Via Area Impedance and Stub Length

Background

It's commonly assumed that the magnitude of the dip in the impedance in the via region is an indicator of stub length. It's believed that the extra metal creates extra capacitance, and that decreases the impedance significantly. This paper is meant to better describe the relationship between stub length and via area impedance.

Why Relating the Dip Amplitude to Stub Length is Misguided

Let's say that dip amplitude is related directly to stub length. Let's say that the dip is a simple rectangle function and the DUT and transmission lines are perfectly matched so they cause no reflections, and the DUT is terminated into a 50ohm load. That leaves us with a simple TDR profile v(t), assuming the transmission line DUT interface is at 0 seconds, and the stub length is L, and a is some relational coefficient, and T is the period of the dip

$$v(t) = -a * L * rect(\frac{t}{T})$$

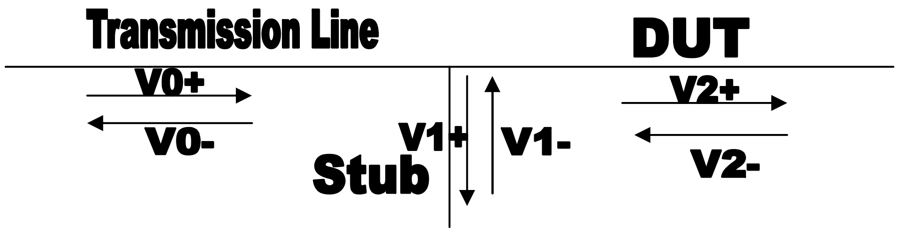
Now that the time response is known a Fourier transform can be done and the response in the frequency domain can be obtained

$$V(\omega) = -a * L * T * Sinc(T * \omega)$$

Assuming that the amplitude of the dip is proportional to stub length means that the frequency content of the response will change in amplitude only with changes in the stub length. This isn't true. The resonance from a stub in the frequency domain will shift higher or lower in frequency depending on the stub length. The relationship of the stub length to resonant frequency is the quarter of the wavelength.

Simulating the Stub on a Transmission Line DUT Interface

Clearly, relating the impedance dip to a length is less than ideal. Establishing a meaningful relationship is desirable. Setting up a way to model the system becomes necessary. A simple way is to use solutions to telegrapher's equation and have traveling and returning monochromatic waves that can be synthesized into a step function. Each section of the model has a different pair of transmitting and returning waves as in the following diagram.



The system has 5 unknowns. The transmitting signal on the transmission line is the source which is a step function. The current can be assumed to be zero at the end of the stub and DUT since it's an open circuit. The voltages on the middle node must be equal. The following set of equations describes the system.

$$v_0 = v_0^+ e^{-\gamma_0 x} e^{\omega t} + v_0^- e^{\gamma_0 x} e^{\omega t}, v_1 = v_1^+ e^{-\gamma_1 x} e^{\omega t} + v_1^- e^{\gamma_1 x} e^{\omega t}, v_2 = v_2^+ e^{-\gamma_2 x} e^{\omega t} + v_2^- e^{\gamma_2 x} e^{\omega t}$$

