

## Measuring PCB, Cable and Interconnect Impedance, Dielectric Constants, Velocity Factor, and Lengths

Controlled impedance printed circuit boards (PCBs) often include a measurement “coupon”, which typically includes sample traces, 6 inches long and constructed as part of the printed circuit board panel. They are measured to assure the PCB stack-up and the accuracy of the PCB transmission lines. These coupons, as well as the actual PCB signal traces, interconnects and cables are typically measured using a Time Domain Reflectometer (TDR). A TDR is generally a large, expensive instrument that includes a high-speed edge pulse and a sampling oscilloscope.

Most modern circuit designs depend on accurate logic signals at the logic receiver. This assurance is based on the careful design of printed circuit board (PCB) transmission lines, interconnects, and cables. For that matter, it is advisable to verify the instrument cables and interconnects at regular intervals. Cable crimps frequently degrade, particularly in low-cost cables, and can significantly impact the quality of the measurement.

PerfectPulse<sup>®</sup>, from Picotest, is a low-cost, pocket-sized pulse generator (J2151A/J2154A). For the J2151A, the signal generator, combined with an included resistive port splitter, and a real time oscilloscope can be used as a precise TDR/TDT measurement systems. It can measure PCB test coupon impedance, cables and bad crimps, trace length, dielectric constant (Dk), and velocity factor ( $V_f$ ). This application note shows how to measure PCB, cable, and interconnect impedance, dielectric constant, velocity factor and cable length with the J2151A or J2154A. The J2154A is single or differential TDR and includes the signal generator and power splitter internally as one unit.

### Theory of the TDR measurement

Signals travel in air at the speed of light, approximately  $3 \cdot 10^8 m/sec$ <sup>1</sup>. The signal velocity is slowed when travelling over a dielectric material. The amount it is slowed down is the

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<sup>1</sup> The actual speed of light is  $2.99792458 \cdot 10^8 m/sec$ , so  $3 \cdot 10^8 m/sec$  is a reasonable approximation

velocity factor ( $V_f$ ) of the signal transmission, sometimes referred to as the velocity of propagation.

Coaxial cable specifications often include the velocity factor, which is typically between 60% and 90% (1). A cable with a velocity factor of 70% means that the signal travels at 0.7 times the speed of light or  $2.1 \cdot 10^8 m/sec$ .

The velocity factor is directly related to the permittivity of the transmission line. The ratio of the permittivity of a cable, or printed circuit board to the permittivity of free space is the dielectric constant of the transmission line or PCB. Dielectric constant is sometimes expressed as  $\epsilon_r$  and sometimes as  $D_k$ . Typical dielectric constant values range from a low of about 2 to as high as about 24.

The relationship between the velocity factor and the dielectric constant is:

$$V_f \text{ (in percentage)} = \frac{1}{\sqrt{D_k}} \cdot 100 \quad (1)$$

Since we know that the signal propagates through the cable or PCB at a speed of light reduced by the velocity factor it is possible to relate time and distance.

$$Time = \frac{Distance}{V_f \cdot 3 \cdot 10^8 m/sec} \quad (2)$$

Solving the signal propagation in units of inches and picoseconds

$$Signal \ Velocity = 84.75 \cdot \sqrt{D_k} \frac{ps}{inch} \quad or \quad \frac{11.81 \ inch}{\sqrt{D_k} \ ns} \quad (3)$$

And therefore, a round trip through the trace or cable is

$$Length = \frac{11.81 \cdot t_{ns}}{2 \cdot \sqrt{D_k}} \text{ inches} \quad (4)$$

And solving for  $D_k$  from a known length

$$D_k = \frac{34.875 \cdot (t_{ns})^2}{(Length \ in \ inches)^2} \quad (5)$$

In a single ended TDR measurement, the high-speed edge travels from the beginning of the transmission line to the end of the transmission line and then reflects to the instrument where it is measured. The signal makes a round trip through the transmission line and the instrument uses the incident and returned signals to measure the propagation time and the reflection coefficient,  $\Gamma$ , which is used to compute the transmission line impedance.

