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Influence of Via Stub Length and Antipad Size on the Insertion Loss Profile

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Abstract
The growing transmission speed and volume of digital content increases the pressure on reduction of overall insertion loss of printed circuit boards permanently.

In today's circuit boards, it is not only the transmission line itself, but also the via structure that impacts the insertion loss profile. To optimize the via, the stub length needs to be reduced by methods like backdrilling the copper out of the unused portion of the PTH.

In this paper, the influence of remaining stub lengths – varied between a couple of mils and 100mils - on the insertion loss profile is evaluated. As a second variable the size of the antipad is chosen and a two factor, multiple level DOE is performed.

Both, single ended and differential insertion loss is investigated and an 'analysis of variance' approach is used to determine the level of influence of the variables stub length and antipad size at various frequencies up to 40GHz.

The frequency of the quarter-wave-length-resonance is correlated to the stub length as well as the increase of the insertion loss well below the resonance point is discussed.

The paper describes the test vehicle, the performed measurements and discusses the electrical performance characteristics of the various test cells. A recommendation for an acceptable stub length is given.

Introduction
Driven by steadily increasing bandwidth demand for networking infrastructure and amount of data handled in ever enlarging server installations, the transmission characteristics of the transmitting channel must be optimized.
Best performance would be reached with a signal path without distortion and zero attenuation. In the imperfect reality, the insertion loss of the transmitting structures needs to be as small as possible and should not show large non-linearities.

For insertion loss reduction, the dielectric loss needs to be minimized by using low Df materials. The second important parameter is the copper loss, which is influenced significantly by the roughness of the signal trace. The application of both adequate oxide replacement and copper foil quality is key, as shown in [1] and [2].

However, there is another element in the transmission channel that needs to be evaluated. The via structure connecting the integrated circuit or connectors to the traces on the innerlayers of the printed circuit board has a huge negative impact on the insertion loss profile, especially, if the via extends significantly beyond the layer that needs to be electrically connected.
As discussed in [3], the via stub creates a large notch in the insertion loss profile at the 'quarter-wave-frequency'.

A commonly used method to reduce the via stub is to 'backdrill': a second drilling step after electro-plating of the through holes removes the copper in the unused portion of the via (see figure 1).
Since this is a mechanical operation, inproving the depth accuracy is not simple and very often complicates the process significantly, which in turn increases cost. It is important to understand, how much stub is still acceptable in a given application to avoid excessive strengthening of the via stub specification.

To get real data on the effect of the via stubs, single ended and differential channels were created with stub lengths varying from practically zero to close to 100mils. As a second parameter, the sizes of the antipads on the reference layers have been modified. Two-port and 4-port S-parameters were collected on these test structures and an 'analysis-of-variance' (ANOVA) [4], [5] approach was used to evaluate the effect of these parameters on the magnitude of the insertion loss as well as on the quarter-wave resonance frequency.

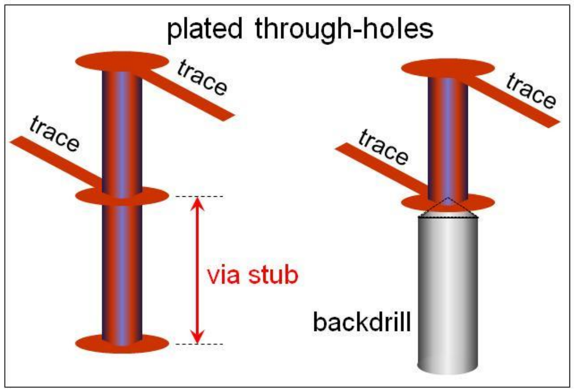

Figure 1
Backdrill Principle

Measurement Results that prompted the Investigation

During a routine measurement of insertion-loss-over-frequency on a 0.220” thick board (see figure 2), significant differences were found, depending on the measured layer. Testing the same layers with backdrilled vias eliminated the differences and resulted in a straight insertion loss curve without the deep resonances (see figure 3).

This finding initiated a thoroughly investigation into the influence of via stubs on electrical performance.