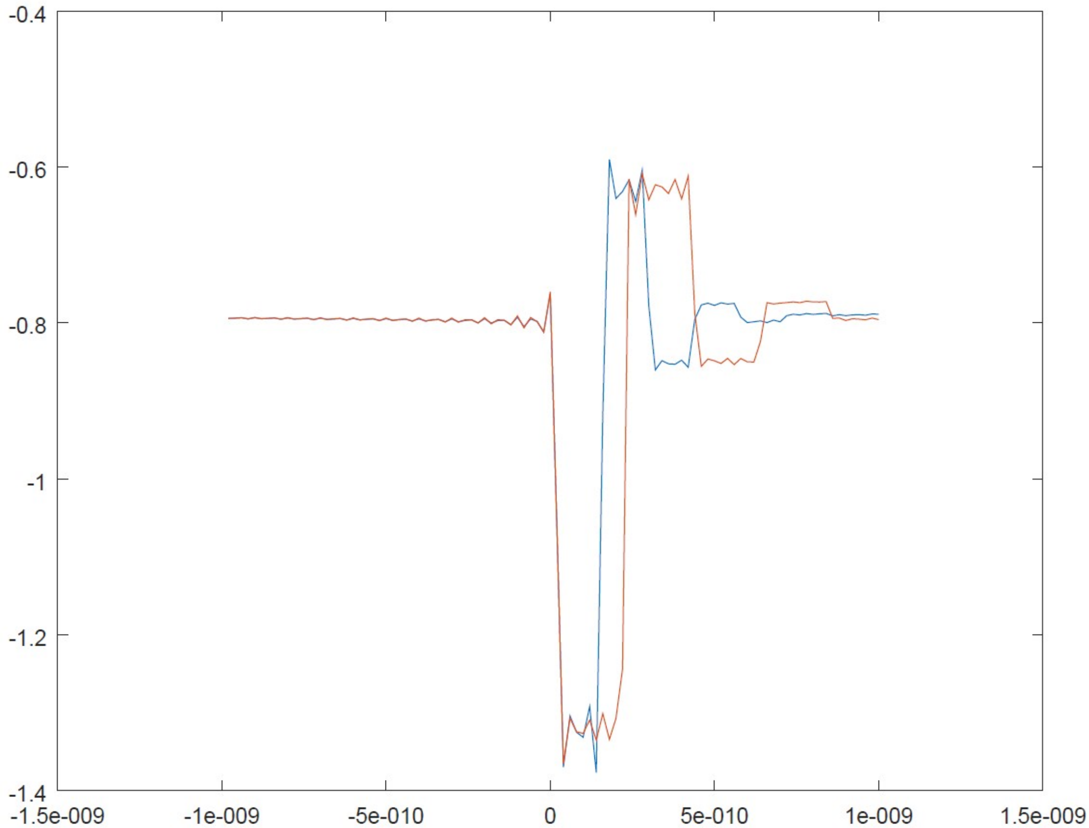
$$i_0 = \frac{v_0^+}{Z_0} e^{-\gamma_0 x} e^{\omega t} - \frac{v_0^-}{Z_0} e^{\gamma_0 x} e^{\omega t}, i_1 = \frac{v_1^+}{Z_1} e^{-\gamma_1 x} e^{\omega t} - \frac{v_1^-}{Z_1} e^{\gamma_1 x} e^{\omega t}, i_2 = \frac{v_2^+}{Z_2} e^{-\gamma_2 x} e^{\omega t} - \frac{v_2^-}{Z_2} e^{\gamma_2 x} e^{\omega t}$$

$$v_0(0) = v_1(0), v_0(0) = v_1(0), i_1(s) = 0, i_2(l) = 0, i_0(0) = i_1(0) + i_2(0)$$

The number of unknowns and equations are equal so a system of equations can be formed and solved to get the coefficients for each frequency.

Solution For DUT with Stub

As expected, the solution for the reflected wave from a longer stub does not result in a deeper dip. It results in a longer dip. The following Picture illustrates this. The blue trace is a simulated trace with a 10mm stub, and the red is a stub with a 15mm stub. The amplitudes in each case are the same. The difference is only in the period of the reflection.



Using the reasoning from the second section a better approximation can be deduced and inspected.

