A Comparison of Resistive Terminators for High Speed Digital Data Transmission

By Jerry Seams
IRC Advanced Film Division, TT electronics

The time and frequency response of a resistive terminator is a key parameter when selecting the proper termination method for high speed digital signal lines

Multi-gigabit per second data rates are now commonplace in the worlds of telecommunications, computing and data networking. With digital data rates reaching beyond 1-Gbit/s, digital designers are now wrestling with a new list of design problems such as transmission line reflections and signal distortion due to poorly chosen transmission line terminators.

By properly choosing a termination matching the characteristic impedance (Z_0) of the transmission line, the energy in a digital transmission line signal can be absorbed and turned into heat instead of being reflected and interfering with other forward propagating signals. Care must be taken, however, when choosing a resistor for high speed transmission line termination—not just any resistor from the top desk drawer will do. A terminating resistor that matches at low frequencies may not remain a match at high frequencies. Lead and bond wire inductance, parasitic capacitance and skin effect can drastically change the impedance of a terminator at high frequencies. This change in impedance, and the resulting signal distortion, can cause false triggering, stair stepping, ringing, overshoot, delays and loss of noise margin in high speed digital circuits [3].

The rise time of the digital signals required to transmit data at multi-gigabit rates is now under 100 ps. The equivalent sine wave frequency of a digital signal (f_{knee}, the knee frequency) can be approximated by dividing 0.5 by the rise time [1]. The knee frequency is the frequency above which harmonics present in the pulse edge may be ignored. The faster the rise time, the higher the knee frequency and the more important high quality terminators become. Digital drivers and SERDES (serializer/deserializer) chips with sub-100 ps rise times are widely available today. By equation (1), the equivalent sine wave frequency of the rising edges of this data stream is approximately 5 GHz.

$$f_{knee} = \frac{0.5}{t_r} \qquad (1)$$

At gigabit per second data rates, the high frequency characteristics of the terminating resistor or resistor network must be taken into consideration to avoid the glitch-causing effects of signal distortion due to a poorly selected terminator. This paper compares the high speed performance of popular resistor technologies and packages used as high speed terminators.

Background

In the past, digital design ignored the transmission line effects of logic interconnections. Generally, as long as the round trip propagation delay of a signal trace or cable was small as compared to the rise time of the digital signal, the reflections generated on the line were ignored and not terminated [1]. The length of the transmission path was assumed to be infinitely short. No reflections can occur on an infinitely short line since there is no propagation time between a signal and its reflection from the end of the line. A transmission line can be considered to be "short" if its
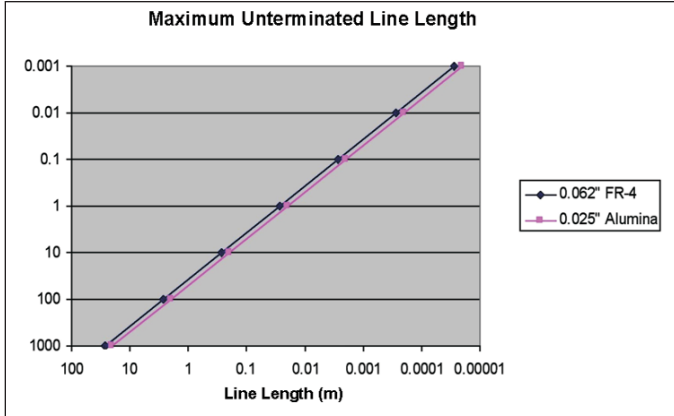
Figure 1 · Maximum physical lengths of unterminated transmission lines.

Figure 2 · Tested terminators. (a) Axial leaded resistor. (b) 0603 chip. (c) QSOP. (d) BGA.