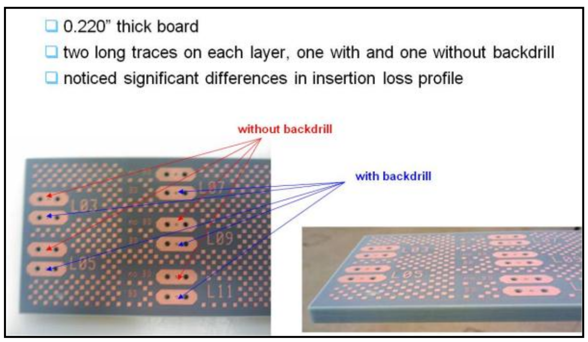

Figure 2
0.220” Thick Board

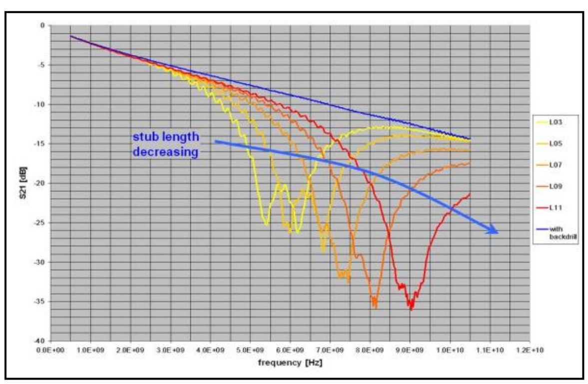

Figure 3
Influence of Stub Length on Insertion Loss Profile

Description of the Test Vehicle

An 8 layer stackup was used for the test vehicle. It contained one offset stripline on layer 3 (referencing to ground layers 2 and 4). Layer 6 was an unused layer and layers 5 and 7 were again ground layers. The outer layers provided the landing patterns for probing. The probing was performed from the top side, which in turn generated maximum via stubs for the layer 3 features.

A mid loss material has been applied for the DOE, as many designs in the 3.125 to 10Gbs+ range are using them. Similar glass styles and thicknesses were used for the cores and prepregs to get a relatively balanced stripline design.

A rather wide line width in combination with 1oz copper delivered minimum DC resistance.

Together with a smooth copper foil, these design attributes were resulting in a relatively small insertion loss.
The complete stackup details can be found in figure 4.

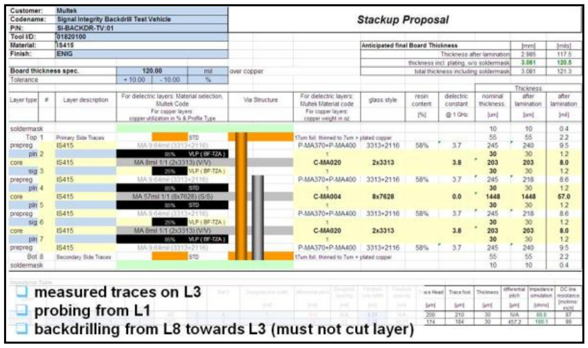

Figure 4
Stackup of the Test Vehicle

The design consisted of single ended and differential transmission lines on layer 3, with a via connecting the lines to the outside at each end of the traces. In addition, single ended and differential impedance test coupons were placed on the panel.

The size of the antipads on the plane layers was identical on L2, L4, L5 and L7, but they were modified between 50mil and 90mil in diameter for the various coupons.

The primary drill (plated through hole) was backdrilled from the bottom side of the test vehicle to different depths, resulting in nominal stub lengths between around 100mil down to practically no stub at all (figure 5). Some of these stub lengths can be seen in figure 6.

- 10 different stub lengths from approximately zero to 100mils
- 4 different antipad sizes from 50mil to 90mil diameter
- 2 identical single ended insertion loss coupons per panel
- one differential insertion loss coupon per panel
- one single ended and one differential impedance coupon per panel
- total of 5 panels

Figure 5
Design Features

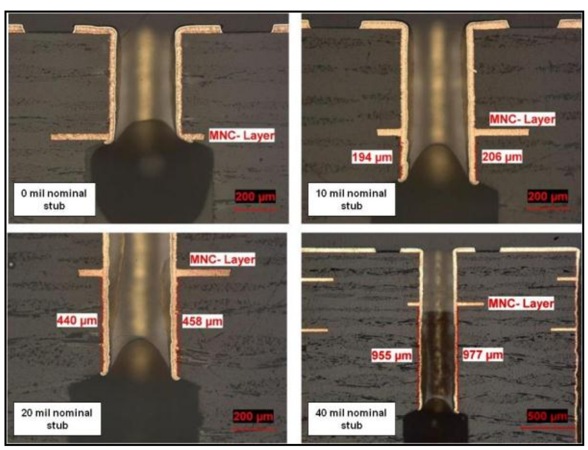

Figure 6
Different Stub Lengths

An overview of the test panel with the various backdrill and insertion loss coupons is given in figure 7 and an example of one of the coupons populated with the flange mount connectors is shown in figure 8.

