Ironwood

GTP contact
0.40 mm pitch

Measurement and Model Results

12/16/2019

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Objective

The objective of these measurements is to determine the RF performance of an Ironwood GTP contact. For G-S-G configurations, a signal pin surrounded by grounded pins is selected for the signal transmission. For G-S-S-G configurations, two adjacent pins are used and all other pins are grounded. Measurements in both frequency and time domain form the basis for the evaluation. Parameters to be determined are pin capacitance and inductance of the signal pin, the mutual parameters, the propagation delay and the attenuation to 100 GHz.

Methodology

Capacitance and inductance for the equivalent circuits were determined through a combination of measurements in time and frequency domain. Frequency domain measurements were acquired with a network analyzer (Agilent HP8510). The instrument was calibrated up to the end of the 0.022" diameter coax probes that are part of the test fixturing. The device under test (DUT) was then mounted to the fixture and the response measured from one side of the contact array. When the DUT pins terminate in an open circuit, a capacitance measurement results. When a short circuit compression plate is used, inductance can be determined.

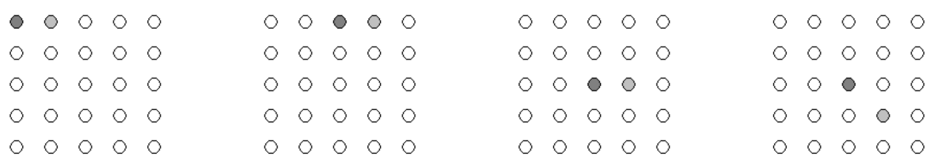
Time domain measurements are obtained via Fourier transform from VNA tests. These measurements reveal the type of discontinuities at the interfaces plus contacts and establish bounds for digital system risetime and clock speeds.

Test procedures

To establish capacitance of the signal pin with respect to the rest of the array, a return loss calibration is performed. Phase angle information for S11 is selected and displayed. When the array is connected, a change of phase angle with frequency can be observed. It is recorded and will be used for determining the pin capacitance. The self-inductance of a pin is found in the same way, except the GTP contact array is compressed by a metal plate instead of an insulator. Thus a short circuit at the far end of the pin array results. Again, the analyzer is calibrated and S11 is recorded. The inductance of the connection can be derived from this measurement.

Setup

Testing was performed with a test setup that consists of a brass plate that contains coaxial probes. The DUT is aligned and mounted to that plate. The opposite termination is also a metal plate with coaxial probes, albeit in the physical shape of an actual device to be tested or a flat plate with embedded coaxial probes. Measurements are performed for a corner pin of the contact array, a pin at the perimeter (edge) and one pin in the center (field), indicated in dark grey:



The second pin (light grey) is the second signal pin for G -S-S-G testing. Mutual parameters are also determined for the diagonal case. Configurations are referred to as G-S-G and G-S-S-G although strictly speaking this is not true. Signal pins are completely surrounded by ground pins since behavior would be very similar if they were connected to 50 Ohm driven pins as is the case in typical BGA environments.

True G-S-G and G-S-S-G configurations require linear arrays.

Figs. 1 and 2 show a typical arrangement base plate and DUT probe:

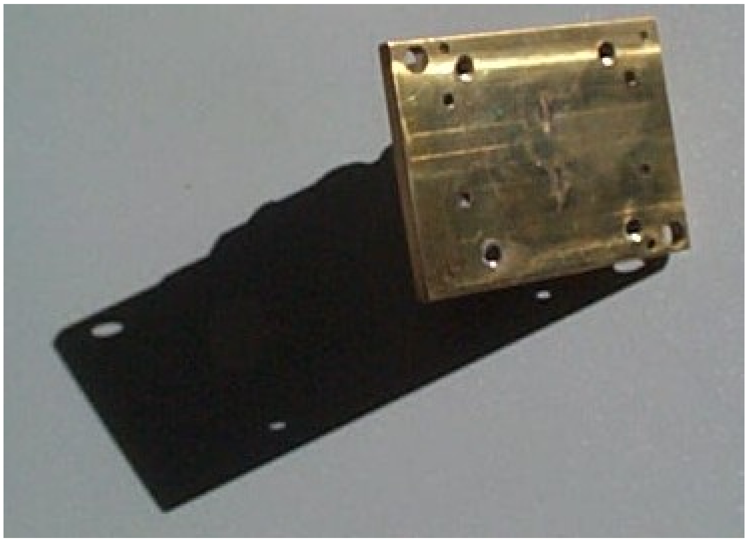


Figure 1 GTP contact base plate example

Figure 2 DUT plate example

The GTP contact and base plate as well as the DUT plate are then mounted in a test fixture as shown in Fig. 3:

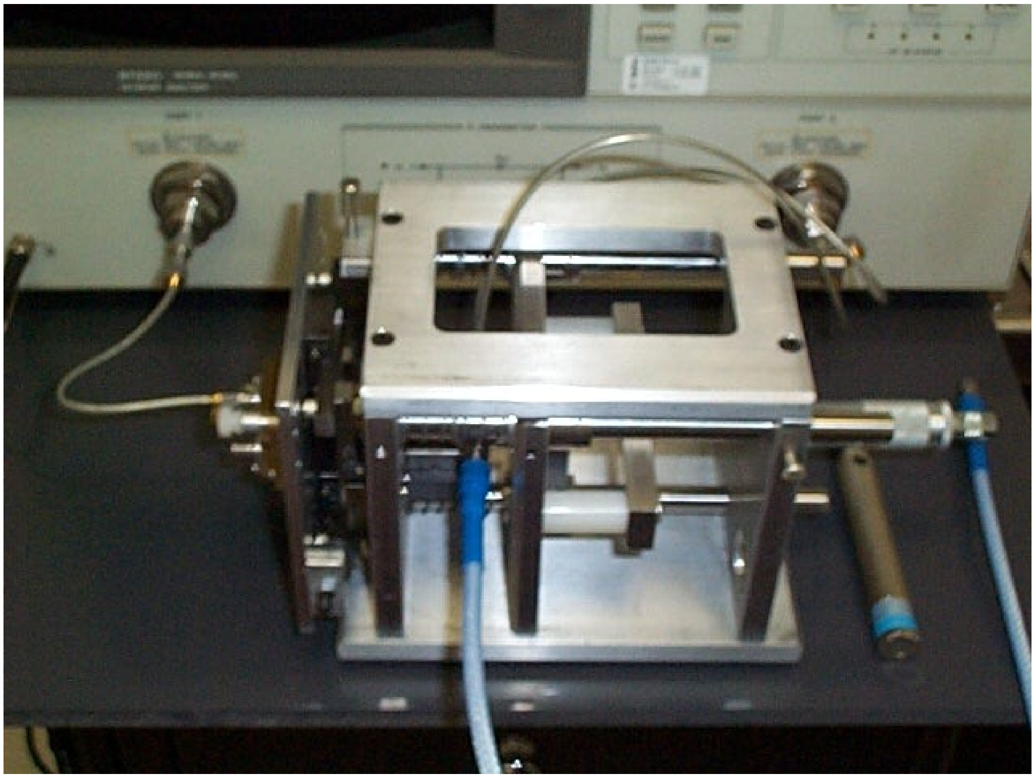
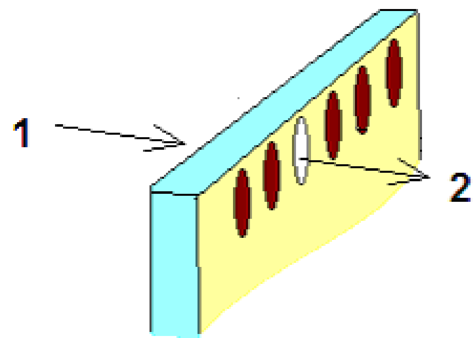


Figure 3 Test fixture example

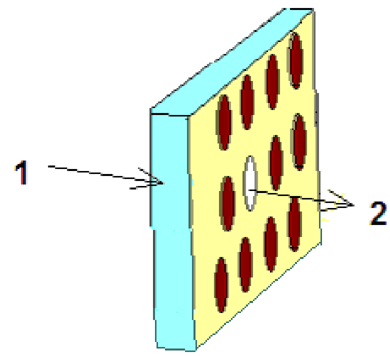
This fixture provides for independent X,Y and Z control of the components relative to each other. X, Y and angular alignment is established once at the beginning of a test series and then kept constant. Z (depth) alignment is measured via micrometer and is established according to specifications for the particular DUT.

Connections to the VNA are made with high quality coaxial cables with K connectors.

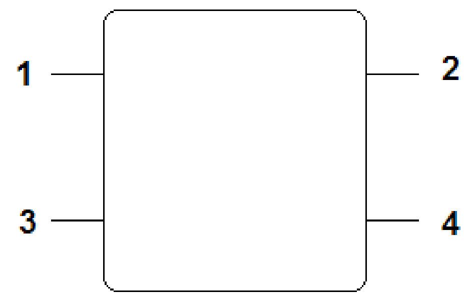
For G-S-G and G-S-S-G measurements, the ports are named as follows:



Single row DUTs



Multi-row DUTS



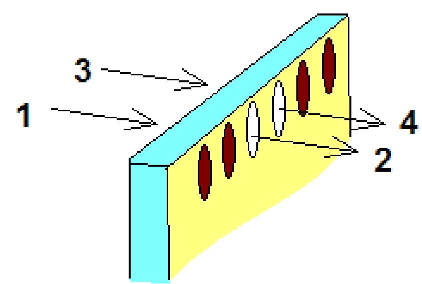


Figure 4 Ports for the G-S-G and G-S-S-G measurements

Signals are routed through two adjacent connections (light areas), unused connections are grounded (dark areas). The corresponding convention applies to the BGA/LGA array case.

Measurements G-S-G

Time domain

The time domain measurements will be presented first. TDR reflection measurements are shown below:

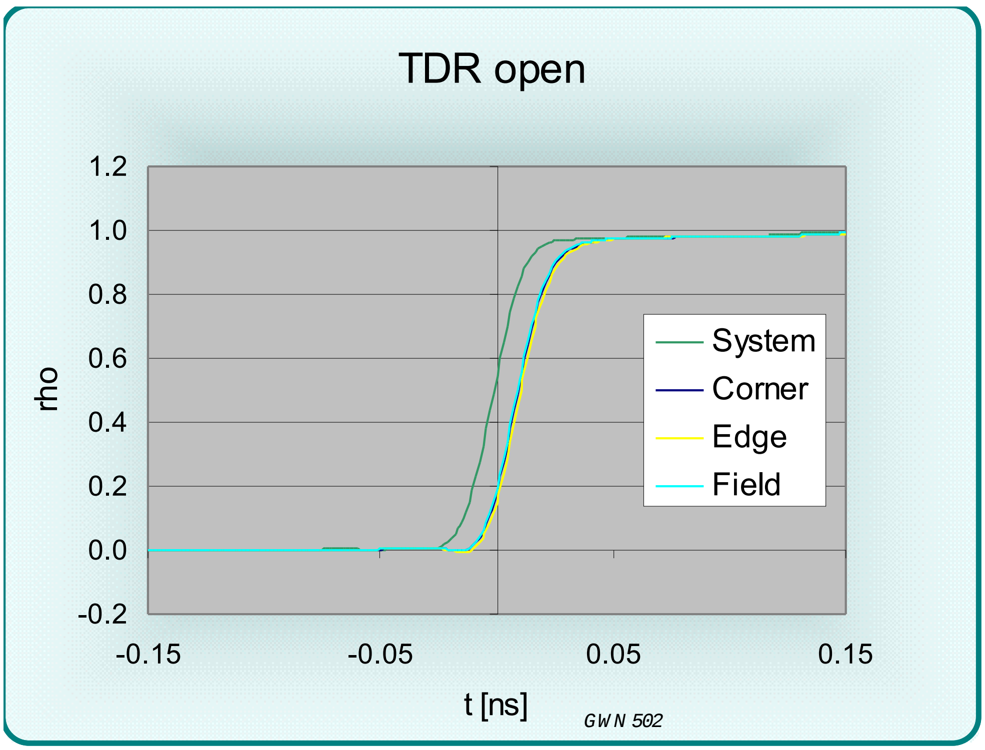


Figure 5 TDR signal from an OPEN circuited GTP contact

The reflected signals from the GTP contact (rightmost traces) show only a small deviation in shape from the original waveform (leftmost trace). The risetime is about 28.5, 28.5 and 28.5 ps for corner, edge and field, respectively and is almost the same as that of the system with the open probe (27.0 ps). Electrical pin length is about 5.3, 5.3 and 4.5 ps, respectively (one way).