electrical length ($l_{electrical}$) is less than 1/6 of the rise time (T_{rise}) of the digital signal [1, 3]. Thus, the line is short if:

$$l_{electrical} \leq \frac{T_{rise}}{6} \qquad (2)$$

The speed at which signals propagate along a transmission line (v_p) can be calculated by dividing the speed of light (c) by the square root of the effective dielectric constant (ε_{eff}) of the dielectric material used in the transmission line [2]:

$$v_p = \frac{c}{\sqrt{\varepsilon_{eff}}} \qquad (3)$$

Then, to calculate the electrical length of a transmission line ($l_{electrical}$), divide the physical length of the transmission line ($l_{physical}$) by the propagation velocity (v_p):

$$l_{electrical} = \frac{l_{physical}}{v_p} \qquad (4)$$

Example:
Consider a 10 cm long transmission line using microstrip construction on 0.062" thick FR-4 board material. The 0.062" thick, FR-4, 50-ohm microstrip has an effective dielectric constant (ε_{eff}) of about 3.4. Calculating the propagation velocity (v_p) from equation (3):

$$v_p = \frac{3 \times 10^8 \text{ m/s}}{\sqrt{3.4}} = 163 \times 10^6 \text{ m/s} \qquad (5)$$

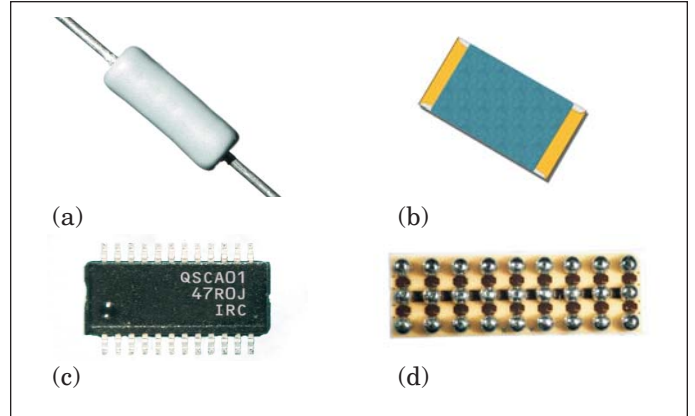The electrical length ($l_{electrical}$) of this line is then cal-

culated from equation (4):

$$l_{electrical} = \frac{0.1 \text{ m}}{163 \times 10^6 \text{ m/s}} = 613 \text{ ps} \qquad (6)$$

in electrical length.
In the case of a digital signal with a 100 ps rise time (T_{rise}), equation (2) yields:

$$l_{electrical} = \frac{l_{physical}}{v_p} \qquad (7)$$

Since the electrical length of the line, ($l_{electrical}$) is greater than 1/6 of the rise time of the signal, the line should be terminated. Using the 1/6 rise time rule, Figure 1 shows the maximum length microstrip transmission line that could remain unterminated for both FR-4 and high purity alumina substrates.

Back in the days of 10 ns rise times, digital designers could generally ignore reflections on transmission lines of up to 0.25 meters in physical length. Today's 100 ps rise times require more circuit board traces to be considered for reflections according to the above rule of thumb. Using 1/6 of the electrical length of a 100 ps rise time requires that lines physically longer than about 3 mm be terminated in order to prevent reflections from inducing signal integrity problems [2]. Nearly all circuit board traces are treated as terminated transmission lines in high speed design today.