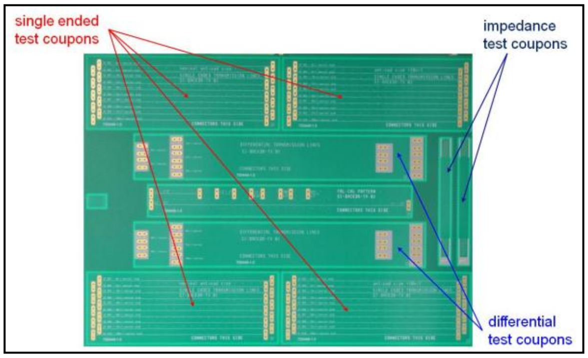

Figure 7
Test Panel Layout

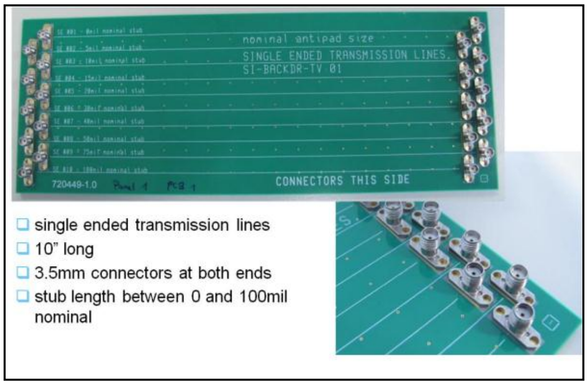

Figure 8
Single Ended Coupon with Connectors mounted

Impedance Control

To assure good matching of the transmission lines to the measurement equipment, the single ended and differential impedance of the traces was measured on each test panel. For ease of testing, dedicated impedance coupons (see figure 7) were used in conjunction with handheld probing heads and a standard, volume manufacturing impedance test system.
The impedance testing confirmed that both the differences between the panels and between the two produced workorders were minimal. The absolute values were slightly below nominal, with an average single ended impedance of 47.6 Ohm and an average differential impedance of 97.2 Ohm on layer 3. The detailed readings can be found in table 1.

Table 1
Impedance Results

average							47.56	48.23	97.19
stds							0.87	0.81	0.91
min							45.80	47.12	96.09
max							48.47	49.89	98.41
cpk							0.98	1.33	2.64
target							50.00	50.00	100.0000
lower spec limit							45.00	45.00	90.00
upper spec limit							55.00	55.00	110.00
tool#	date	time	part#	serial#	workorder	datecode	sig3 -8.25mil	sig6 - 8.25mil	sig3 -7.25mil
Polar3	4/20/2012	21:41	SI-BACKDR-TV	1	720449-1	1612	48.29	49.89	97.48
Polar3	4/20/2012	21:44	SI-BACKDR-TV	2	720449-1	1612	46.89	47.75	97.75
Polar3	4/20/2012	21:44	SI-BACKDR-TV	3	720449-1	1612	45.80	48.94	97.93
Polar3	4/20/2012	21:43	SI-BACKDR-TV	4	720449-1	1612	46.81	48.44	98.41
Polar3	4/20/2012	21:43	SI-BACKDR-TV	5	720449-1	1612	48.47	47.12	98.39
Polar3	5/22/2012	12:52	SI-BACKDR-TV	2	720513-1	2012	48.06	47.51	96.41
Polar3	5/22/2012	12:54	SI-BACKDR-TV	1	720513-1	2012	47.30	47.64	96.09
Polar3	5/22/2012	12:54	SI-BACKDR-TV	3	720513-1	2012	48.46	48.60	96.72
Polar3	5/22/2012	12:55	SI-BACKDR-TV	4	720513-1	2012	48.00	48.44	96.23
Polar3	5/22/2012	12:55	SI-BACKDR-TV	5	720513-1	2012	47.52	48.00	96.45

Single Ended Insertion Loss Testing

Measurement of single ended and differential insertion loss of the transmission lines including the effect of the via stubs was performed on a 4-port vector network analyzer capable of going to 40GHz. High quality coaxial cables with 2.92mm connectors with a frequency rating of 40GHz were used.

A minimum warm-up period of 2 hours was ensured prior to calibration of the vector network analyzer. For this purpose an electronic calibration module, connected directly to the end of the coaxial cables was used.
After completion of the calibration, the cables connected directly to the compression mount connectors on the test boards, without any additional adapters needed.
Full 2-port and 4-port S-parameters were measured on all test boards. The data was transferred into a spreadsheet and statistics software to allow plotting of the parameters and further evaluations, like the analysis-of-variance (ANOVA) to find the ‘vital few’ parameters.

The setup for single ended insertion loss testing can be found in figure 9.

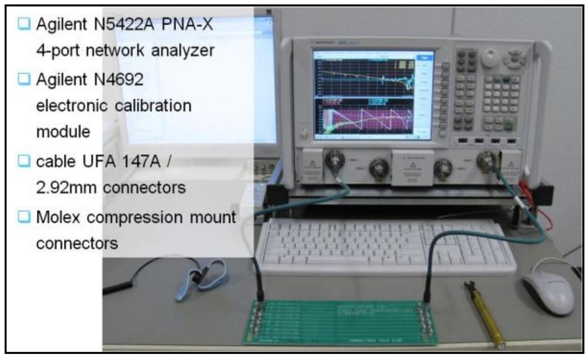

Figure 9
Single Ended Insertion Loss Test Setup

A screenshot of typical measurement data is shown in figure 10. The orange trace in the upper portion of the display is the magnitude of insertion loss over the full frequency range for a coupon with a very short stub, where the yellow trace is for a long stub. The lower part of the screenshot shows magnitude and phase for all four single ended S-parameters.