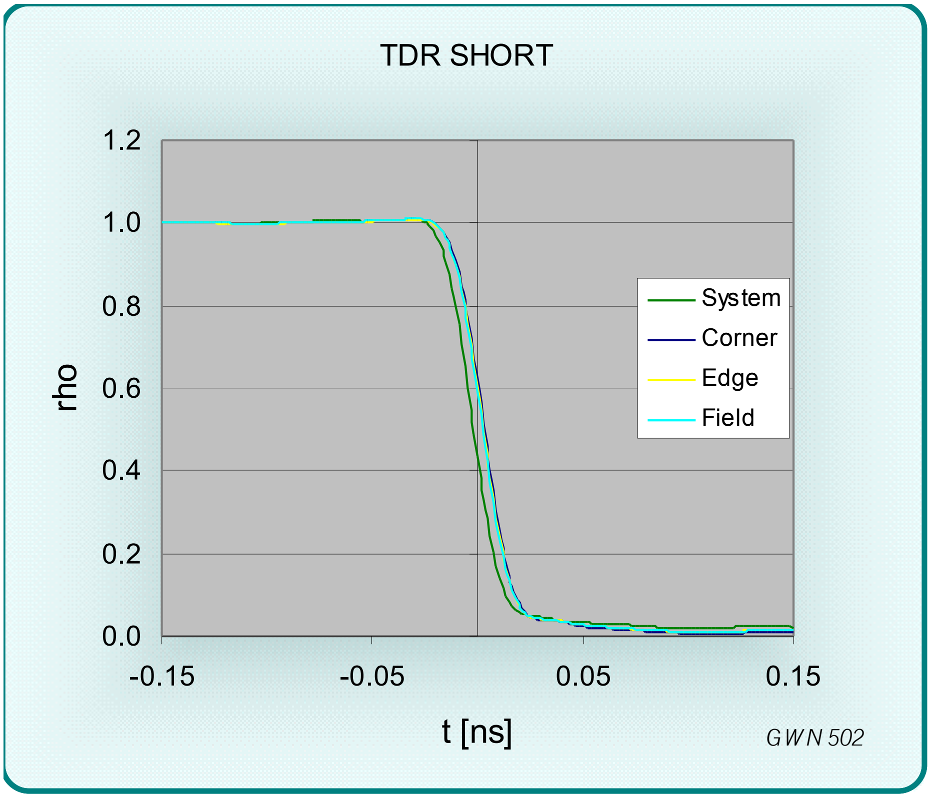


Figure 6 TDR signal from a SHORT circuited GTP contact

For the short circuited GTP contact the fall time is about 27.0, 27.0 and 27.0 ps for corner, edge and field, respectively. There is no increase over the system risetime of 28.5 ps caused by the contact impedance levels.

Open/short circuit measurements were performed on a 40 GHz VNA with a 20 ps effective risetime, thru measurements on a 100 GHz VNA with an effective 12 ps rise time (10%-90%).

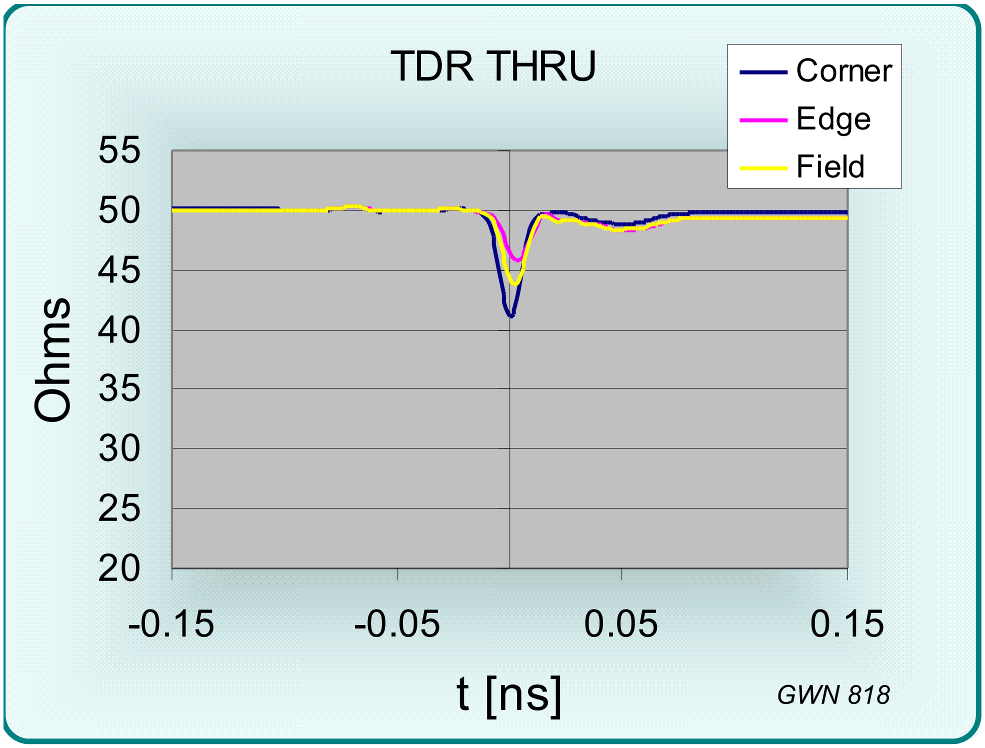


Figure 7 TDR measurement into a 50 Ohm probe

The thru TDR measurement shows both no perturbation to the signal and a capacitive response. The peaks correspond to an impedance of 41.1, 45.7 and 43.7 Ohms for corner, edge and field, respectively. Contact pressure has an impact on parasitic capacitance and therefore impedance. The different tests had to be conducted at different contact pressures, hence the scatter in the data. It should be kept in mind that the impedance recorded here is not as high or as low as actually found in the specimen because of the risetime of the time step, in this case 12 ps. For connections with comparable or shorter electrical lengths this does not allow the peak to reach its full height.

The TDT performance for a step propagating through the contact arrangement was also recorded:

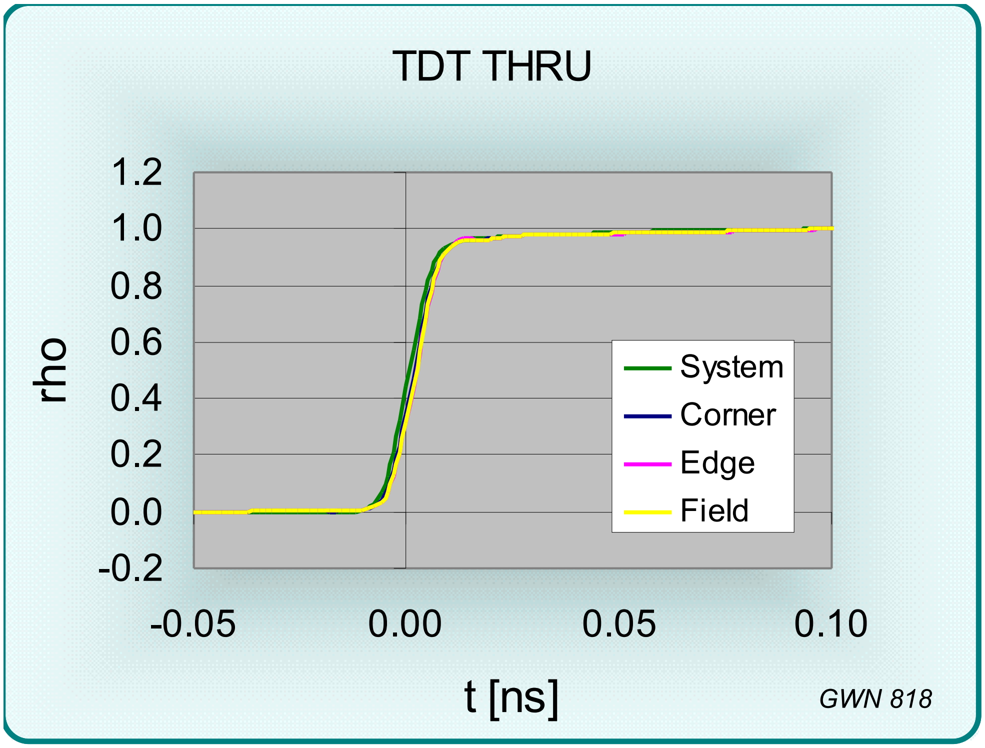


Figure 8 TDT measurement

The TDT measurements for transmission show an identical risetime from the pin array (10-90% RT = 12.0, 12.0 and 12.0 ps for corner, edge and field, respectively, the system risetime is 12.0 ps). The added delay values at the 50% point are 1.2, 1.6 and 1.5 ps, respectively. There is no signal distortion. If the 20%-80% values are extracted, the risetimes are only 7.5, 9.0 and 9.0 ps, respectively vs. 9.0 ps system risetime.

Frequency domain

Network analyzer reflection measurements for a single sided drive of the signal pin with all other pins open circuited at the opposite end were performed to determine the pin capacitance. The analyzer was calibrated to the end of the probe and the phase of S11 was measured. From the curve the capacitance of the signal contact to ground can be determined (see Fig. 10).

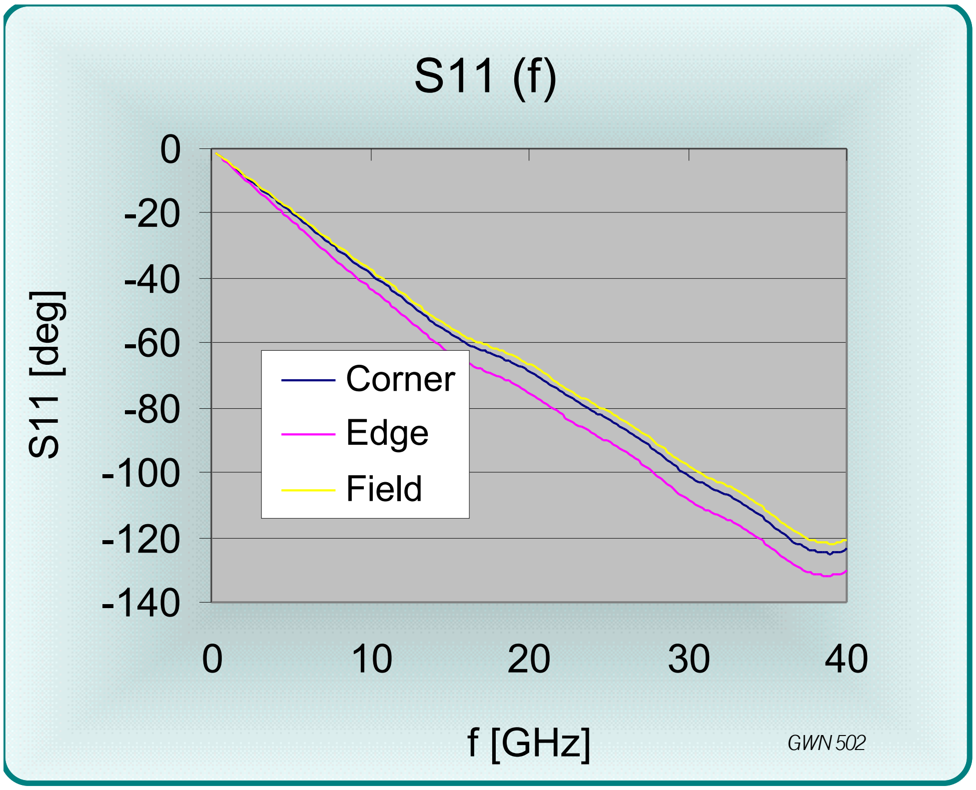


Figure 9 S11 phase (f) for the open circuited signal pin

There are no aberrations in the response.