$$\Gamma = \frac{Z_{TL} - Z_0}{Z_{TL} + Z_0} \quad (6)$$

where  $Z_{TL}$  is the transmission line impedance and  $Z_o$  is the reference impedance, typically 50Ω.

$$\text{Solving for impedance, } Z_{TL} = Z_o \frac{1+\Gamma}{1-\Gamma} \quad (7)$$

Putting this all together, the TDR source generates a fast-edge signal, which is split into two equal magnitude signals. One signal is used by the oscilloscope to monitor the reflection signal and the other signal is delivered to the transmission line. The reflected voltage is used to calculate the impedance while the round-trip signal time is used to calculate either the dielectric constant of the transmission line or the length of the transmission line, depending on which of the values is unknown. The dielectric constant can be determined from the signal propagation time and the length can be determined from the signal propagation time and the velocity factor,  $V_f$ .

### Measurement setup

Figure 1 shows a picture of the TDR measurement setup. One TDR splitter port is connected to the oscilloscope. Since many lower bandwidth scopes use BNC connectors an RF adapter might be required. High quality adapters, preferably calibration quality adapters are recommended. The second TDR port is connected to the measurement sample using a high-quality cable, high bandwidth 1-port probe, or connectors as applicable. Figure 2 shows the Picotest demo board used in the measurements in this application note.

The general procedure to make the TDR connections are,

1. Connect the J2151A/J2154A to the port splitter and connect the port splitter to the oscilloscope as shown in Figure 1. Connect a coaxial cable or probe to the TDR port of the splitter.
2. Set the oscilloscope trigger slope to the falling edge and set the trigger close to the left side of the screen.
3. Use a measurement function or place cursors to measure the width of the negative pulse. The functions or methods used for each measurement are discussed in the following sections.