Figure 10
Screen Shot of Single Ended Insertion Loss Testing

For single ended structures, 4 different antipad sizes and 10 different stub lengths were measured on 5 panels with 2 identical coupons each, which resulted in 400 full 2-port S-parameter matrices, spanning the frequency range from 10MHz up to 40GHz with 2048 points.
To exclude odd readings in the data, the magnitude of the insertion loss was plotted for each of the 400 measurements in one chart, see figure 11.

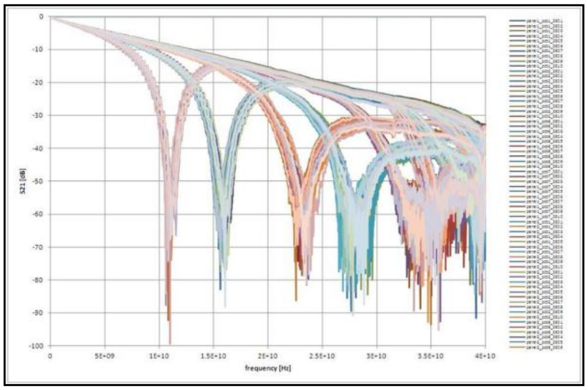

Figure 11
Raw Data for S21 Magnitude

To get a less noisy picture of the influence of the stub length and the antipad sizes, the data of the 5 panels and two identical coupons for each stub length / antipad size combination were averaged and plotted (figure 12). The via stubs cause a large resonant dip, with the longest stubs creating the notches in the insertion loss curve at lower frequencies than the shorter stubs. The antipad size is generating some small changes, but with a less clear effect than the stub length. To evaluate the influence of the antipad size, an analysis-of-variance was performed, which is presented in figures 17, 19, 20.

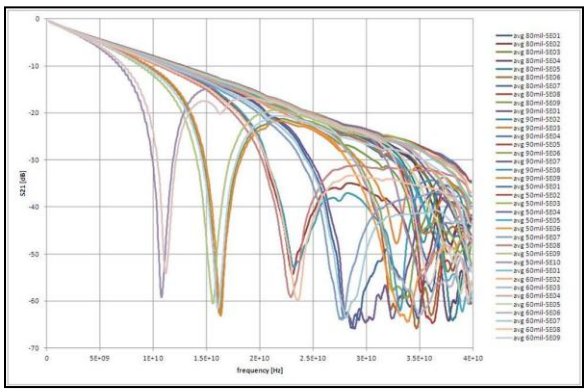

Figure 12
Average Data for S21 Magnitude

To answer the question of the maximum acceptable stub length, the additional insertion loss caused by the via stubs is extracted from this data with a de-trend operation and plotted in figure 13.

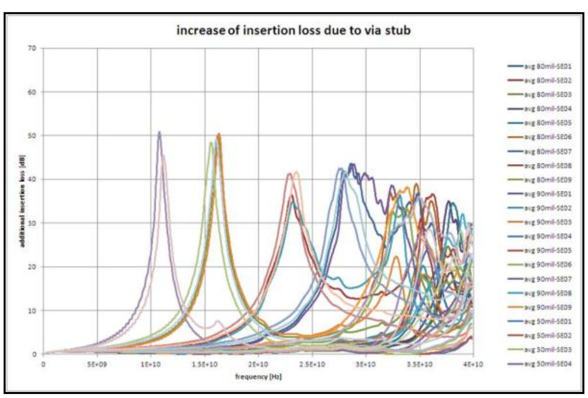

Figure 13
Additional Loss caused by the Via Stubs

As an example, a maximum additional insertion loss of 5dB might be acceptable at frequencies up to 20GHz. Using the chart in figure 13 and adding a forbidden zone (red hatched box), it can be found, that the stub lengths SE08, SE09 and SE10 are too long and therefore add to much insertion loss. The stub length SE07 is barely acceptable in this example, whereas all shorter stub lengths pass the requirement (see figure 14).

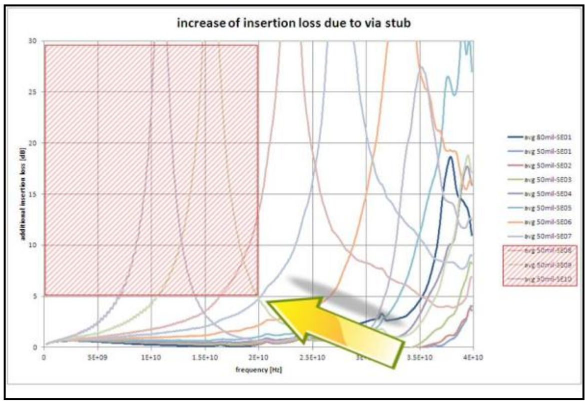

Figure 14
Maximum acceptable Stub Length

Beside evaluating the magnitude of insertion loss, the return loss was also plotted (figure 15). Obviously, the effect of stub length and antipad size is much less pronounced than in the insertion loss charts.