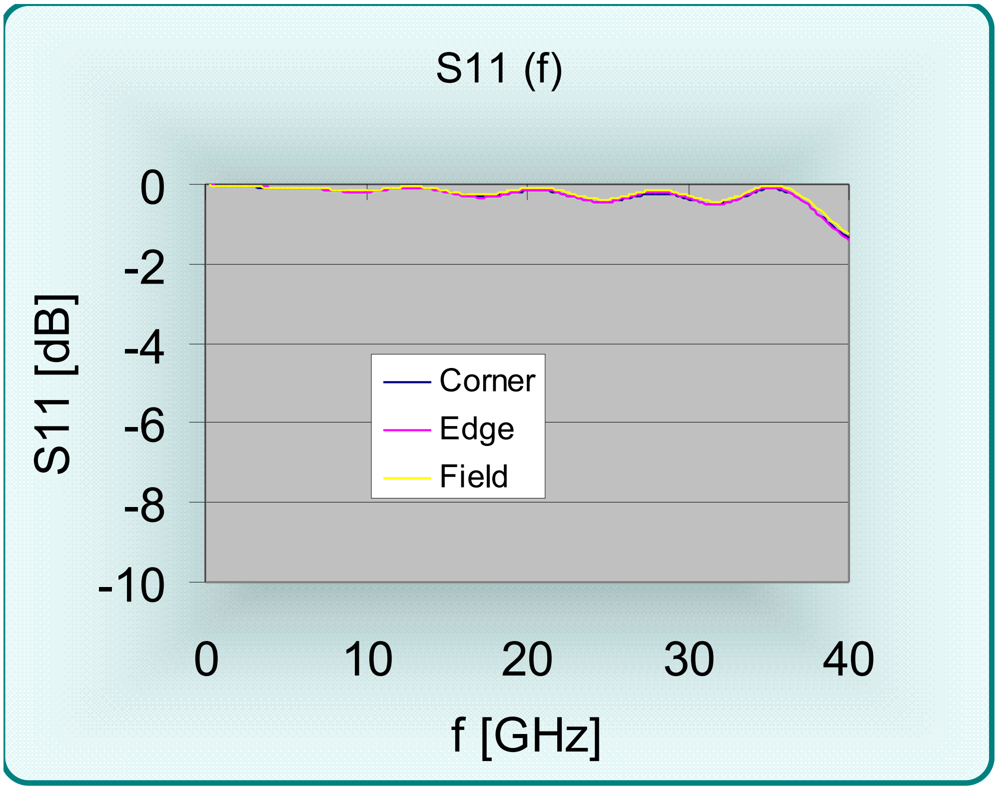


Figure 10 S11 magnitude (f) for the open circuited signal pin

While ideally the magnitude of S11 should be unity (0 dB), minimal loss and radiation in the contact array are likely contributors to S11 (return loss) for the open circuited pins at elevated frequencies.

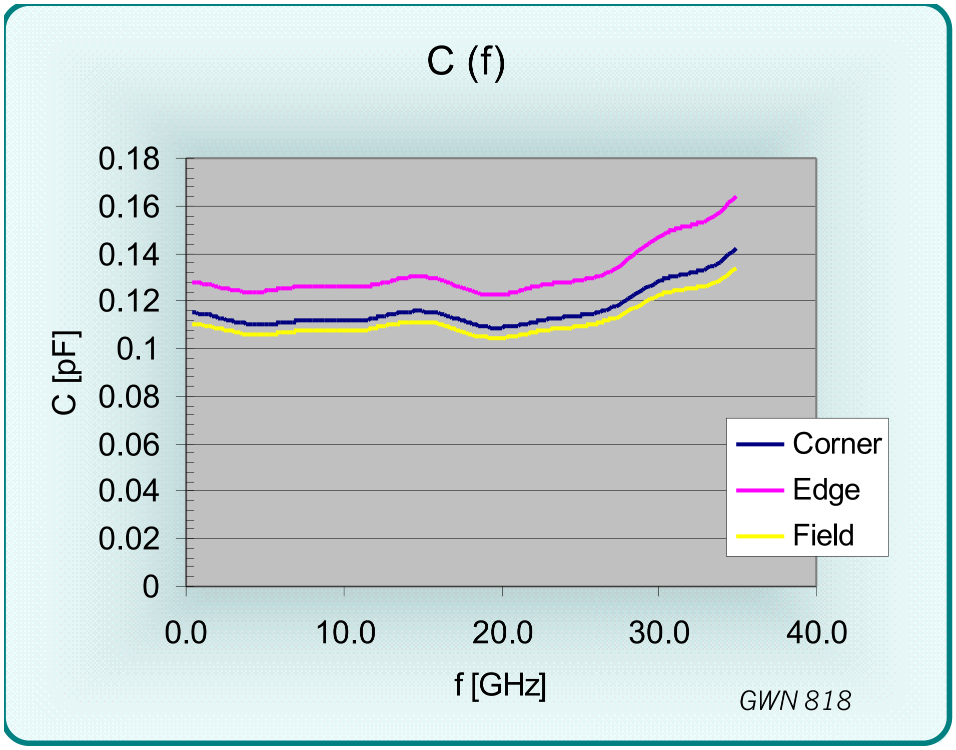


Figure 11 C(f) for the open circuited signal pin

Capacitance is 0.114, 0.127 and 0.109 pF for corner, edge and field, respectively, at low frequencies. Contact pressure has an impact on parasitic capacitance and different tests had to be conducted at different contact pressures, hence the scatter in the data. The rise in capacitance toward 35.1 GHz is due to the fact that the pins form a transmission line with a length that has become a noticeable fraction of the signal wavelength. The lumped element representation of the transmission environment as a capacitor begins to become invalid at these frequencies and so does the mathematical calculation of capacitance from the measured parameters. This merely means the model of a lumped capacitor is not valid anymore. Instead, a transmission line model or a multi-section model must be applied beyond this frequency. As is evident from time domain and insertion loss measurements this does not imply that the DUT does not perform at these frequencies.

The Smith chart measurement for the open circuit shows no resonances. A small amount of loss is present.

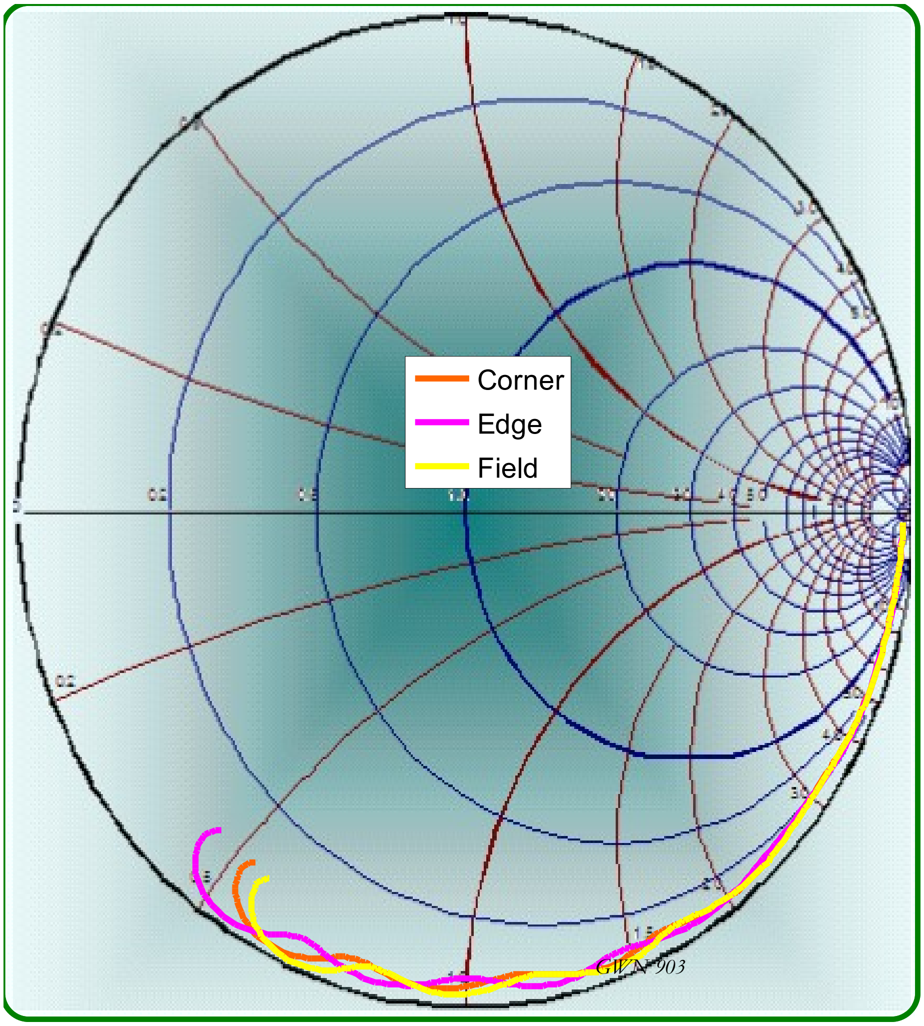


Figure 12 Reflections from the open circuited GTP contact

To extract pin inductance, the same types of measurements were performed with a shorted pin array. Shown below is the change in reflections from the GTP contact. Calibration was established with a short placed at the end of the coax probe.

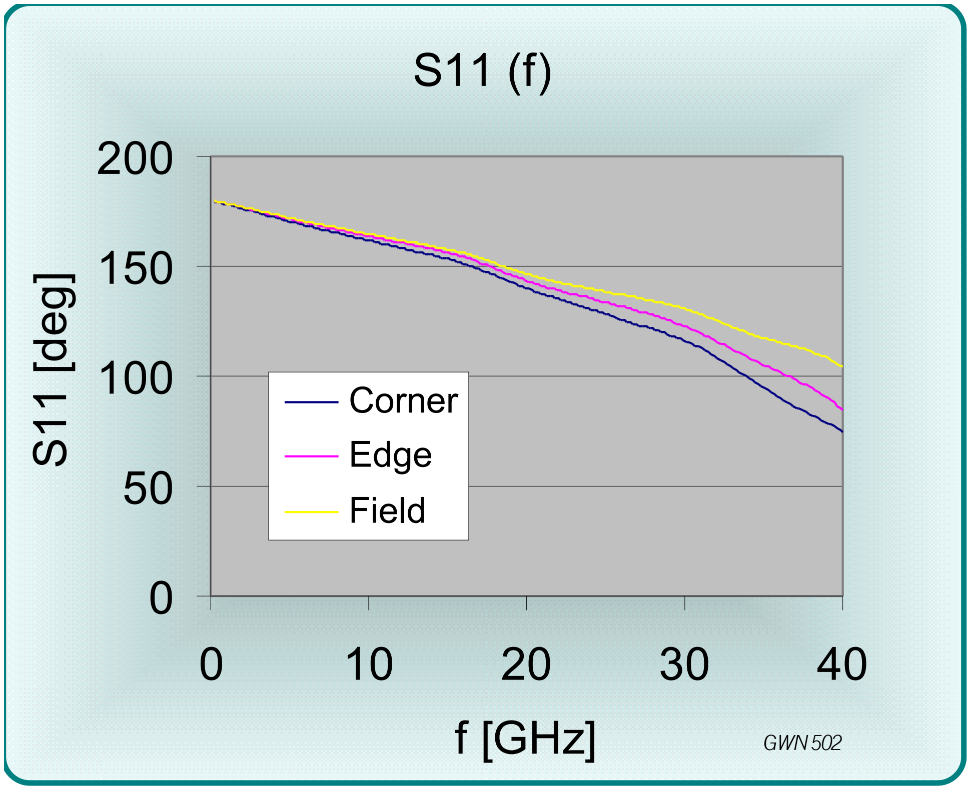


Figure 13 S11 phase (f) for the short circuited case

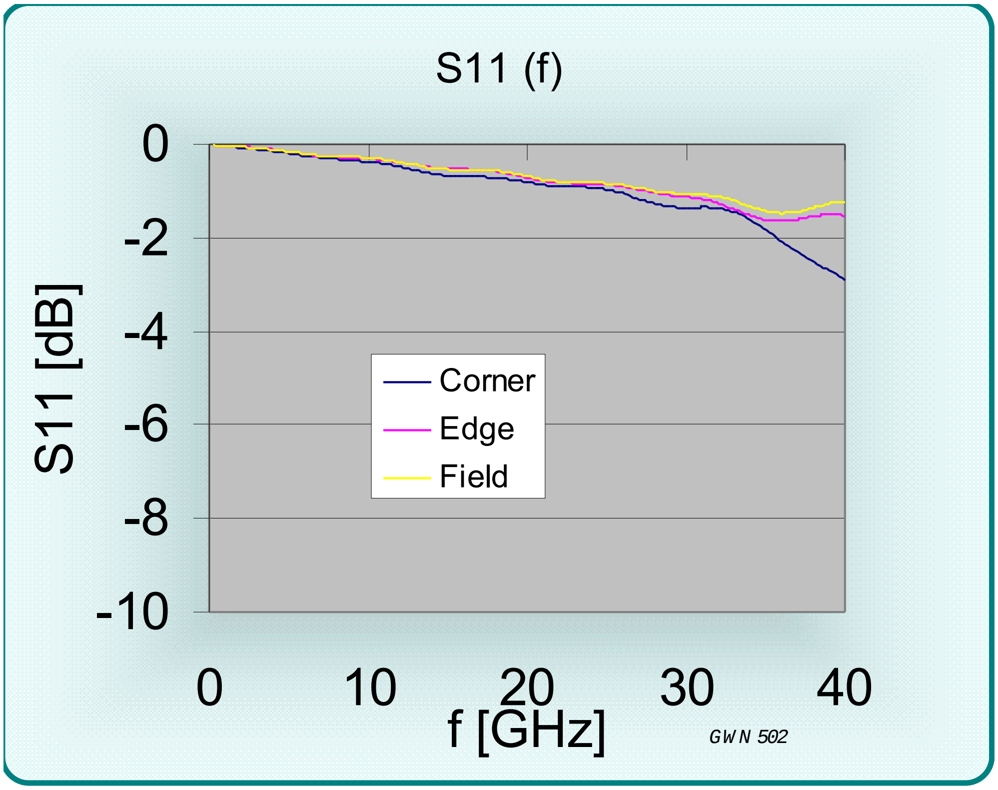


Figure 14 S11 magnitude (f) for the short circuited case

A small S11 return loss exists, likely the result of minimal loss and radiation.