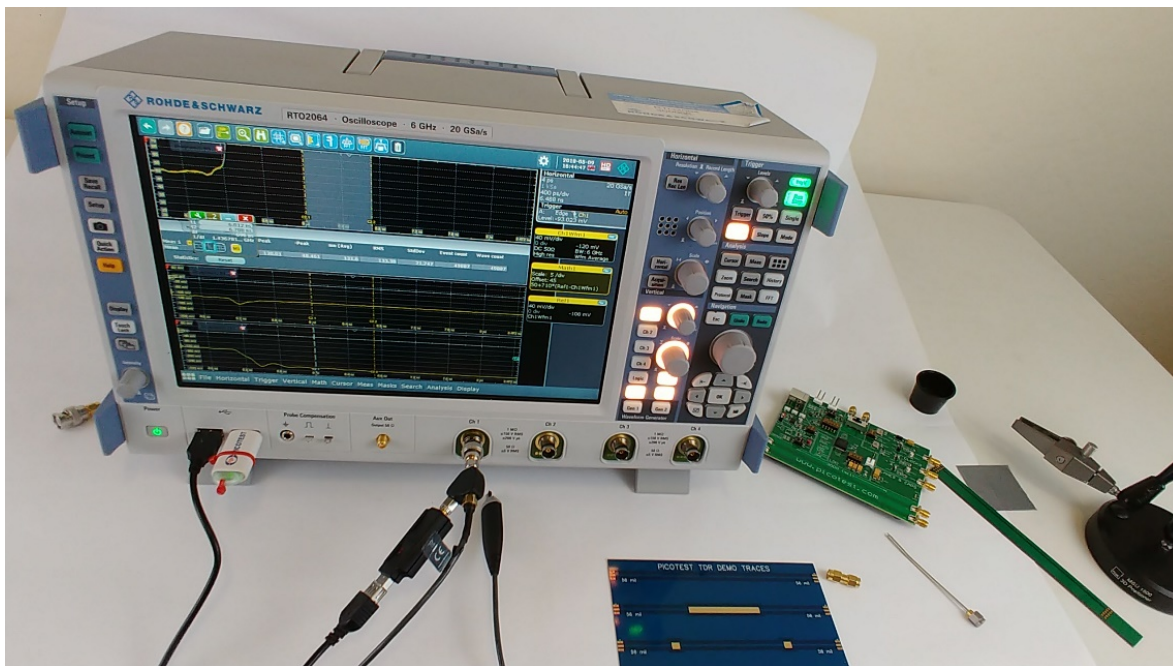


Figure 1: Measurement setup for the TDR measurements in this application note. The setup uses the PerfectPulse® USB connected TDR with a splitter (included) that has one output connected to the DUT and the other connected to the oscilloscope.



Figure 2: Picotest TDR demo board.

## Measuring PCB, cable and interconnect impedance

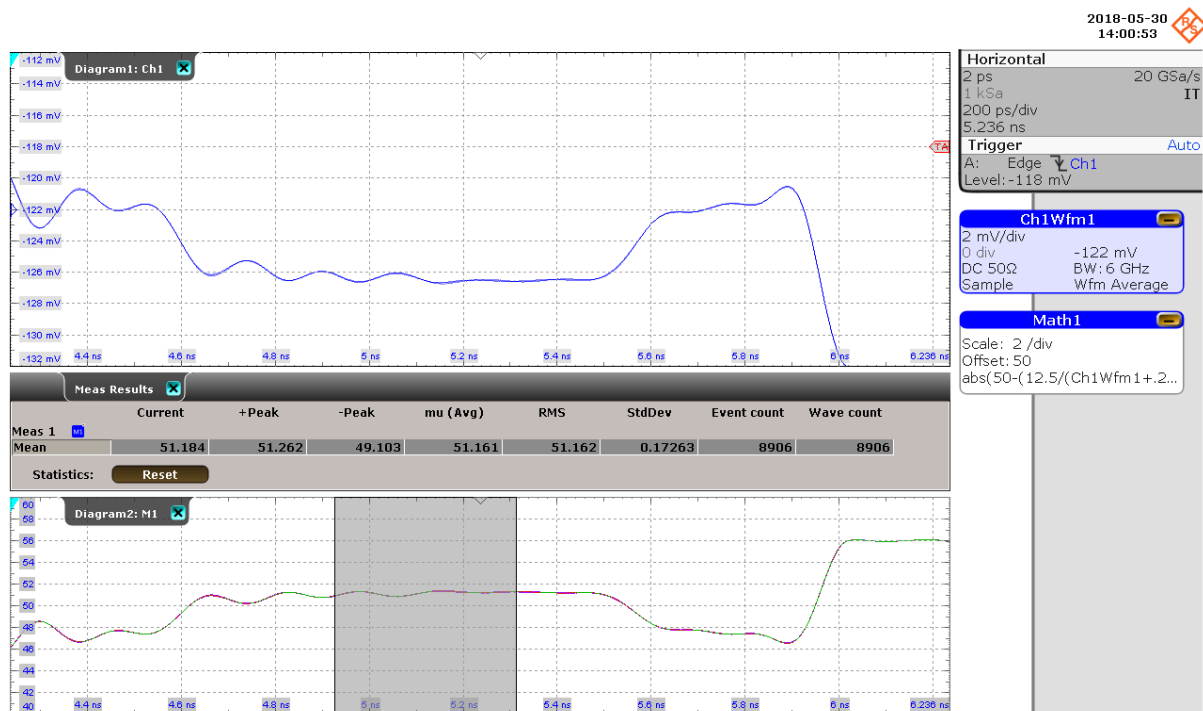
The measured oscilloscope voltage can be converted into impedance by the following equation,

$$R_{DUT} = \frac{2 \cdot R_{GEN} \cdot V_{SCOPE}}{V_{GEN} - 2 \cdot V_{SCOPE}} \quad (8)$$

Where  $R_{DUT}$  is the impedance of the device under test (DUT),  $R_{GEN}$  is the generator output impedance ( $50 \Omega$ ), and  $V_{SCOPE}$  is the voltage received in the oscilloscope ( $-500 \text{ mV}$ ). This can be further reduced as,

$$R_{DUT}(\text{in } \Omega) = \frac{12.5}{V_{SCOPE} + 0.25} - 50 \quad (9)$$

The equation can usually be applied within the oscilloscope, using a math function, to obtain the impedance. The scope values can also be exported to use with a program like Mathcad, Matlab, or Octave to plot the DUT impedance functions using this equation.