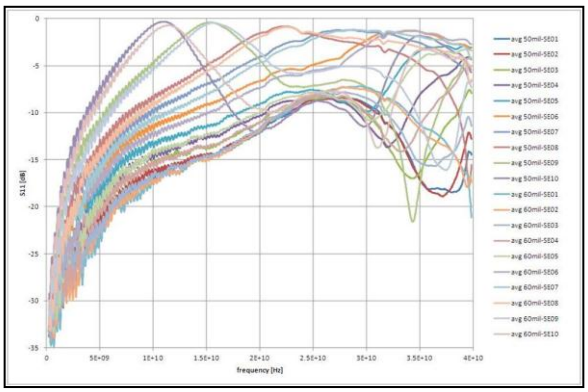

Figure 15
Averages for single ended Return Loss

Because of the wide maxima at the resonance frequency in the return loss chart, no numerical evaluation was performed here. However, plotting the insertion loss and the return loss in one chart confirmed the expected alignment of the dips in insertion loss (IL) and maxima in return loss (RL) regarding frequency, which is shown in figure 16 for the longer stubs.

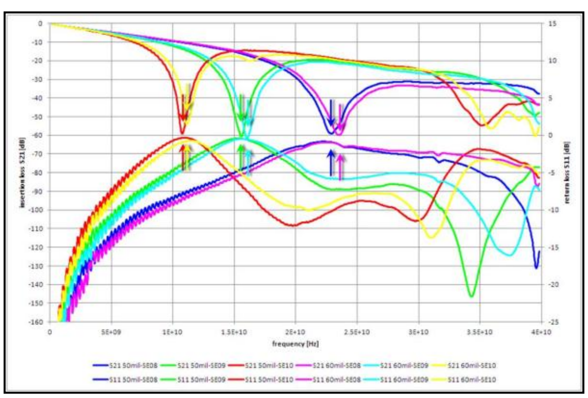

Figure 16
Alignment Insertion Loss and Return Loss

The charts provided a good overview about the influence of the stub length and the antipad sizes, but to get quantitative data on the level of influence, ANOVA evaluations were performed.
The first ANOVA shows the influence of the parameters “stub length” and “antipad size” on the resonance frequency (figure 17).

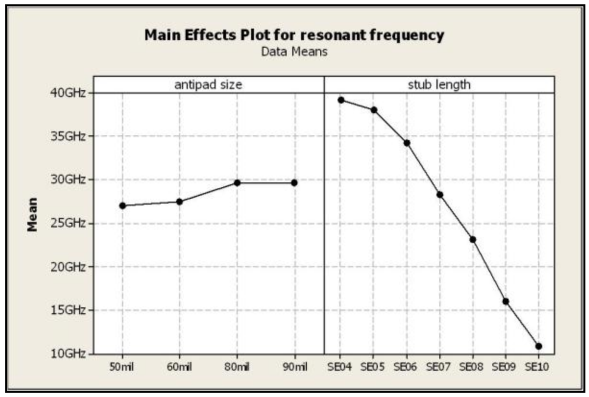

Figure 17:
ANOVA Chart for Resonance Frequency

The main effect plot demonstrates, that larger antipad sizes increase resonance frequency slightly. The main driver however is the stub length, with the short stub length SE04 resulting in a resonance at close to 40GHz, whereas the longest stub (SE10) creates a resonance only marginally above 10GHz.
To quantify the effect of the two parameters 'antipad size' and stub length, the numeric output from the ANOVA evaluation is used. The data show, that the stub length accounts for 98% of the variation in the resonance frequency, where the antipad size has an effect of less than 2% (figure 18).

```
General Linear Model: resonant frequen versus antipad size, stub length

Factor        Type   Levels  Values
antipad size  fixed       4  50mil, 60mil, 80mil, 90mil
stub length   fixed       7  SE04, SE05, SE06, SE07, SE08, SE09, SE10


Analysis of Variance for resonant frequency, using Adjusted SS for Tests

Source        DF       Seq SS       Adj SS       Adj MS       F      P
antipad size   3  3.83060E+19  1.42535E+18  4.75118E+17    0.84  0.492
stub length    6  2.26578E+21  2.26578E+21  3.77629E+20  666.95  0.000
Error         16  9.05929E+18  9.05929E+18  5.66205E+17
Total         25  2.31314E+21


S = 752466163   R-Sq = 99.61%   R-Sq(adj) = 99.39%
```