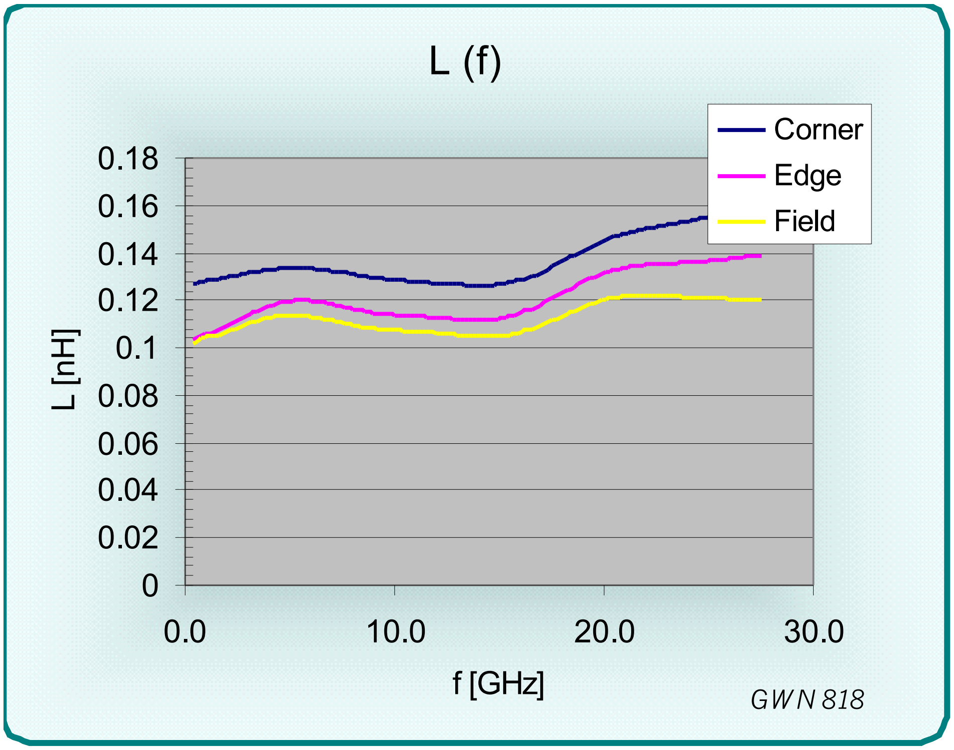


Figure 15 L(f) for the GTP contact

The phase change corresponds to an inductance of 0.13, 0.11 and 0.11 nH for corner, edge and field, respectively, at low frequencies. Toward 30.5 GHz inductance increases. At these frequencies, the transmission line nature of the arrangement must be taken into account and the simple lumped element value is no longer valid. This inductance is the loop inductance for the particular pitch and arrangement since self inductance is purely a mathematical construct and has little bearing on performance of the pin in the actual environment.

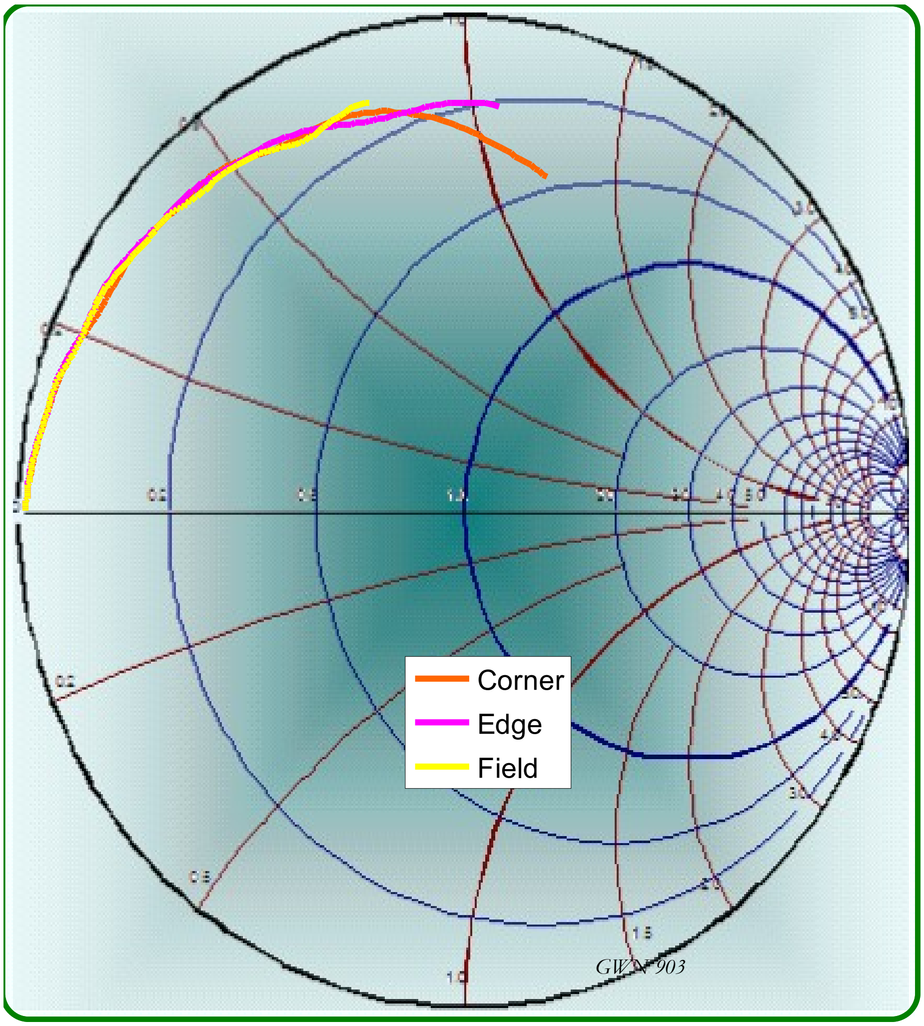


Figure 16 Short circuit response in the Smith chart

Only a small amount of loss is noticeable in the Smith chart for the short circuit condition.

An insertion loss measurement is shown below for the frequency range of 50 MHz to 40 GHz.

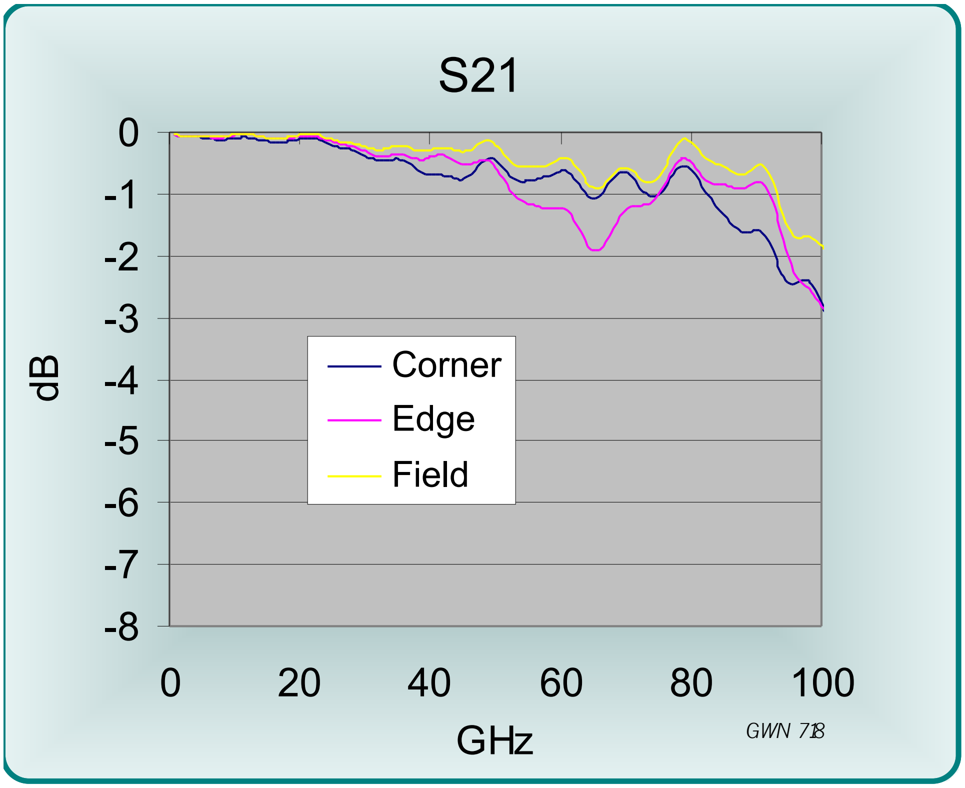


Figure 17 Insertion loss S21 (f)

Insertion loss is less than 1 dB to about 64.3, 52.8 and 93.7 GHz (corner, edge, field). The 3 dB point is not reached before >100, >100 and >100 GHz.

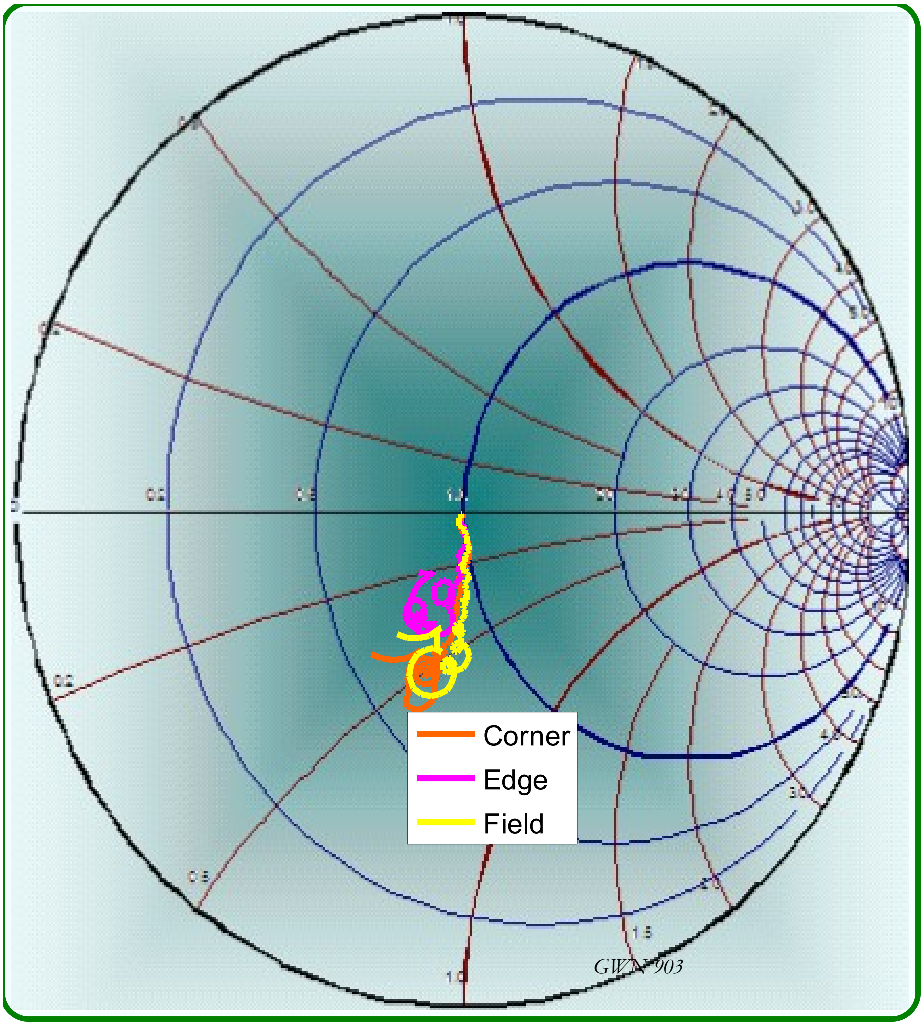


Figure 18 Smith chart for the thru measurement into a 50 Ohm probe

The Smith chart for thru measurements shows a good match at low frequencies. At higher frequencies reactive components become apparent.