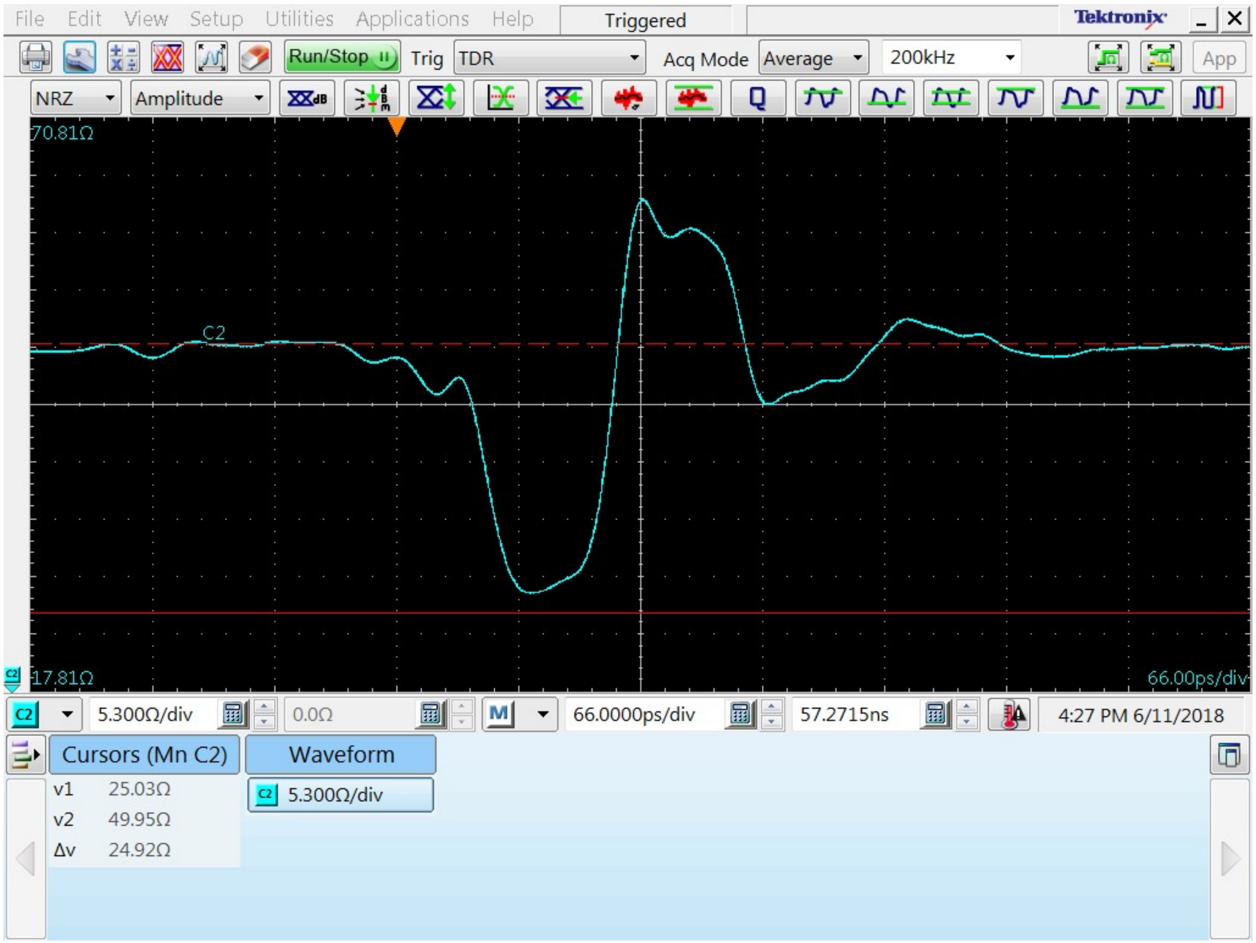
$$v(t) = -A * rect(\frac{t}{aL})$$

Now the period of the dip is a function of the stub length. In the frequency domain the response has the following form

