Calibration Substrate
CS-5

INTRODUCTION:

The Model CS-5 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-5 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-5 calibration substrate and Table 1 lists the elements. The circuits have been designed for probes with ground-signal-ground tip configuration, and can accommodate probe tip spacing ranging from 75 to 250 micrometers. Other circuits available from GGB Industries, Inc., accommodate probe spacings from 30 to 2540 micrometers (um) and for ground-signal and signal-ground configurations.

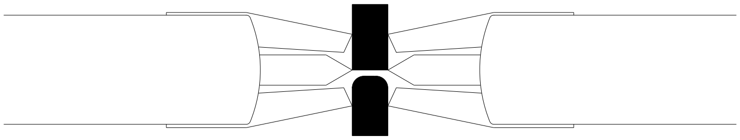
Standard elements for calibrating a microwave measurement system consist of opens, shorts, matched loads, and throughs. These four elements have electrical characteristics that are very different from one another so that each one by itself contributes an important part to the calibration. In principle 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 50 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 50 and 61 are mixed opens and shorts. Elements 70 through 76 are matched loads and 80 through 86 are 200 um long throughs. Elements 40 and 42 are an offset open and short and are intended to be used in conjunction with load 44, through 46, and offset load 20. Elements 90, 91, 110, and 111 are for use with right angle probe configurations. Lines 100, 101, and 102 are employed for LRL = Line-Reflect-Line (which is equivalent to TRL = Through-Reflect-Line) calibration to be described later. The long line 10 is 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 are the long offset short 00, the long offset 50 ohm load 01, 12.5 ohm resistor pair 32, 100 ohm resistor pair 37, and 25 ohm resistor pair 38. These last few elements are intended to provide added flexibility in cross-checking the calibrations.

Probe Tip Positioning:

For accurate calibration, it is essential to place the probe tips accurately on the calibration structures. Special alignment structures 41, 43, and 45 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 50-75 microns (2-3 mils) of over-drive and then the substrate or preferably the probe are rotated so the ground contacts just touches the edges 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 for the through and open pads in Figure 3.

Fig.2



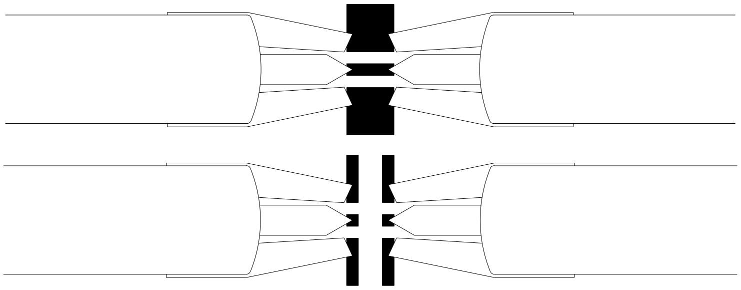


Fig.3

For LRL calibrations alignment structures 33, 34, 35, and 36 are used. For the First (shorter) line use structure 33 in the same way as structure 41. Then move only the right probe to the right side of 34 for alignment to line 100. In the same way use 33/35 for line 101 and 33/36 for line 102.

Probe Over-drive:

As the probe is lowered to make contact with the test structures on the substrate, the ground tips will contact the circuit first. Further lowering of the probe will cause the grounds to flex and the center tip then makes contact. To ensure reliable contact, 1.5 to 3 mils (40-75um) of vertical over-travel is recommended from the point at which the grounds first make 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) (which is equivalent to TRM=Through-Reflect-Match)
LRL (Line, Reflect, Line) (which is equivalent to TRL=Through-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 pair of precision 100 ohm thin film resistors to provide a precise 50 ohm termination, accurate to 0.25% at low frequencies. At high frequencies the load can 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 80 through 86** consist of 50 ohm coplanar lines that are 200 um long. The probe tips should contact the line 25 um from the ends so that the length of the line between contacts is 150 um. The high dielectric constant alumina substrate results in a **propagation velocity that is 0.442** that of free space so the **equivalent free space electrical equivalent length is 340um and the delay is 1.13 ps.** If the alignment structures 41, 43, or 45 are used then the probes will have the proper 150 um spacing. The through 46 is intended for use with the elements 20, 40, 42, and 44 which include offset opens and offset shorts.

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, open pads, offset opens, or offset shorts 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. In the CS-5 standard substrate, the 200 um line and the shorting bar are employed in both LRL and LRM. The second line of LRL is line 100 for V and W-band, line 101 for 8 to 67GHz, and line 102 for 5 to 40 GHz, and the characteristic impedance of this second line sets the calibration impedance. Line dispersion at frequencies below about 5 GHz limits the accuracy of the LRL method at low frequencies unless the results are corrected for the dispersion. An electrical length or delay must be entered into the network analyzer to account for the delay in the second line.

Line 100 is physically 550 microns long and when probed with a standard 25 micron overlap has a free space electrical length of 1,130 microns which is equivalent to a delay of 3.77 ps.