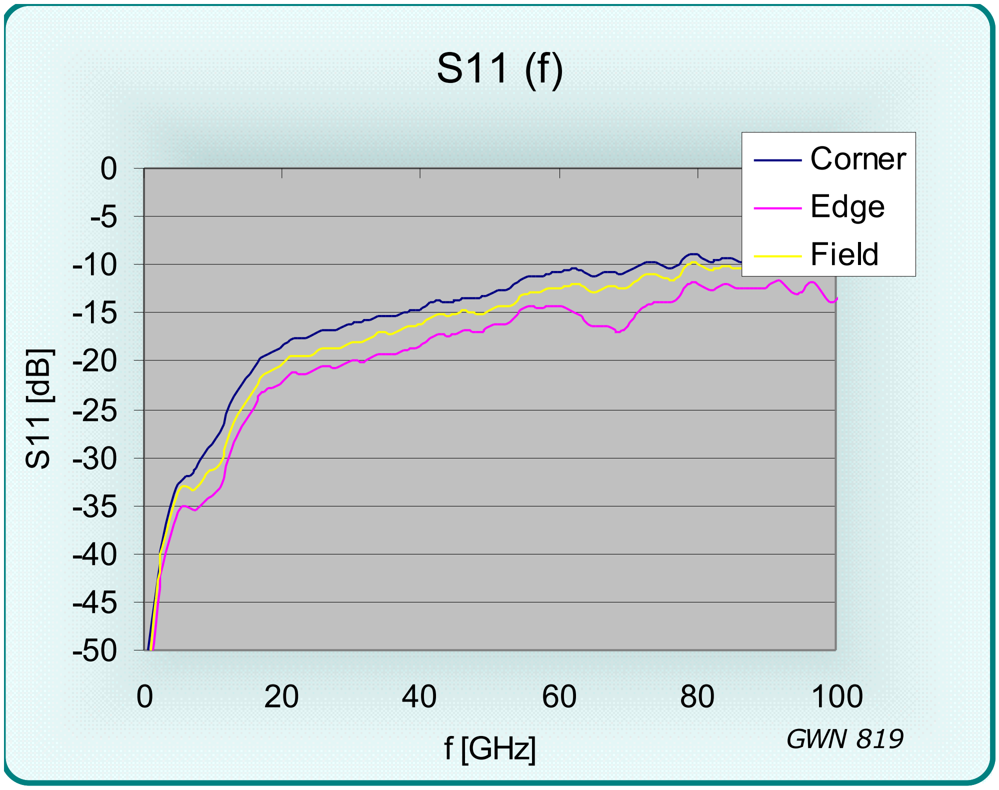


Figure 19 S11 magnitude (f) for the thru measurement into a 50 Ohm probe

Return loss reaches -20 dB at 16.9 GHz, 30.0 GHz and 20.7 GHz for corner, edge and field sites. Again, contact pressure has an impact on parasitic capacitance and different tests had to be conducted at different contact pressures, hence the scatter in the data. The level of the return loss for the thru measurement is lowest for the edge configuration since its characteristic impedance is closest to 50 Ohms.
Open/short measurements were performed on a 40 GHz VNA , thru measurements on a 100 GHz VNA.

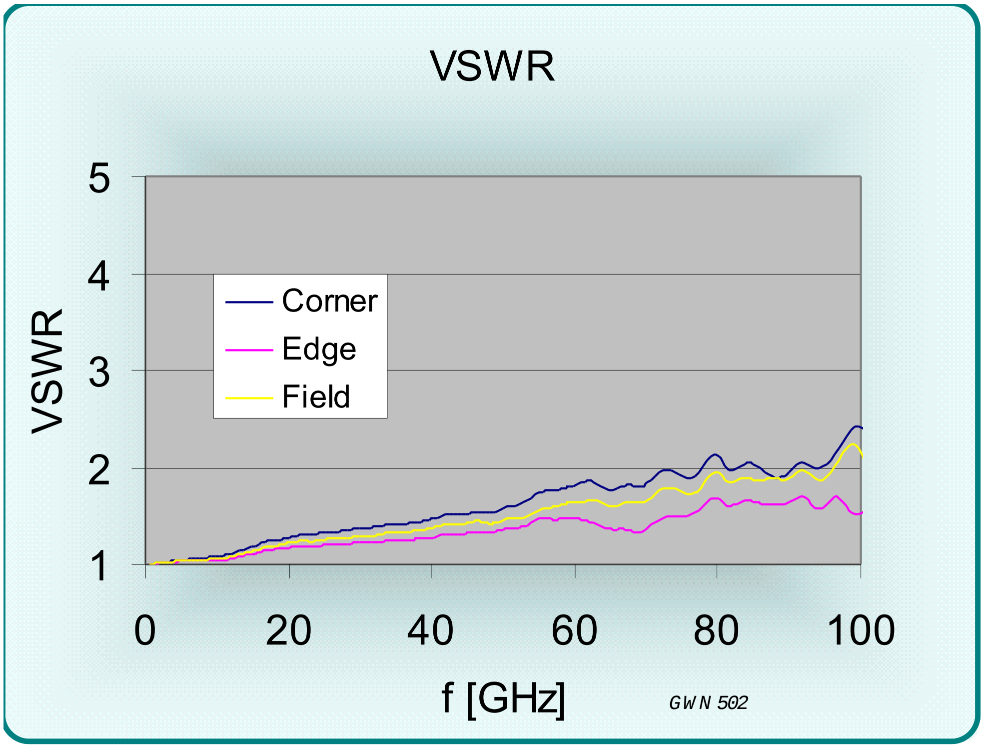


Figure 20 Standing wave ratio VSWR (f) [1 / div.]

The VSWR remains below 2 : 1 to a frequency of 90.4, >100 and 109.5 GHz (corner, edge, field).

Crosstalk was measured in the G-S-S-G configuration by feeding the signal pin and monitoring the response on an adjacent pin. Measurement results can be found in the section on the G-S-S-G configuration.

The mutual capacitance and inductance values will be extracted from G-S-S-G models and are also listed in that section.

Measurements G-S-S-G

Time domain

G-S-S-G transmission measurements were performed with a near symmetric 'field' configuration on a 40 GHz VNA, mutual parameter determination was performed on all sites. Again, the time domain measurements will be presented first. A TDR reflection measurement is shown in Fig. 21 for the thru case at port 1 to port 2:

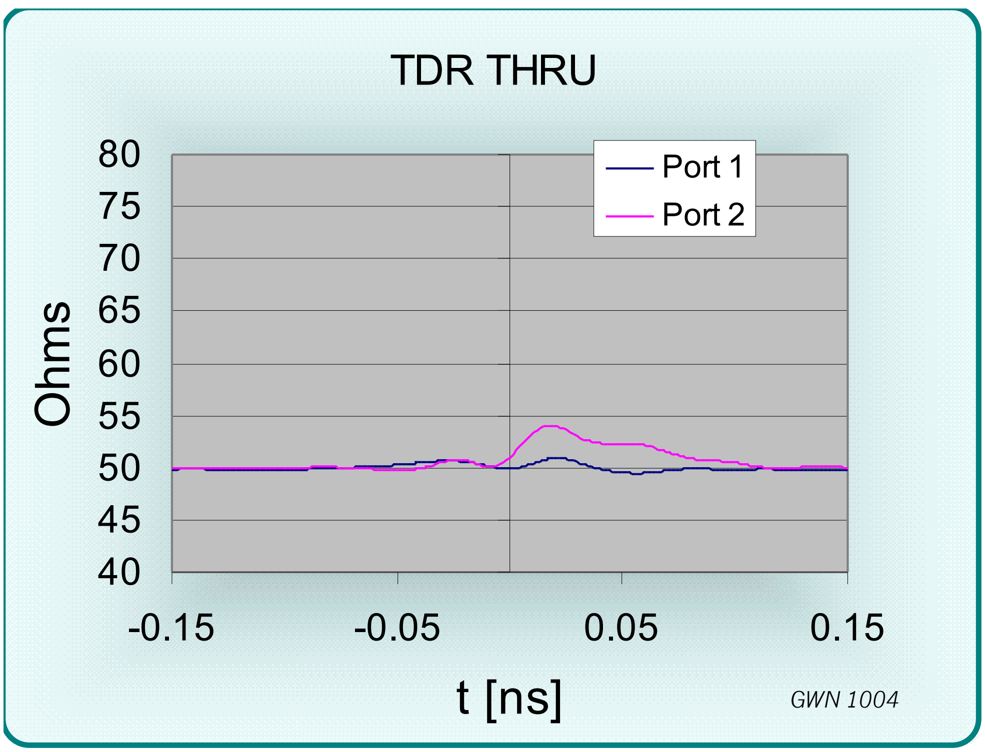


Figure 21 TDR through DUT into a terminated probe

The thru TDR measurement from port 1 to port 2 shows no perturbation to the signal. The low peak corresponds to a transmission line impedance of 50.9 Ohms. This is higher than in the G-S-G case since one of the adjacent pins is not grounded.

The TDT performance for a step propagating through the G-S-S-G pin arrangement was also recorded:

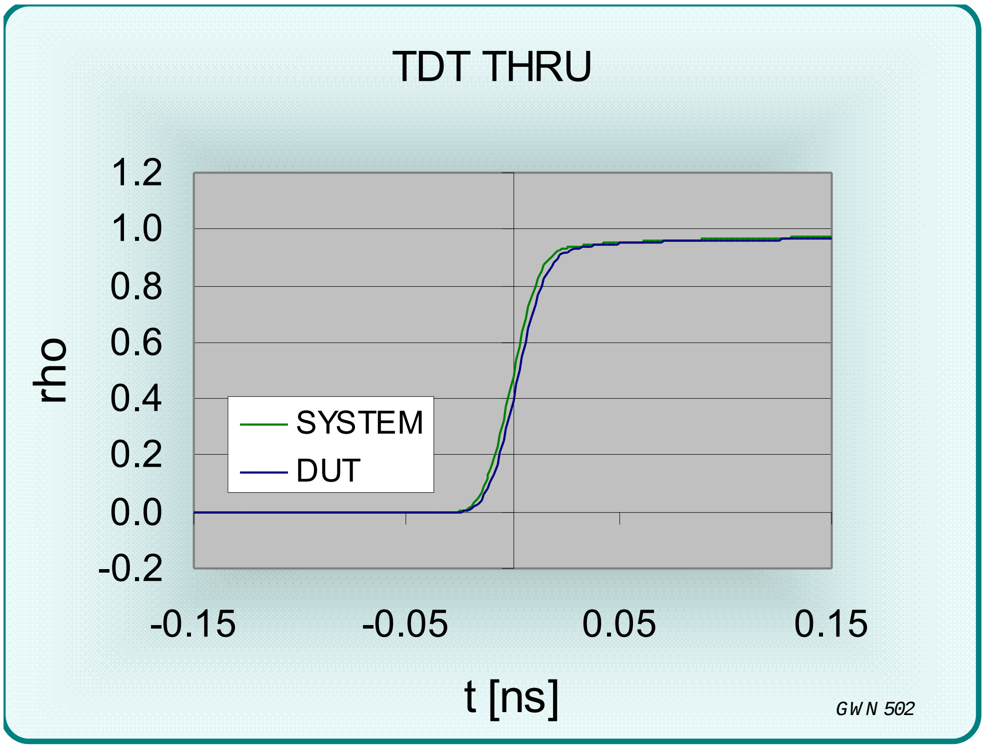


Figure 22 TDT measurement

The TDT measurements for transmission shows almost the same risetime from the pin array (10-90% RT = 30.0 ps) as the system risetime (28.5 ps). The added delay at the 50% point is 1.5 ps. The 20%-80% values are 19.5 ps and 18.0 ps, respectively.