**Figure 3:** Measurement of trace 4 from the top in the Picotest TDR demo board shown in Figure 3 shows the step change in impedance from 47 to 52 Ohms. Impedance is plotted using (9).

## Measuring dielectric constant and velocity factor

No calibration is required for the measurement of dielectric constant. This is a time measurement and based on a known value of length, the dielectric constant,  $D_k$ , can be determined from (5). Velocity factor ( $V_f$ ) can be determined from (1) for a known value of length. The measurement setup is shown in Figure 1.

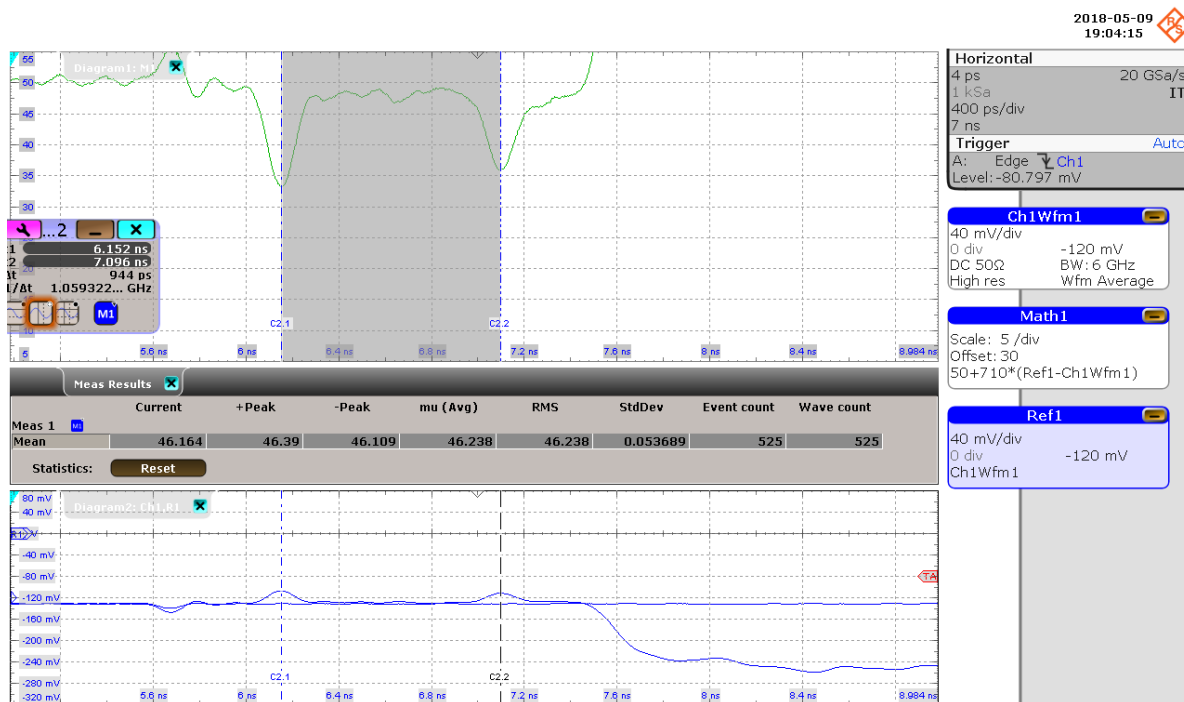
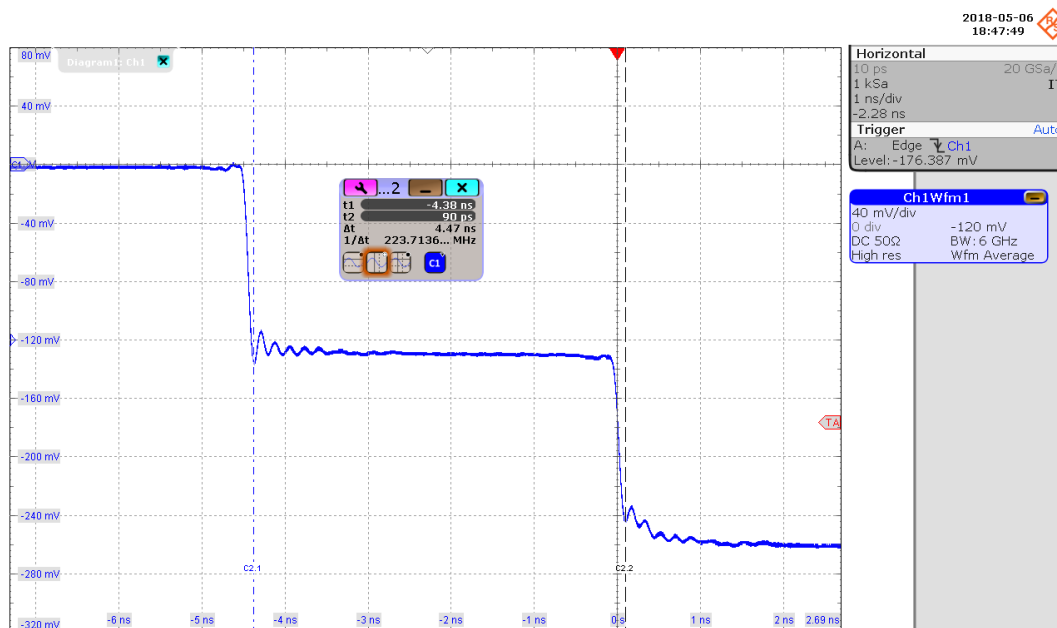