$$V(\omega) = -AaL * Sinc(aL\omega)$$

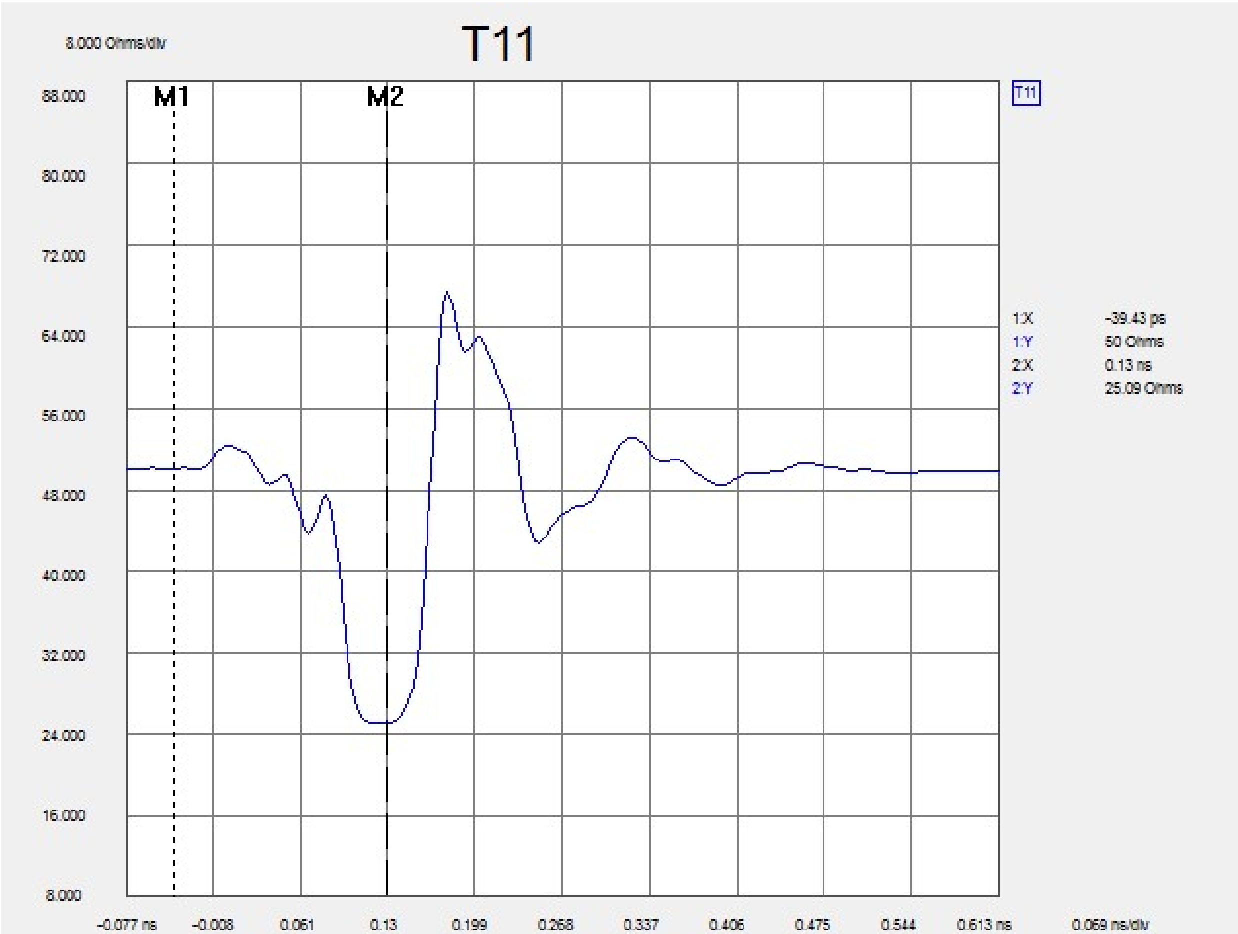
This result, unlike in the second section makes intuitive sense in the frequency domain. The intensity of the response is still a function of the stub length but also the longer the stub the lower the resonant frequencies go. Conversely, shorter stubs have smaller responses and those responses are higher in frequency. From deduction, a will be the reciprocal of propagation velocity.

The real dip amplitude from a stub in the via area is half the system impedance. This is true for a stub of any length but zero. A TDR signature from a coupon that was never backdrilled leaving a long stub follows



When considering that the limit of the TDR is 28ps in the best case, the fact that the dip doesn't quite reach 25ohms is easy to understand. The experimental results match very well the simulated one.

The following is a picture from a 40GHz VNA



A Note about Feasibility

The frequency in this simulation went up to 30GHz, which is rather high, and the stub lengths are rather long. To properly resolve smaller stubs in a lab the rising edge of the TDR will have to be proportionally shorter. A real limit exists in resolving stub responses correctly because in many cases even if the equipment can generate an appropriate rising edge, the board-via interface needs to be equally sophisticated. This isn't true in many cases.