Frequency domain

Network analyzer reflection measurements for the G-S-S-G case were taken with all except the pins under consideration terminated into 50 Ohms (ports 1-4). As a result, the scattering parameters shown below were recorded for reflection and transmission through the contact array.

First, an insertion loss measurement is shown for port 1 to port 2.

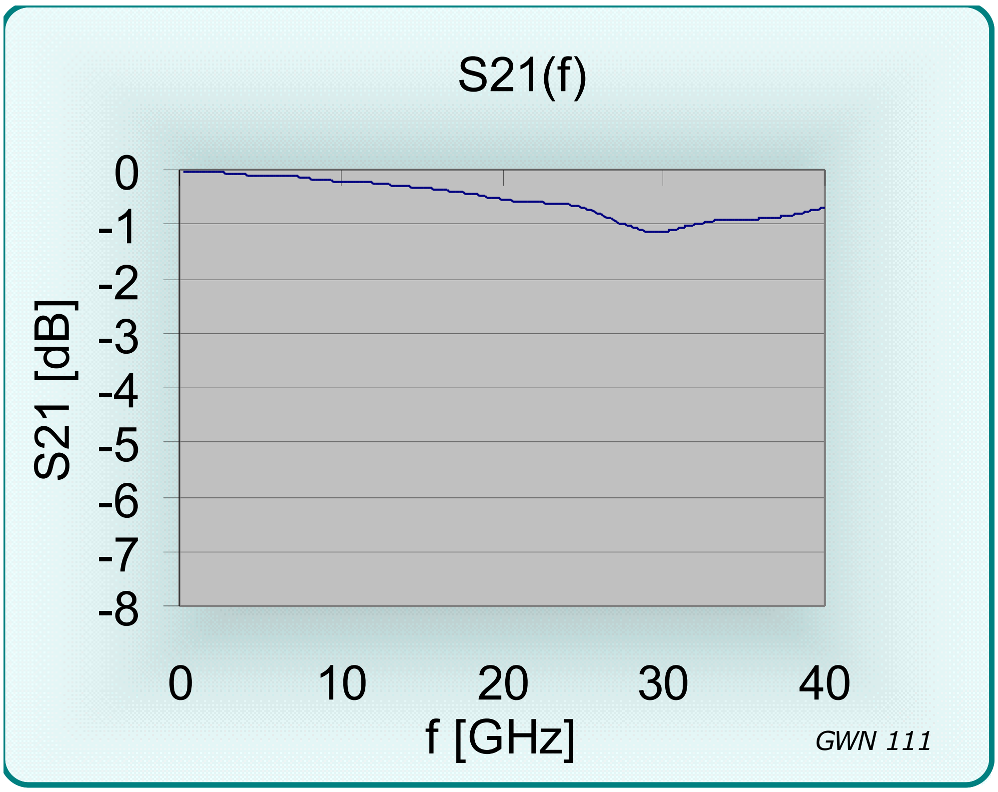


Figure 23 Insertion loss S21 (f)

Insertion loss is less than 1 dB to about 27.7 GHz. The 3 dB point is not reached before >40 GHz.

Insertion loss is higher than in the G-S-G case because of the diversion of some signal energy from the thru connection to the adjacent second signal pin (Fig.23 is not a differential measurement, differential parameters can be obtained from the s4p file).

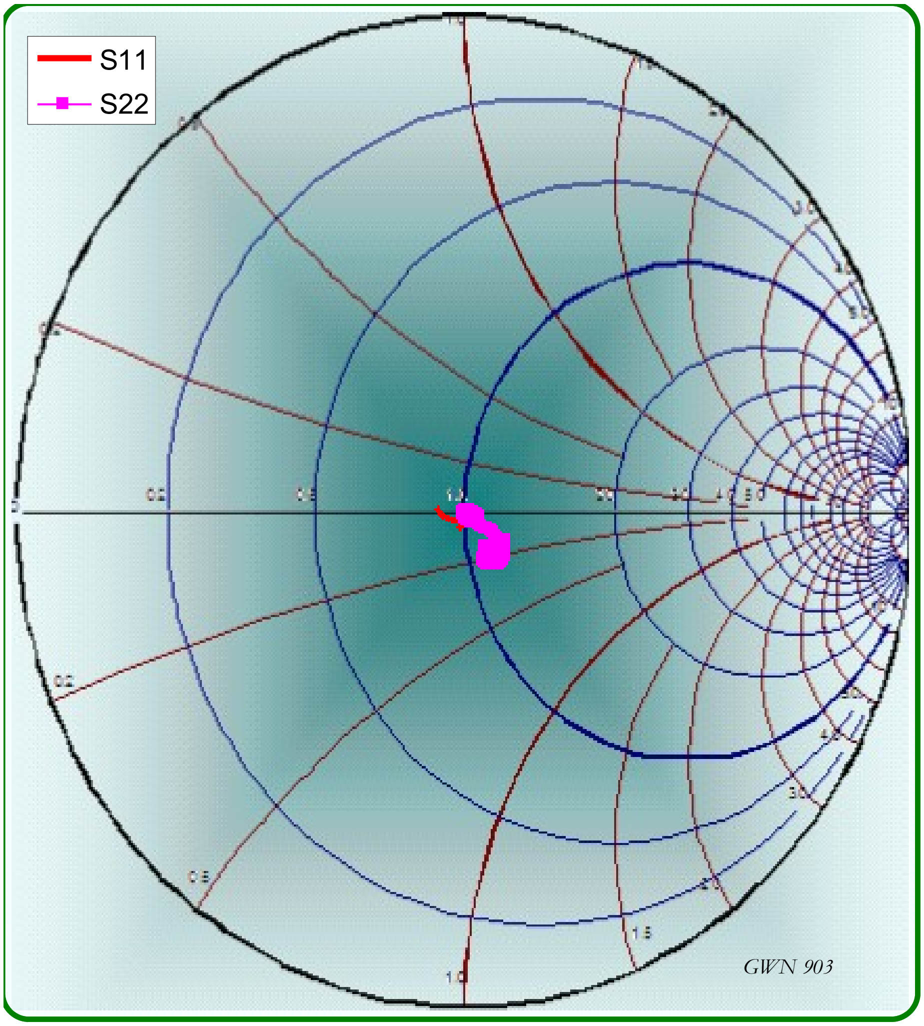


Figure 24 Smith chart for the thru measurement into a 50 Ohm probe

The Smith chart for the thru measurements shows a good match at low frequencies with some reactive components as frequency increases.

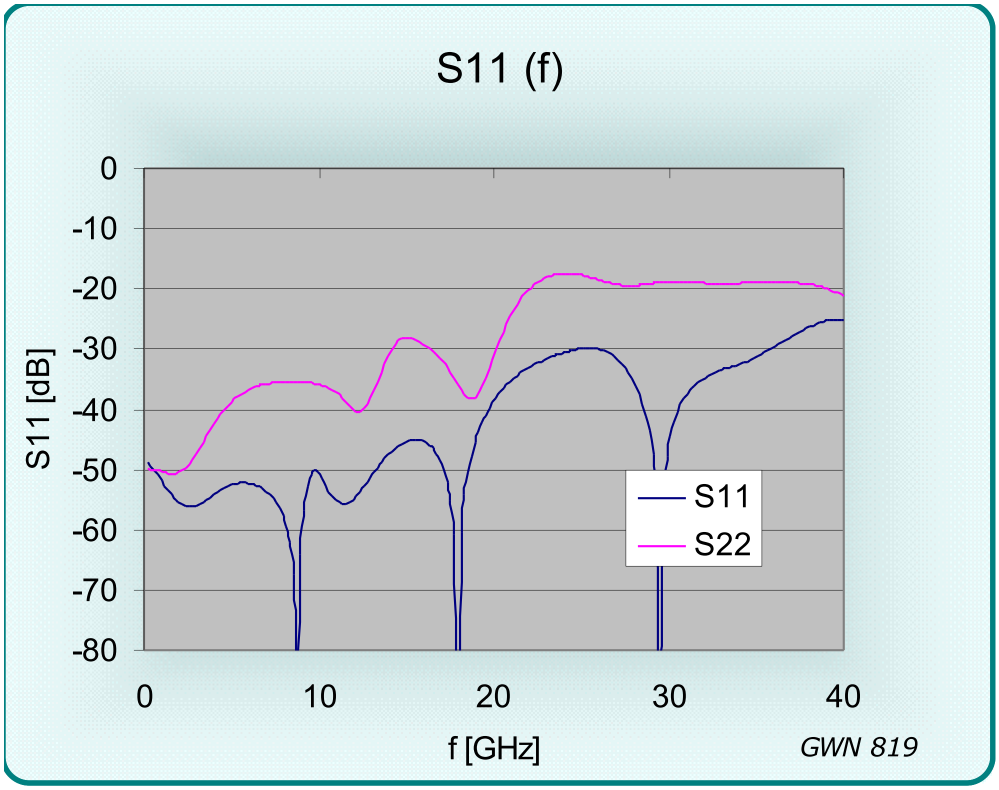


Figure 25 S11 magnitude (f) for the thru measurements into a 50 Ohm probe

The value of the return loss for the thru measurement reaches -20 dB at >40 GHz (S11) and 22.1 GHz (S22).

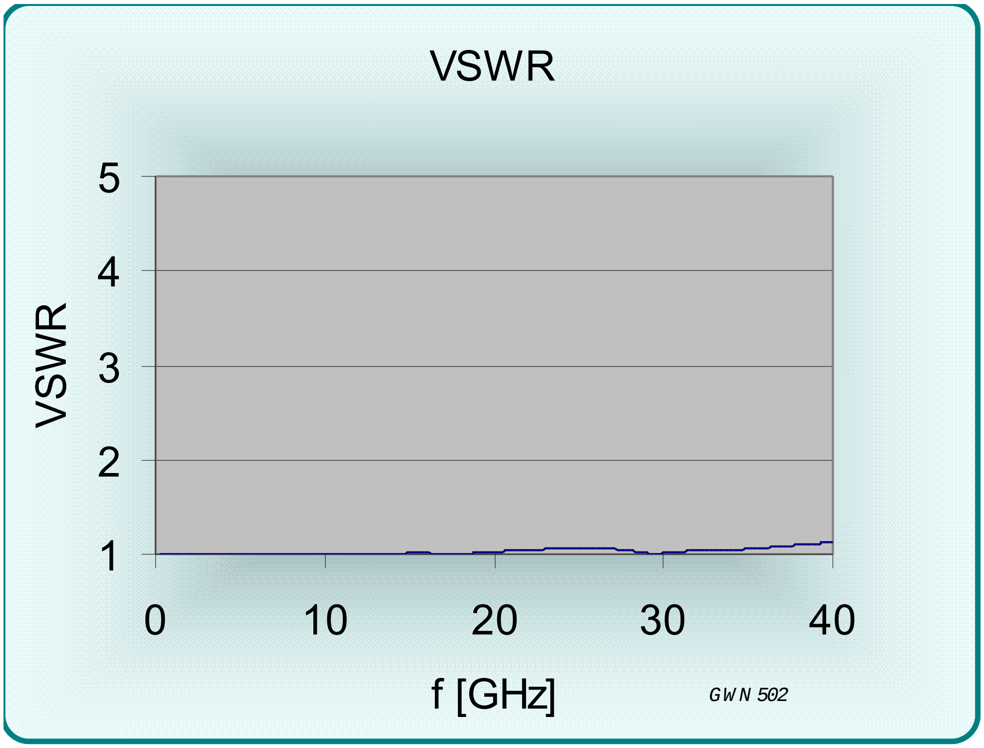


Figure 26 Standing wave ratio VSWR (f) [1 / div.]

The VSWR remains below 2 : 1 to a frequency of >40 GHz.