Line 101 is physically 1,000 microns long and when probed with a standard 25 micron overlap has a free space electrical length of 2,148 microns which is equivalent to a delay of 7.16 ps.

Line 102 is physically 1,500 microns long and when probed with a standard 25 micron overlap has a free space electrical length of 3,278 microns which is equivalent to a delay of 10.93 ps.

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 always produce a calibration that is referenced to the center of the 200 um through line.

When entering the line lengths into the network analyzer, if the first line is defined as 340 microns free space electrical length or 1.13 ps delay, then the second line is defined as the lengths outlined in the paragraphs above.

If the first line is defined as 0 length then the lengths for lines 100, 101, and 102 given above should be reduced by an free space electrical length of 340 microns or 1.13 ps. To produce a phase reference plane at the probe tips after calibration, the reference must be offset by half the first line delay.

The resistor material at the edges of the lines 10, 100, 101, and 102 are 50 micrometers shorter than the lines themselves, 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 0.442 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 200 um line (80-86) only travel 150 um which corresponds to a free space electrical length of 340 um or 1.13 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 coplanar lines are dispersive below about 5 GHz so that even a line that is only 150 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 and LRL routines, 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.

Special offset open structure 40 has been included to provide added flexibility of calibration. These structures have the advantage that the probe tip environment is more nearly identical to that of the through than that of the open pads. The length of the offset however must be included in the calibration parameters and this length is not precisely defined because of fringing fields at the open end.

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. Offset short 42 is included to complement the offset opens and provide added flexibility of calibration. However, as with the offset opens, one must specify the length of the offset short and that length is somewhat indeterminate because of the fringing currents at the shorted end.

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:

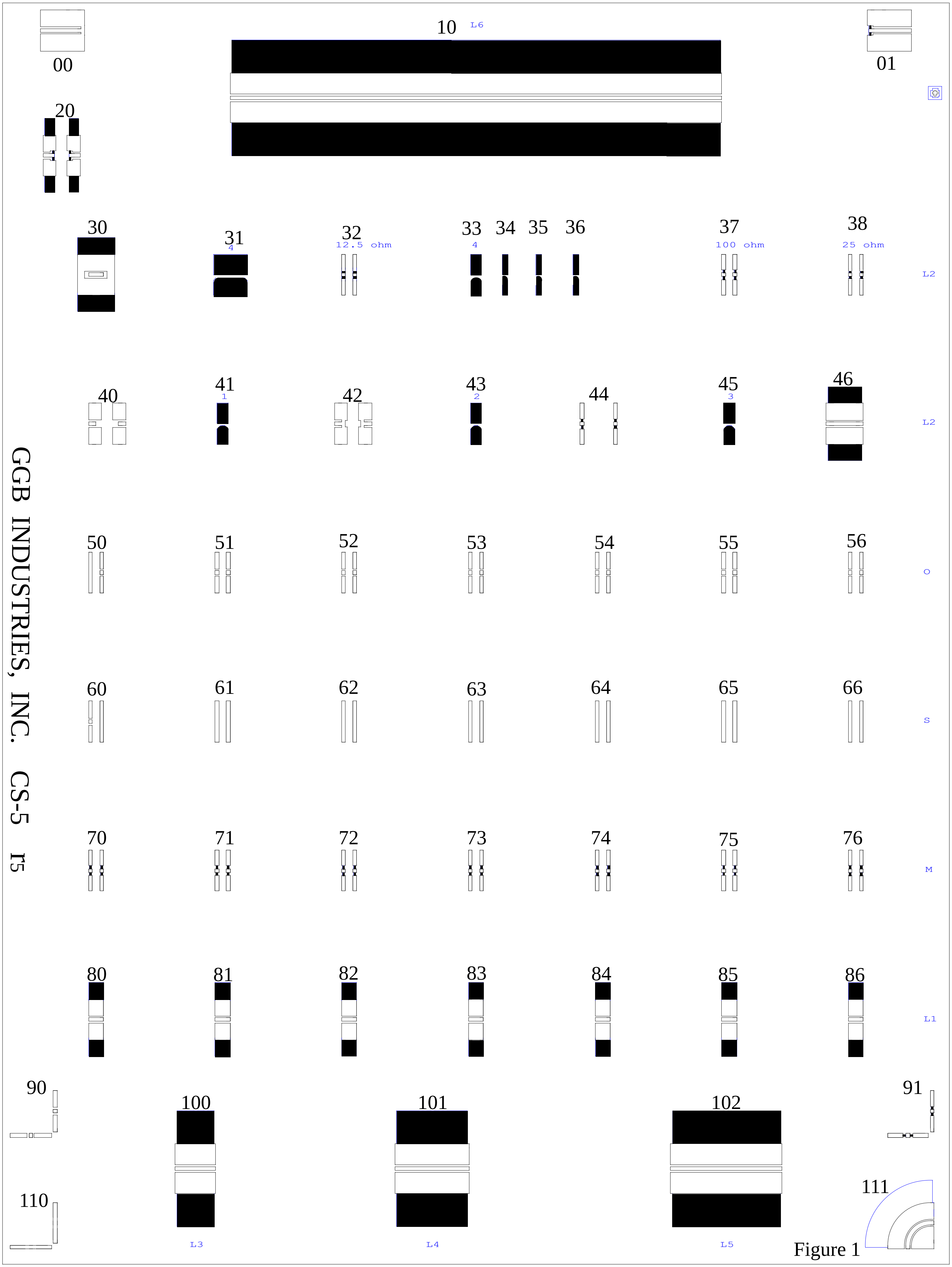
The elements employed during calibration can couple signals to adjacent structures. For example, while calibrating using the throughs 84, 85, 86 or 111, a small portion of the calibrating signal couples to line 102. At the resonant frequency of line 102, (approximately 46 GHz), the line could absorb a noticeable fraction of the calibrating signal to produce an anomaly in the calibration. The resistive extensions on the ground planes of line 102 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 a glass microscope slide. 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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100 ohm
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25 ohm
L2
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111
L3
L4
L5