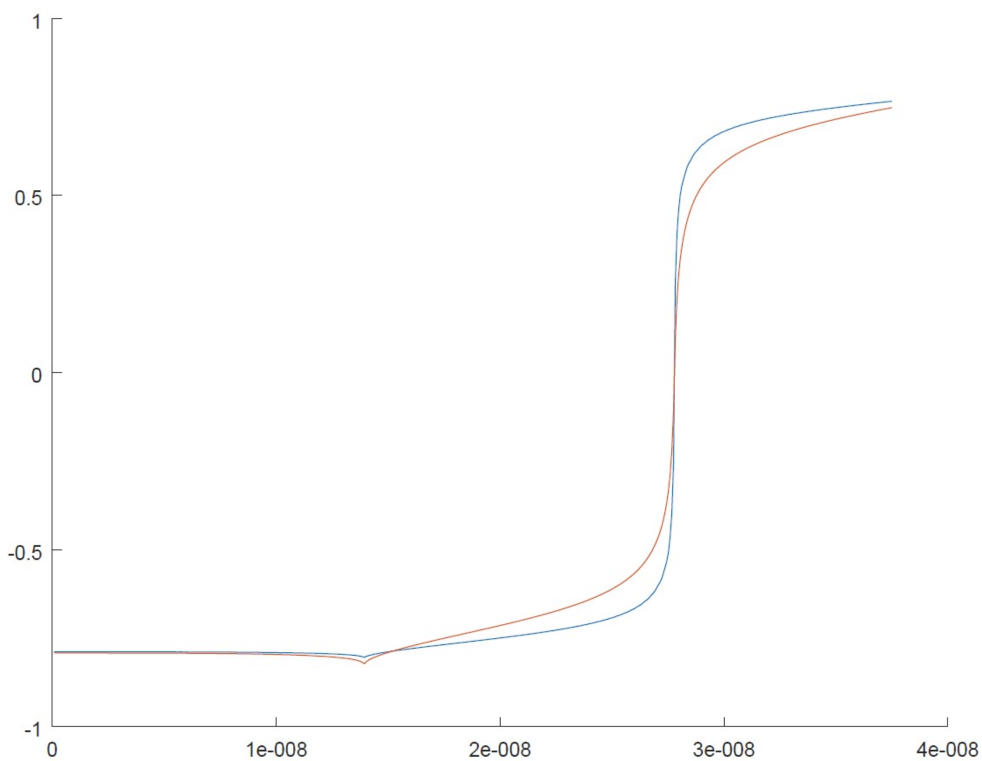
Why does the dip seem proportional to stub length?

As stated in the previous section, having enough bandwidth delivered to the stub to get the true response is not common. The rising edge rate is constrained. In a case where the rising edge is repeatably constrained the amplitude will depend on the width of the dip as illustrated below. The dashed line is the response with an infinitely steep edge rate.

The stub on the left is a length L and the right is a stub 2L. The depth of the stub response on the right will be deeper, since the same slope will travel longer along the voltage axis as its period is longer. This creates a linear relationship between stub length and TDR response dip, but still highly susceptible to changes in bandwidth and rising edge.

Other Factors That Baffle Stub Length measurement from Amplitude measurements

Another factor that influences the response in the transmission line DUT interface area is heterogeneity of the two mediums. The transmission line area and DUT in the case of PCB testing has significantly more loss. This was simulated. The results follow.



This represents, a transmission line, DUT, and open circuit, respectively simulated TDR response. Notice there is still a dip in the response at the transmission line DUT interface. This is a consequence of there being an interface of two dissimilar series losses. The blue is with a series loss R and the red is with a series loss 2R. The dip is proportional to series loss on the DUT side. This makes accurate measurements of the stub from an amplitude measurement susceptible to changes in bandwidth and changes in loss between the DUT and the transmission line.

Conclusion

If a large pool of stubs is measured, with repeatable bandwidth, losses, and known stub lengths a heuristic linear relationship can be made. This relationship can be used to approximate stubs in cases of similar loss and bandwidth. If the bandwidth changes or losses change on either side the relationship will change. Having adequately sophisticated equipment to make high bandwidth measurements of stubs and using the width of the dip in the response is the only way to determine stub length in the time domain. In this last case, the length will be known with a simple propagation delay calculation with known propagation velocity.