- **antipad size accounts for 1.7% of the variation → minor influence**
- **stub length accounts for 98% of the variation → major influence**
- **less than 0.5% in the error term**

Figure 18:
ANOVA General Linear Model for Resonance Frequency

Another ANOVA was performed to investigate the influence of panel number, PCB number, antipad size and stub length on the absolute insertion loss value. This can be done for every frequency in the captured data (10MHz to 40GHz). Here only the data for 5GHz and 10GHz are presented as an example.
For both frequencies, there is hardly any variation over the PCB number / location of the coupon on the panel. Some variation can be seen between the 5 manufactured panels. Again the antipad size has a small influence, with the larger clearances causing less insertion loss. The main contributor is the stub length, causing an increase in the single ended insertion loss from around 4.5 to 5.5dB at 5GHz. The ANOVA main effect plots for 5GHz and 10GHz are shown in figure 19 and figure 20.

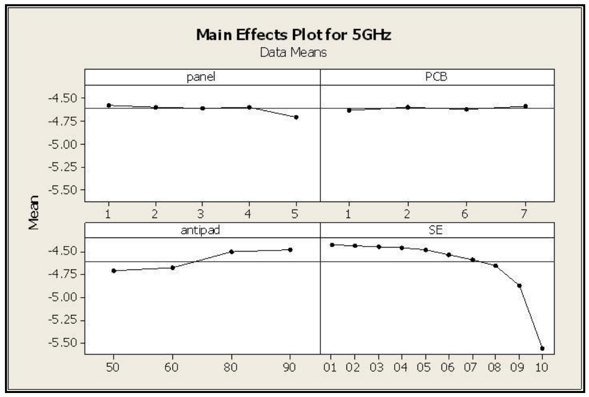

Figure 19:
Main Effect Plot for Insertion Loss at 5GHz

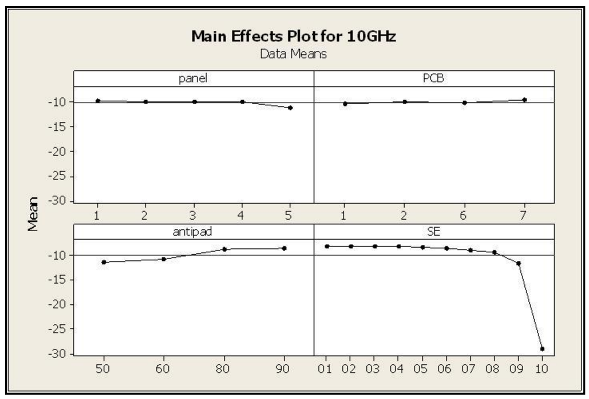

Figure 20:
Main Effect Plot for Insertion Loss at 10GHz

Using the numeric output of the ANOVA at 5GHz (frequency chosen as one example), shows the panel to be a minor influence causing only 1.8% of the variation. The antipad size is a second order influence with an effect of 11.3% and the stub length is again the major influence, being the cause of 83.2% of the variation. Details are given in figure 21.

```
General Linear Model: 5GHz versus panel, antipad, SE

Factor   Type   Levels  Values
panel    fixed       5  1, 2, 3, 4, 5
antipad  fixed       4  50, 60, 80, 90
SE       fixed      10  01, 02, 03, 04, 05, 06, 07, 08, 09, 10


Analysis of Variance for 5GHz, using Adjusted SS for Tests

Source    DF   Seq SS   Adj SS  Adj MS       F      P
panel      4   0.4770   0.0701  0.0175    5.41  0.000
antipad    3   3.0815   0.8301  0.2767   85.45  0.000
SE         9  22.6476  22.6476  2.5164  777.07  0.000
Error    316   1.0233   1.0233  0.0032
Total    332  27.2293


S = 0.0569063   R-Sq = 96.24%   R-Sq(adj) = 96.05%
```

- **panel accounts for 1.8% of the variation → minor influence**
- **antipad size accounts for 11.3% of the variation → second order influence**
- **stub length accounts for 83.2% of the variation → major influence**

Figure 21:
ANOVA General Linear Model for Insertion Loss at 5GHz

Differential Insertion Loss Testing

The setup for the differential insertion loss testing can be found in figure 22. A 4-port vector network analyzer was calibrated at the connector interface to the device-under-test with an electronic calibration module. The use of the eCal module lead to a significantly faster, easier and virtually error proof calibration process, especially for the 4-port calibration.
On the test board, the interface to the VNA was provided with flange mounted compression type connectors.