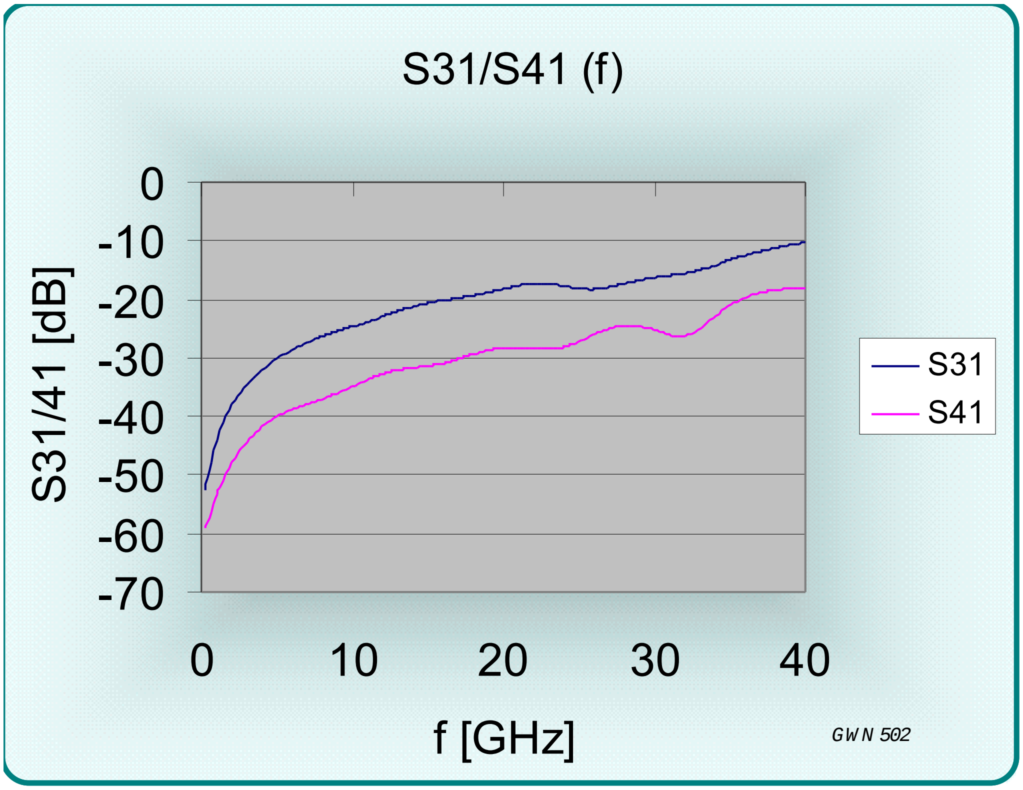


Figure 27 Crosstalk as a function of frequency

The graph shows forward crosstalk from port 1 to port 4 (S41, far end crosstalk {FEXT}) and backward crosstalk from port 1 to the adjacent terminal (port 3, S31, near end crosstalk {NEXT}). The -20 dB point is reached at 16.5 GHz (S31) and not before 35.7 GHz (S41).

For the purpose of model development the open circuit and short circuit backward crosstalk S31 is also recorded. It is shown below for the different sites. Model development yields a mutual capacitance of 0.016, 0.013, 0.014 and 0.005 pF and a mutual inductance of 0.09, 0.05, 0.05 and 0.018 nH for corner, edge field and diagonal sites, respectively.

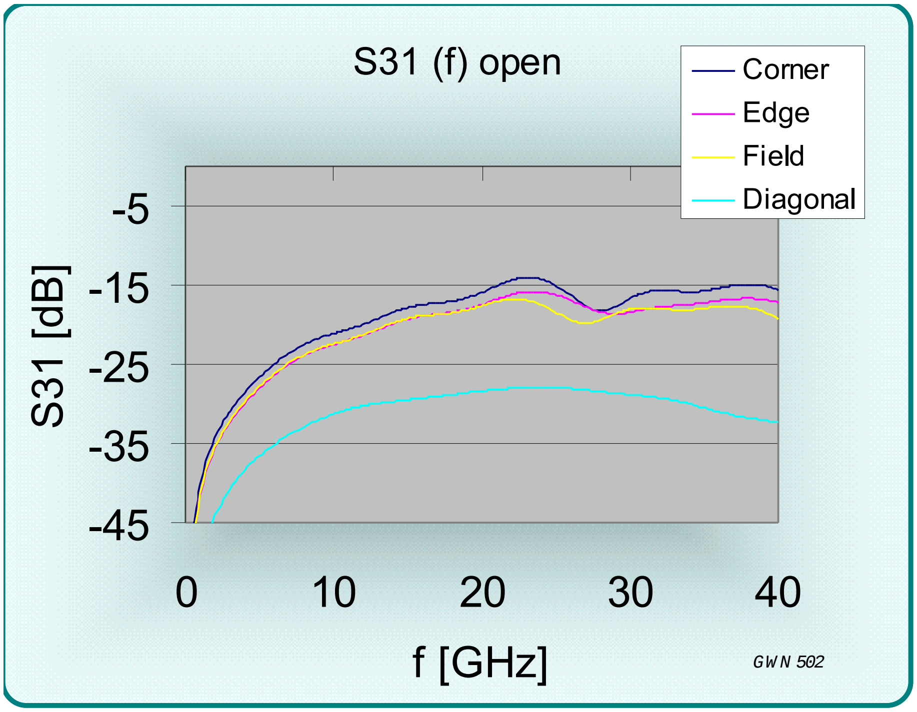


Figure 28 Open circuit crosstalk from port 1 to port 3

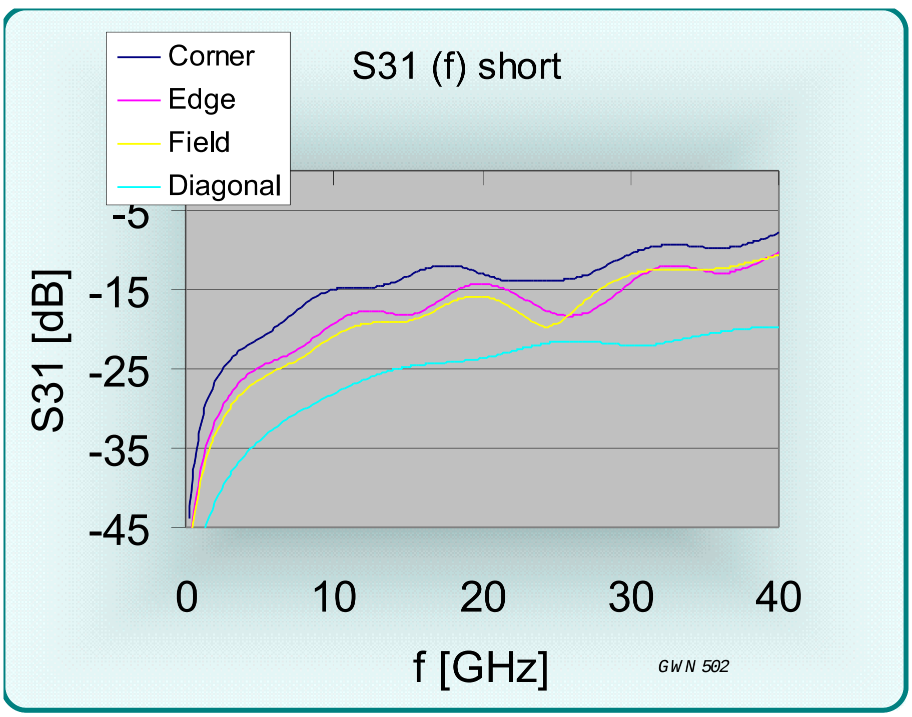


Figure 29 Short circuit crosstalk from port 1 to port 3

SPICE Models

A lumped element SPICE model for the Ironwood GTP contact in G-S-G configuration is shown below:

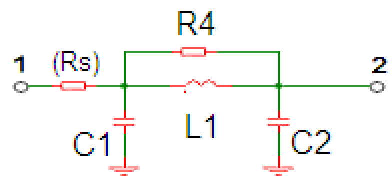


Figure 30 Lumped element SPICE model

The resistance value (R4) approximates the loss term encountered. The series resistance Rs is very small and does not significantly impact S-parameters. It can be determined by DC measurements but is not included in this model.

The values for the elements are

Site	**Cg=C1+C2**			**L1**		**R4**	
Corner		0.114	pF	0.13	nH	160	Ohms
Edge		0.127	pF	0.11	nH	50000	Ohms
Field		0.109	pF	0.11	nH	50000	Ohms
Diagonal		0.109	pF	0.11	nH	50000	Ohms

Toward the cutoff frequency of the Pi section the lumped element model becomes invalid. This happens above 62 GHz for the above model. Accuracy of the model is better than 0.5 dB up to 45.2, 52.3 and 63.2 GHz for C,E,F. The second model developed is a transmission line model:

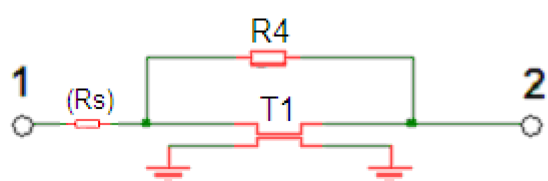


Figure 31 Transmission line model for the GTP contact

Again, R4 describes loss and the series resistance Rs is very small and not included. The array configuration with signal pins surrounded by ground pins provides a transmission line environment with the following parameters:

	Zo		L		R4	
Corner	41.1	Ω	1.19	ps	50000	Ω
Edge	45.7	Ω	1.61	ps	50000	Ω
Field	31.0	Ω	3.39	ps	50000	Ω

Values computed here are generally lower than those measured by TDR. A possible cause is a more complex equivalent circuit with short sections of low impedance transmission line that cannot be resolved by the limited risetime TDR measurement.
Accuracy for S21 is better than 0.5 dB to 64.8, 52.8 and 60.4 GHz for C,E,F.

The lumped model does not remain valid at high frequencies. Alternatives are to split this model into multiple sections with the same total capacitance and inductance or to use a transmission line model. For models that are more accurate at high frequencies it is recommended to use a multi-pole SPICE subcircuit representation or sNp Touchstone S-parameters.

Frequency domain

The model's phase responses are also divided into lumped element and transmission line equivalent circuits.

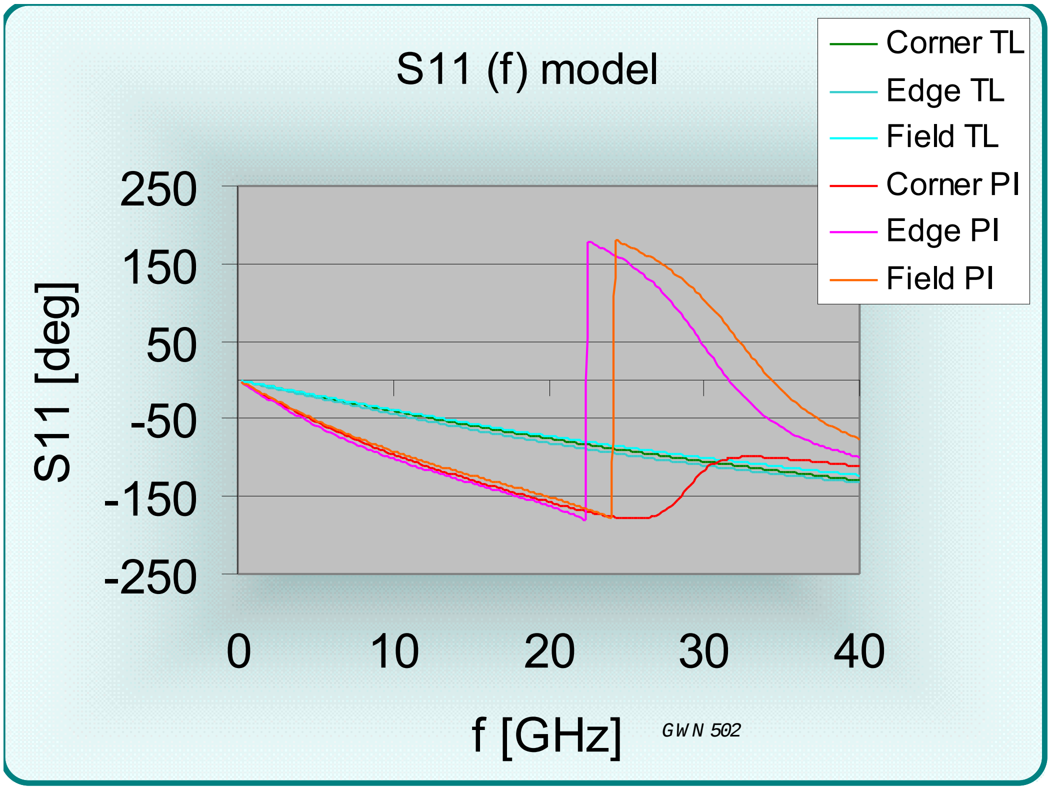


Figure 32 S11 phase (f) for open circuited case

The evolution of phase with frequency is comparable to that measured.
The lumped element model has a cutoff frequency of about 62 GHz.