Figure 1

CS-5 Calibration Substrate Key (Table 1) (rev.5)

(all structures for GSG probes with 75 to 250 micrometer pitch)

Location #	Description	Coordinates (X,Y)
00	550 micrometer offset short	(-2350,-5278) from 41 for left probe
01	550 micrometer offset 50 ohm load	(9150,-5278) from 41 for right probe
10	6600 micrometer 50 ohm coplanar line	(200,-4373) from 41 for left probe
20	125 micrometer offset 50 ohm loads (pair)	(-2263,-1600) from 31
30	200 micrometer 50 ohm coplanar line with connected grounds	(-1700,-2000) from 41
31	450 micrometer spacing alignment structure	(0,0)
32	12.5 ohm loads (pair)	(1700,-2000) from 41
33	Home 33	(3400,-2000) from 41
34	Home 33/34 (left probe on 33, right probe on 34)	(0,0)
35	Home 33/35 (left probe on 33, right probe on 35)	(0,0)
36	Home 33/36 (left probe on 33, right probe on 36)	(0,0)
37	100 ohm loads (pair)	(6800,-2000) from 41
38	25 ohm loads (pair)	(8500,-2000) from 41
40	100 micrometer offset opens (pair)	(-1650,2000) from 31
41	Home #1 150 micrometer spacing alignment structure	(0,0)
42	100 micrometer offset shorts (pair)	(1650,2000) from 31
43	Home #2 150 micrometer spacing alignment structure	(3400,0) from 41
44	50 ohm loads (pair)	(4950,2000) from 31
45	Home #3 150 micrometer spacing alignment structure	(6800,0) from 41
46	500 micrometer 50 ohm coplanar line	(8250,2000) from 31
50	shorting bar (left), open pads (right)	(-1700,2000) from 41
51	open pads (pair)	(0,2000) from 41
52	open pads (pair)	(1700,2000) from 41
53	open pads (pair)	(3400,2000) from 41
54	open pads (pair)	(5100,2000) from 41
55	open pads (pair)	(6800,2000) from 41
56	open pads (pair)	(8500,2000) from 41
60	open pads (left), shorting bar (right)	(-1700,4000) from 41
61	shorting bar (pair)	(0,4000) from 41
62	shorting bar (pair)	(1700,4000) from 41
63	shorting bar (pair)	(3400,4000) from 41
64	shorting bar (pair)	(5100,4000) from 41
65	shorting bar (pair)	(6800,4000) from 41
66	shorting bar (pair)	(8500,4000) from 41
70	50 ohm loads (pair)	(-1700,6000) from 41
71	50 ohm loads (pair)	(0,6000) from 41
72	50 ohm loads (pair)	(1700,6000) from 41
73	50 ohm loads (pair)	(3400,6000) from 41
74	50 ohm loads (pair)	(5100,6000) from 41
75	50 ohm loads (pair)	(6800,6000) from 41
76	50 ohm loads (pair)	(8500,6000) from 41
80	200 micrometer 50 ohm coplanar line	(-1700,8000) from 41
81	200 micrometer 50 ohm coplanar line	(0,8000) from 41
82	200 micrometer 50 ohm coplanar line	(1700,8000) from 41
83	200 micrometer 50 ohm coplanar line	(3400,8000) from 41
84	200 micrometer 50 ohm coplanar line	(5100,8000) from 41
85	200 micrometer 50 ohm coplanar line	(6800,8000) from 41
86	200 micrometer 50 ohm coplanar line	(8500,8000) from 41
90	right angle open pads (pair)	(0,0)
91	right angle 50 ohm loads (pair)	(11775,0) from 90
100	550 micrometer 50 ohm coplanar line	(-3940,12000) from 33/34
101	1000 micrometer 50 ohm coplanar line	(-990,12000) from 33/35
102	1500 micrometer 50 ohm coplanar line	(2710,12000) from 33/36
110	right angle shorting bars (pair)	(0,1500) from 90
111	right angle 50 ohm coplanar line	(11775,1500) from 90