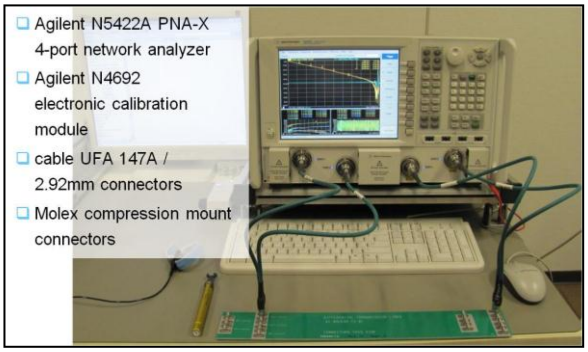

Figure 22:
Differential Insertion Loss Setup

Figure 23 shows a screenshot of two different stub lengths superimposed. The upper portion of the display shows the amplitude of the differential insertion loss SDD21. The orange trace is for a coupon with nearly optimum backdrilling (minimum stub), with the yellow trace showing SDD21 for a differential pair with long via stubs.
The bottom portion of the screenshot displays the amplitude (left) and phase (right) of all 16 mixed mode S-parameters.

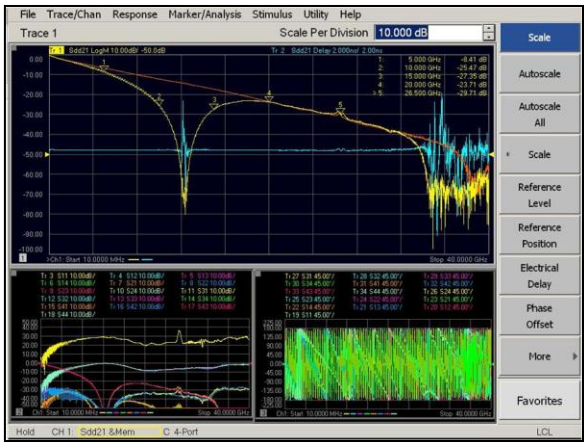

Figure 23:
Screen Shot of Differential Insertion Loss Testing

For the differential testing, mixed mode S-parameters were measured on 10 different stub lengths, 2 different antipad sizes and 5 panels, testing from 10MHz to 40GHz with 2048 points.
Similar as with the single ended data, the magnitude of the differential insertion loss was plotted for all 100 differential pairs to check for unusual readings (figure 24). The averages over the 5 panels were plotted for the 10 stub lengths and 2 antipad sizes, to visualize the impact of the parameters (figure 25).

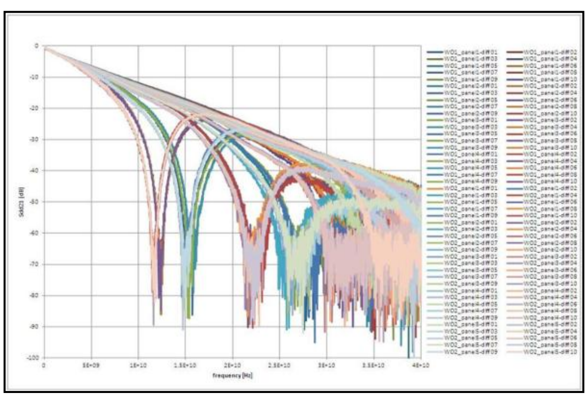

Figure 24:
Raw Data of SDD21 Magnitude

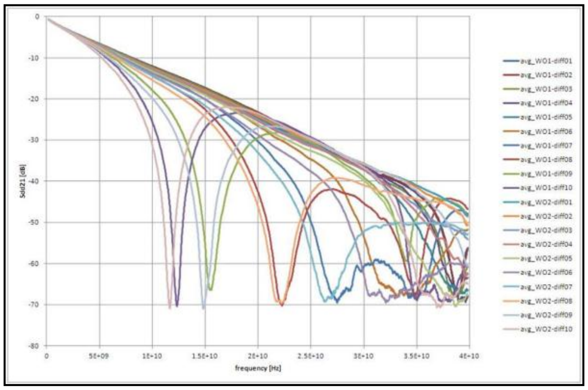

Figure 25:
Average Data for Magnitude of SDD21

Figure 25 clearly demonstrates the increase of the resonant frequency for shorter stub lengths and also some smaller changes caused by the antipad size. To get the full picture on the influence of the panel, the antipad size and the stub length, an analysis-of-variance on the magnitude of SDD21 was conducted for various frequencies. Figure 26 shows the main effect plot of this ANOVA for a frequency of 5GHz.

