also, if the spacing between the probes were different, the calibration would be slightly different. When the probes are moved after calibration to measure a real device, it is evident that these crosstalk signals also change leading to further errors. It is therefore important that crosstalk should be as small as possible. For the structures included on the calibration substrate, crosstalk is very small and can be neglected. However, if the devices to be measured require probe-to-probe placement less than 150 um, crosstalk could limit the accuracy of the measurement.

Spurious Modes:

The elements employed during calibration can couple signals to adjacent structures. For example, while calibrating using the throughs 80 to 86, a small portion of the calibrating signal couples to line 100. At the resonant frequency of line 100, the line could absorb a noticeable fraction of the calibrating signal to produce an anomaly in the calibration. The resistive extensions on the ground plane of line 100 prevent this by damping out the resonance. The through lines are designed to propagate the balanced coplanar mode where the electric and magnetic fields are confined near the gap between the center line and the ground planes. However, if the substrate is placed on a metallic holder, a small fraction of the signal can propagate as a microstrip mode with the metallic holder acting as the ground plane. This mode can be reduced by placing the substrate on an electrically insulating holder such as glass. Some workers in the field place a layer of microwave absorbing material under the substrate to damp out such spurious modes.

Calibration Stability:

The accuracy of a calibration will deteriorate with time as a result of unavoidable variations in the environment of the test system. The network analyzer itself will change with time and such changes are included in the stability specifications of your network analyzer. Temperature variations in the cabling between the network analyzer and the probe can be responsible for most of the calibration drift. As the temperature in the measurement lab varies, the cabling lengthens or shortens resulting in phase errors. Special low temperature coefficient cables should be employed and the test lab should be temperature stabilized to minimize the changes. Low temperature coefficient cables in various lengths and connector styles are available from GGB Industries, Inc.

Device Measurement:

Much larger measurement errors than those incurred in the calibration result from the differences between the probing environment of the device structures and that of the standard substrate. Usually the material is different, (e.g. gallium arsenide v/s alumina) and more importantly, the line width and spacing leading to the device to be tested are different than those on the standard substrate. A technique called "de-embedding" can aid in correcting these differences. The basic strategy is to include on the substrate with the device to be tested (DTBT) a set of structures similar to those that connect to the DTBT. For example, if the DTBT includes probe pads with connecting lines then identical pads with connecting lines but without the device can be tested with a probe that has been calibrated with the standard substrate. Those test results can then be used to correct for the influence of the pads and the interconnecting lines on the measurement of the DTBT. For more detailed analyses of these techniques see references 23, 25, and 26 which are available upon request.

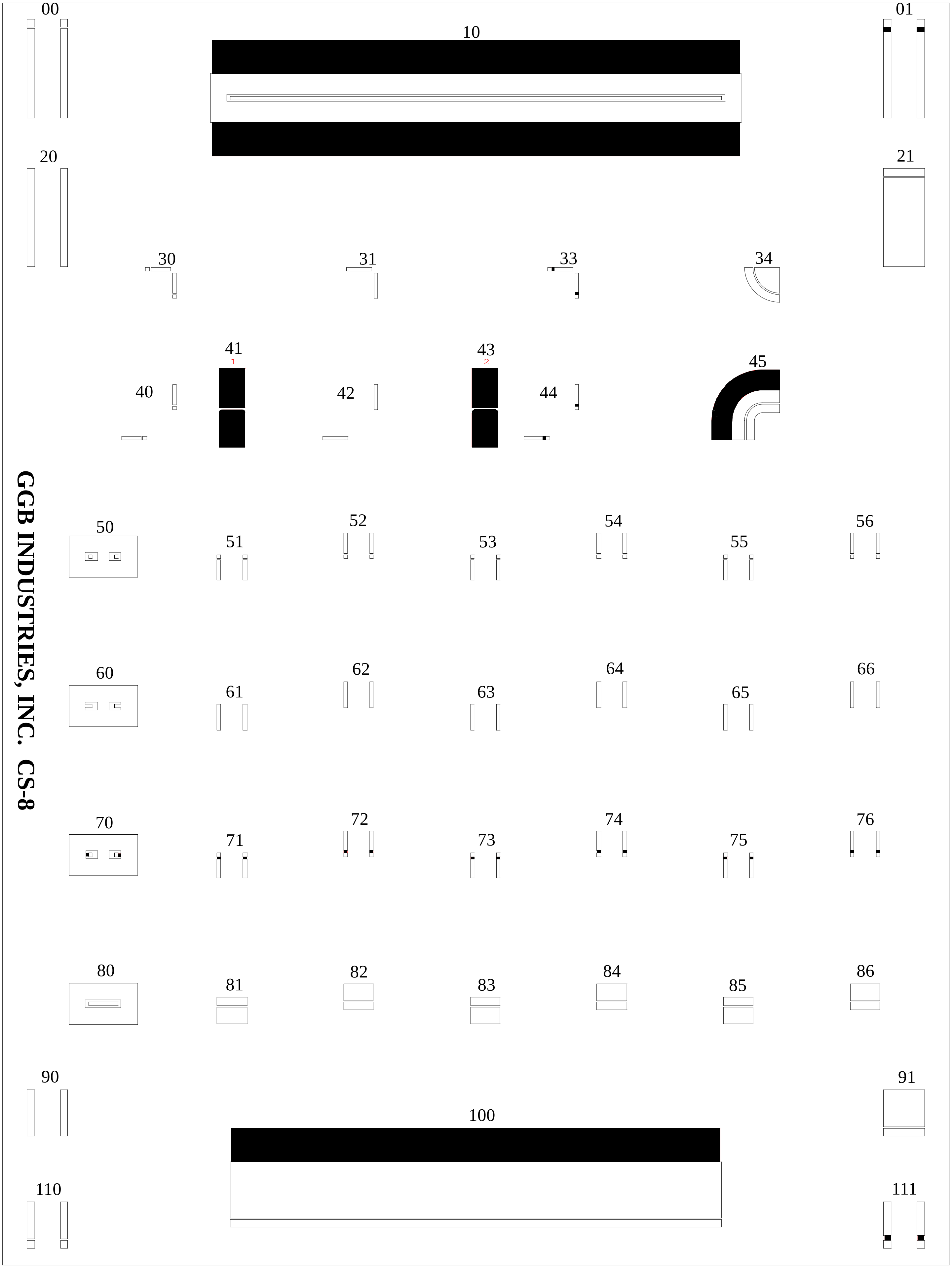

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Figure 1

CS-8 Calibration Substrate Key

(all structures for probes with one ground)