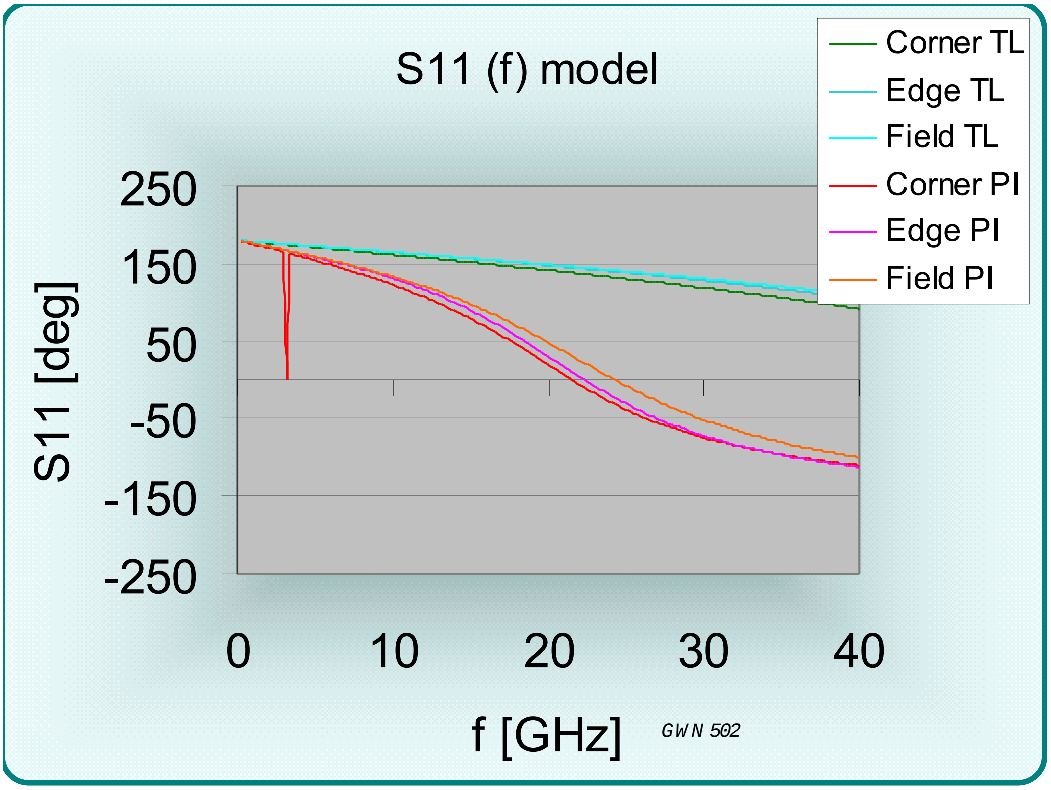


Figure 33 S11 phase response (short circuit)

The short circuit phase evolution with frequency is also comparable to that actually measured.

The insertion loss results below also clearly demonstrate the limits of the lumped element model. As the frequency approaches the cutoff frequency for the Pi section, insertion loss increases significantly. The transmission line model does not suffer from this shortcoming.

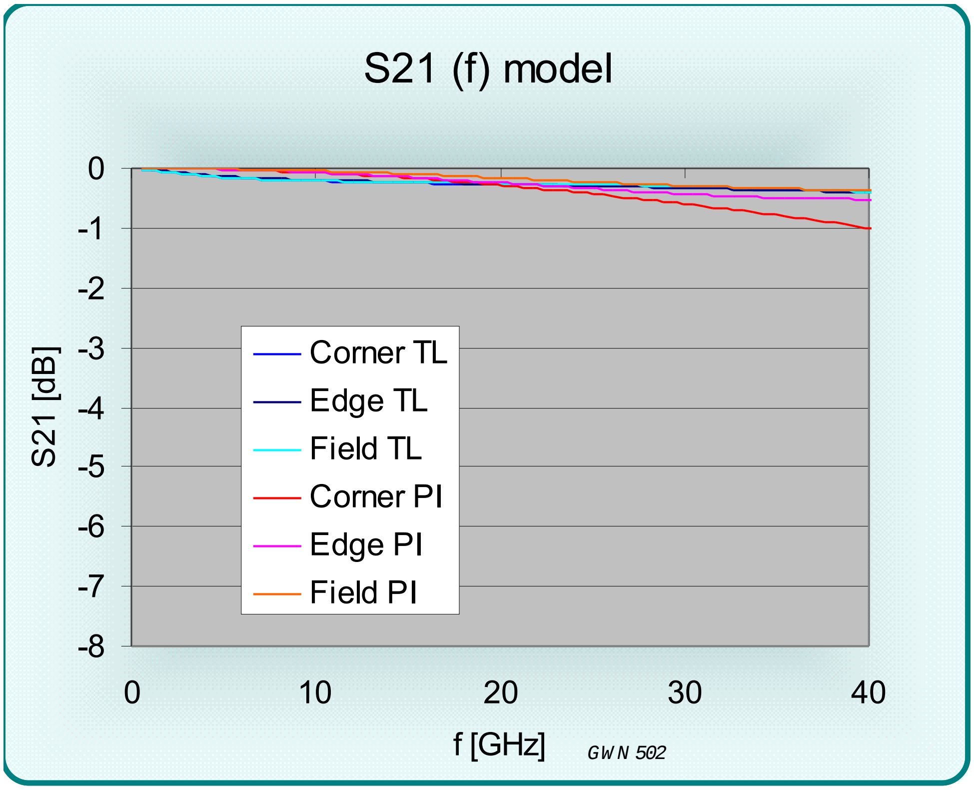


Figure 34 Insertion loss as a function of frequency

The lumped element frequency domain model used for evaluating the mutual elements also consists of the lumped model for the single pin plus a mutual inductance and two coupling capacitors. The model was used in configurations corresponding to the actual measurements. Contact resistance is again omitted because of negligible impact.

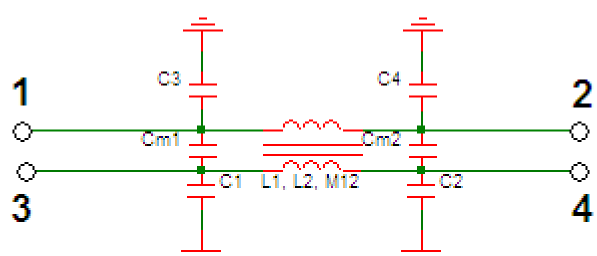


Figure 35 Equivalent circuit for G-S-S-G (mutual coupling)

The limitations for the G-S-S-G models are the identical to the G-S-G version.

The values for this model are:

Site	C1,2,3,4		Cm1,Cm2		L1, L2	M	
Corner	0.057		0.008	pF	0.13	0.093	nH
Edge	0.063		0.007	pF	0.11	0.053	nH
Field	0.055		0.007	pF	0.11	0.045	nH
Diagonal	0.055		0.003	pF	0.11	0.018	nH

The lumped model does not remain valid at high frequencies. Alternatives are a split of the lumped model into multiple sections, e.g. three sections with 1/3 the values for the total capacitance or inductance each or the use of a transmission line model with coupled transmission lines and added loss terms as shown below (field site only):

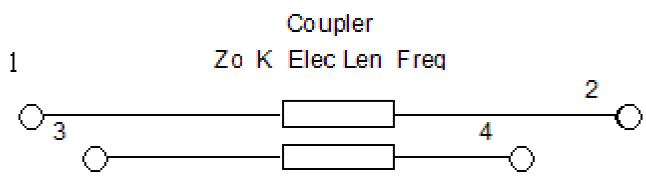


Figure 36 Transmission line equivalent circuit for crosstalk

The model shows two coupled transmission lines with the respective in- and outputs. Its elements are Z_o, L_{el}, k and $f_{(180deg)}$:

Field	43.7	Ω	1.5	ps	0.43	139.6	GHz

Simulations are performed like the measurements where S31 measures the backward crosstalk (NEXT), while ports 2 and 4 are terminated in 50 Ohms. Likewise, the forward crosstalk S41 (FEXT) is determined with ports 2 and 3 terminated into 50 Ohms.

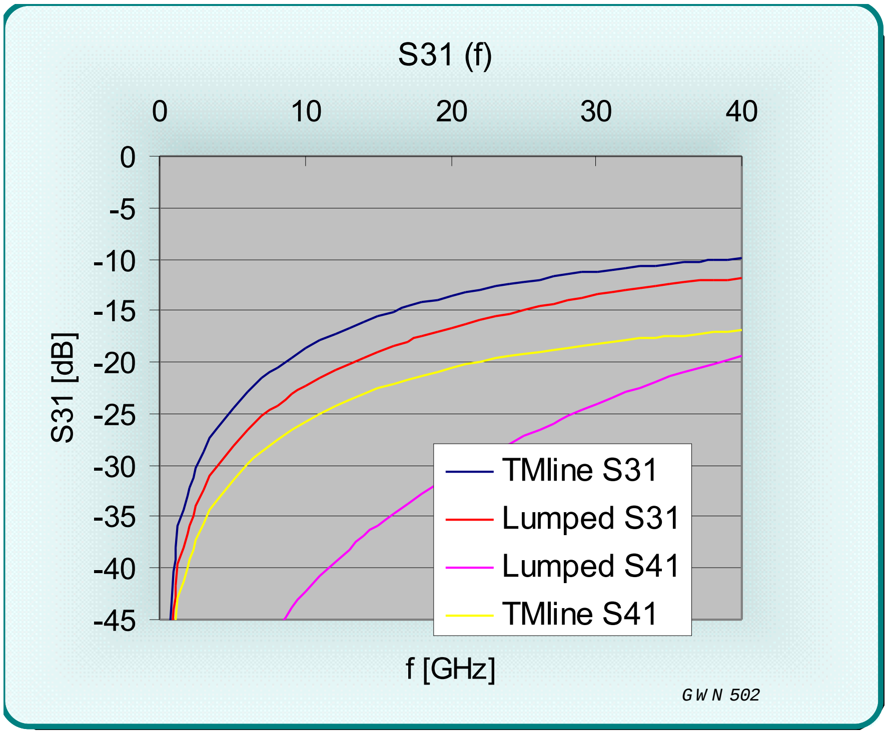


Figure 37 Crosstalk S31 and S41 [dB] as a function of frequency

The TM line model for S41 underestimates crosstalk. This is of little consequence, however, since the overall level of forward crosstalk is low to begin with. Again, model limit frequencies as noted in the G-S-G case apply. For fully accurate representations Touchstone parameters (SnP) or optional multi-pole representations should be used.

Summary sheet

Note: Contact pressure has an impact on parasitic capacitance and different tests had to be conducted at different contact pressures, hence there is some scatter in the data.

Ironwood

GTP contact

0.40 mm pitch

12/16/2019

Measurement results:

	Corner	Edge	Field	
Delay	1.2	1.6	1.5	ps
Risetime open	28.5	28.5	28.5	ps
Risetime short	27	27	27	ps
Risetime thru, 50Ω	12	12	12	ps
Insertion loss (1dB)	64.3	52.8	93.7	GHz
Insertion loss (3dB)	>100	>100	>100	GHz
VSWR (2:1)	90.4	>100	109.5	GHz

PI equivalent circuit component values:

Site	Cg=C1+C2		L1		R4	
Corner	0.114	pF	0.13	nH	160	Ohms
Edge	0.127	pF	0.11	nH	50000	Ohms
Field	0.109	pF	0.11	nH	50000	Ohms
Diagonal	0.109	pF	0.11	nH	50000	Ohms

It should be noted that there are 2 capacitors in the PI equivalent circuit. Each of them has half the value listed here. R4 is not the series resistance (Cres) but in parallel with L1; please see report for explanation.

Mutual component values:

Site		Cm		M	
Corner		0.016	pF	0.093	nH
Edge		0.013	pF	0.053	nH
Field		0.014	pF	0.045	nH
Diagonal		0.005	pF	0.018	nH

It should be noted that there are 2 capacitors in the PI equivalent circuit. Each of them has half the value listed here.

Transmission line equivalent circuit values:

Site	Zo		td	
Corner	41.1	Ω	1.2	ps
Edge	45.7	Ω	1.6	ps
Field	43.7	Ω	1.5	ps

The impedance listed is that observed in the time domain measurements. It is different than that calculated from the measured L,C parameters because of the limited time domain signal risetime.