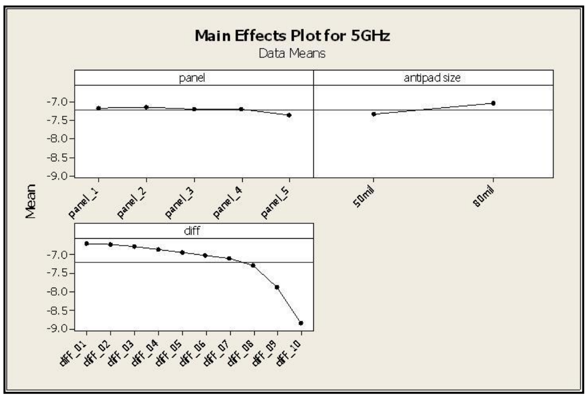

Figure 26:
Main Effect Plot for Mag(SDD21) at 5GHz

The main effect plot confirms a very small panel-to-panel variation. The effect of the antipad size is slightly larger, but the main influence clearly is the stub length. To get quantitative data on the effects, the numerical ANOVA data is evaluated, showing the panel to have only a 0.7% variation and the antipad size to account for 3.5% of the variation. 91.3% of the variation is caused by the stub length, which therefore has the by far largest influence (figure 27).

```
General Linear Model: 5GHz versus panel, antipad size, diff

Factor        Type   Levels  Values
panel         fixed       5  panel_1, panel_2, panel_3, panel_4, panel_5
antipad size  fixed       2  50mil, 80mil
diff          fixed      10  diff_01, diff_02, diff_03, diff_04, diff_05,
                             diff_06, diff_07, diff_08, diff_09, diff_10


Analysis of Variance for 5GHz, using Adjusted SS for Tests

Source        DF   Seq SS   Adj SS  Adj MS       F      P
panel          4   0.2908   0.0467  0.0117    0.48  0.753
antipad size   1   1.4273   1.8685  1.8685   76.33  0.000
diff           9  36.7577  36.7577  4.0842  166.83  0.000
Error         72   1.7627   1.7627  0.0245
Total         86  40.2385


S = 0.156465   R-Sq = 95.62%   R-Sq(adj) = 94.77%
```

- panel accounts for 0.7% of the variation → minor influence
- antipad size accounts for 3.5% of the variation → second order influence
- stub length accounts for 91.3% of the variation → major influence

Figure 27:
ANOVA General Linear Model for Differential Insertion Loss at 5GHz

Cross Section Evaluation

After completing the TDR and VNA evaluation, actual stub length measurements of the launch vias have been made using cross sections. Figure 28 shows examples of the depths, between “SE01”, which was virtually no stub at all to “SE10”, the maximum stub length.

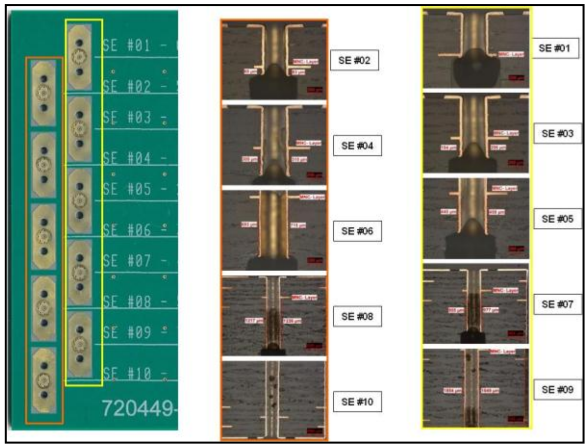

Figure 28:
Cross Sections of Via Stubs

The measured stub length was plotted against the nominal stub length (figure 29). Obviously, actual stub lengths and target stub lengths correlate tightly. This can be considered as proof that the backdrilling operation was well under control.

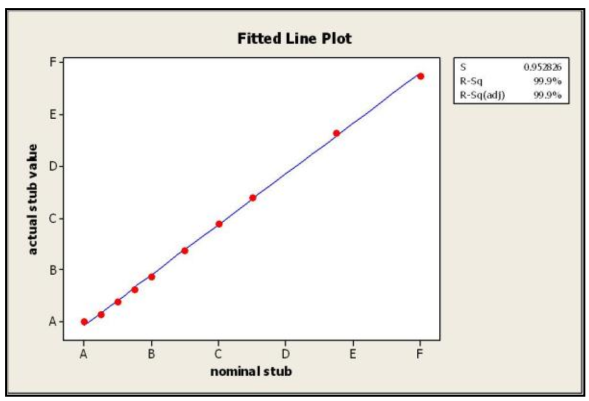

Figure 29:
Fitted Line Plot for Actual versus Nominal Stub Length

Summary

In this investigation, data were generated to predict the additional insertion loss generated by via stubs of the launch vias. The effect on the frequency of the resonant notch in the loss profile was also demonstrated. Both parameters were evaluated over various stub lengths and antipad sizes.

The data confirmed that a larger via stub reduces the resonant frequency and increases the overall insertion loss. It was demonstrated in addition, that a smaller antipad size has the same effect, but to a much smaller degree.

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Biography

Alexander Ippich is working as a senior signal integrity engineer with Multek Inc. Previously, he held various positions in Application Engineering and R&D.

He worked also in the development of thin film TFT matrixes and LCD displays.

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