Location #	Description	Coordinates (X,Y in micrometers)
00	open pads (500 to 1250 micrometer pitch)	(0, 0) from 00
01	50 ohm loads (500 to 1250 micrometer pitch)	(11500, 0) from 00
10	6600 micrometer 50 ohm coplanar line (50 to 250 micrometer pitch)	(175, 4155) from 41
20	shorting bars (500 to 1250 micrometer pitch)	(0, 2025) from 00
21	550 micrometer long 50 ohm line (500 to 1250 micrometer pitch)	(11500, 2025) from 00
30	right angle open pads for G,S probes (pair) (50 to 250 micrometer pitch)	(0, 0) from 30
31	right angle shorting bars for G,S probes (pair) (50 to 250 micrometer pitch)	(2700, 0) from 30
33	right angle load for G,S probes (pair) (50 to 250 micrometer pitch)	(5400, 0) from 30
34	right angle 50 ohm line for G,S probes (50 to 250 micrometer pitch)	(8100, 0) from 30
40	right angle open pads for S,G probes (pair) (50 to 250 micrometer pitch)	(0, 0) from 40
41	350 micrometer spacing alignment structure #1	(0, 0) from 41
42	right angle shorting bars for S,G probes (pair) (50 to 250 micrometer pitch)	(2700, 0) from 40
43	350 micrometer spacing alignment structure #2	(3400, 0) from 41
44	right angle 50 ohm loads for S,G probes (pair) (50 to 250 micrometer pitch)	(5400, 0) from 40
45	right angle 50 ohm line for S,G probes (pair) (50 to 250 micrometer pitch)	(8100, 0) from 40
50	open pads for non mirror image probes (pair) (50 to 250 micrometer pitch)	(-1725, 2000) from 41
51	open pads (pair) (50 to 250 micrometer pitch)	(0, 2000) from 41
52	open pads (pair) (50 to 250 micrometer pitch)	(1700, 2000) from 41
53	open pads (pair) (50 to 250 micrometer pitch)	(3400, 2000) from 41
54	open pads (pair) (50 to 250 micrometer pitch)	(5100,2000) from 41
55	open pads (pair) (50 to 250 micrometer pitch)	(6800,2000) from 41
56	open pads (pair) (50 to 250 micrometer pitch)	(8500,2000) from 41
60	shorting bar for non mirror image probes (pair) (50 to 250 micrometer pitch)	(-1750, 4000) from 41
61	shorting bar (pair) (50 to 250 micrometer pitch)	(0, 4000) from 41
62	shorting bar (pair) (50 to 250 micrometer pitch)	(1700, 4000) from 41
63	shorting bar (pair) (50 to 250 micrometer pitch)	(3400, 4000) from 41
64	shorting bar (pair) (50 to 250 micrometer pitch)	(5100, 4000) from 41
65	shorting bar (pair) (50 to 250 micrometer pitch)	(6800, 4000) from 41
66	shorting bar (pair) (50 to 250 micrometer pitch)	(8500, 4000) from 41
70	50 ohm loads for non mirror image probes (pair) (75 to 250 micrometer pitch)	(-1750,6000) from 41
71	50 ohm loads (pair) (50 to 250 micrometer pitch)	(0, 6000) from 41
72	50 ohm loads (pair) (50 to 250 micrometer pitch)	(1700, 6000) from 41
73	50 ohm loads (pair) (50 to 250 micrometer pitch)	(3400, 6000) from 41
74	50 ohm loads (pair) (50 to 250 micrometer pitch)	(5100, 6000) from 41
75	50 ohm loads (pair) (50 to 250 micrometer pitch)	(6800, 6000) from 41
76	50 ohm loads (pair) (50 to 250 micrometer pitch)	(8500, 6000) from 41
80	50 ohm coplanar line for non mirror image probes (50 to 250 micrometer pitch)	(-1725, 8000) from 41
81	400 micrometer long single sided line (50 to 250 micrometer pitch)	(0, 8000) from 41
82	400 micrometer long single sided line (50 to 250 micrometer pitch)	(1700, 8000) from 41
83	400 micrometer long single sided line (50 to 250 micrometer pitch)	(3400, 8000) from 41
84	400 micrometer long single sided line (50 to 250 micrometer pitch)	(5100, 8000) from 41
85	400 micrometer long single sided line (50 to 250 micrometer pitch)	(6800, 8000) from 41
86	400 micrometer long single sided line (50 to 250 micrometer pitch)	(8500, 8000) from 41
90	shorting bars (250 to 500 micrometer pitch)	(0, -1500) from 110
91	550 micrometer long 50 ohm coplanar line (250 to 500 micrometer pitch)	(11500, -1500) from 110
100	6600 micrometer single sided line (50 to 800 micrometer pitch)	(175, 10914) from 41
110	open pads (250 to 500 micrometer pitch)	(0, 0) from 110
111	50 ohm loads (250 to 500 micrometer pitch)	(11500, 0) from 110

Table 1