Figure 4: Measurement of 3rd trace from the top in the Picotest TDR demo board shown in Figure 3. Signal travelled 3" forward and 3" backward in 944 ps. So, based on (5),  $D_k = 3.45$ , Based on (1),  $V_f = 53.84\%$ .

## Measuring trace or cable length

It is assumed that the cable velocity factor is known prior to the measurement and most cable manufacturers publish this parameter. If not, a small known piece of the cable can be cut to measure the velocity factor as shown in the previous section. After measuring the round trip time using TDR-oscilloscope combination, we can measure the length using (4) with the known value of  $V_f$ . An example is shown in Figure 5.



**Figure 5:** Measurement of RTK028 cable that has a velocity factor of 70 %. The round trip took 4.47 ns and so the length is calculated based on (4) as 0.47 m. (The actual length of the cable was 0.5 m).

### Tips for Measurement

- Use high quality cables and probes. If RF adapters are required, use calibration quality adapters.
- Measure the flattest portion of the impedance signal. This is typically between 50% and 75% of the trace/cable length.
- Using gated cursors to obtain the mean value in this range.
- Reducing the bandwidth degrades resolution but provides a lower noise result. A standard IPC coupon can generally be measured using a 1GHz-2GHz oscilloscope.

### Conclusion

The Picotest J2151A or J2154A are good choices for low cost TDR/TDT using an existing oscilloscope. They can be used to measure PCB test coupons impedance, to test cables and bad crimps, trace length, Dk, and velocity factor. This application note shows how to use J2151A/J2154A to measure PCB, cable and interconnect impedance, dielectric constants ( $D_k$ ), velocity factor ( $V_f$ ) and length. For additional information and products please visit <https://www.picotest.com/measurements/MeasuringPCB.html>.