Selection and Testing of Resistive Terminators
The selection of resistive terminations is crucial to the signal integrity of high speed digital design. A resistive terminator is, often erroneously, considered to be a lumped element with no reactive properties. But in real
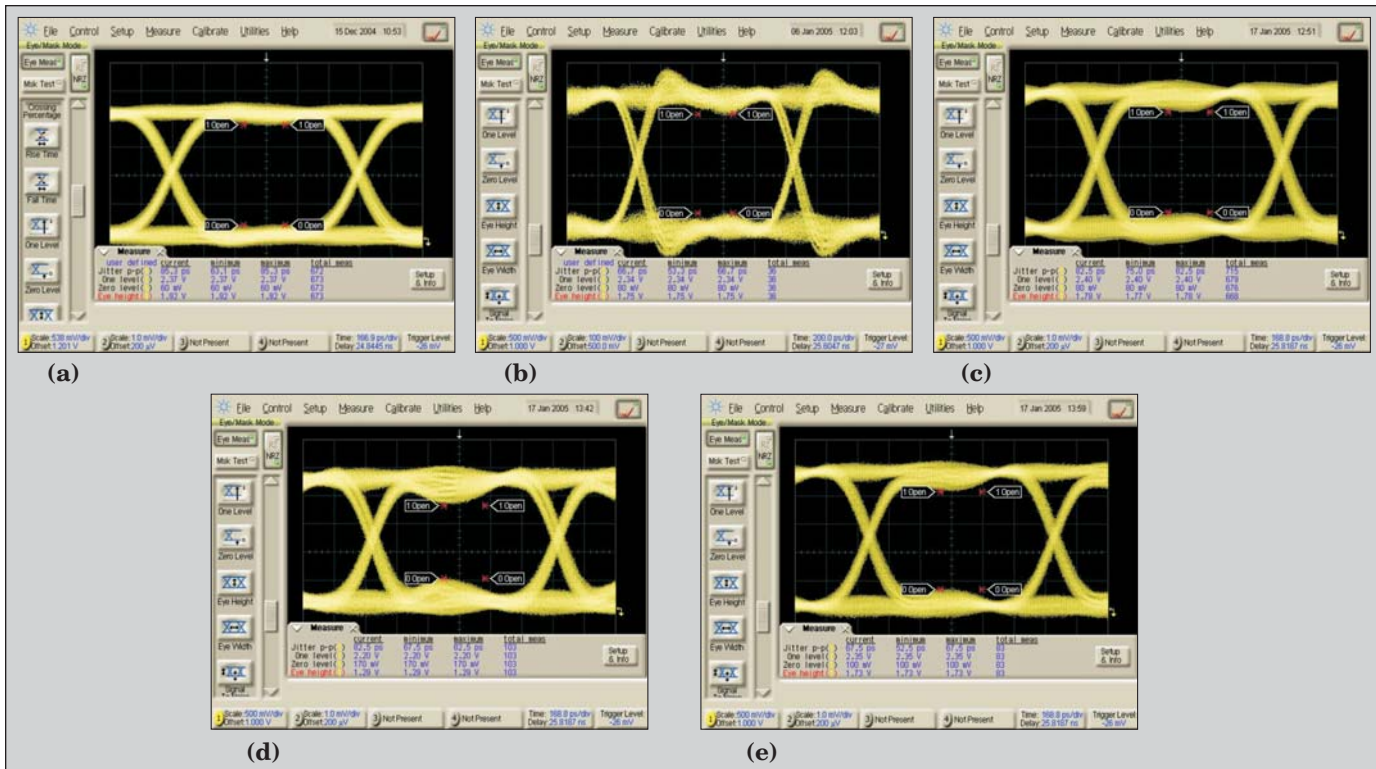
Figure 3 · 1 Gbit/s eye diagram displays of signals terminated by: (a) reference resistor; (b) axial leaded RN55; (c) 0603 chip; (d) QSOP; (e) BGA.

designs, parasitic capacitance and inductance existing in terminators can kill an otherwise well thought out high speed design.

This note compares the performance of four different types of thin film resistors in high speed digital terminator applications: an axial leaded RN55 size discrete, an 0603 size discrete chip, a QSOP array, and a BGA array. Data is presented in the time domain since this is the preferred domain for most high speed digital design efforts [4]. All resistors are 50 ohms at DC nominal except for the QSOP array which is 47 ohms DC nominal resistance.

The axial discrete is an IRC model BR5, the 0603 chip is IRC model PFC-W0603HF, the QSOP is IRC model GUS-QSCA, and the BGA is IRC model CHC-CC0910B. The devices tested are shown in Figure 2 using an Agilent Infiniium DCA 86100A oscilloscope with 54754A plug-in and Agilent 54701A 2.5 GHz probes in conjunction with a Tektronix DG2040 differential data generator at 1 Gbit/s. Eye diagrams for each of the DUTs are shown in Figure 3. In addition, a thin film microwave calibration reference resistor was measured for comparison to the DUTs.

Eye diagrams at a signaling rate of 1 Gbit/s for the reference resistor and DUTs are shown in Figures 3a through 3e. A summary of the eye diagram measurements is shown in Figure 4. The BGA array shows the best performance—nearly as good as the reference in terms of eye

Device	Eye Closure (%)	Overshoot (%)
Reference	16	7
Axial Discrete	23	24
0603 Chip Discrete	23	9
QSOP Array	36	10
BGA Array	20	4

Figure 4 · Eye diagram measurement summary.

closure and slightly better than the reference in terms of overshoot. The axial discrete and the QSOP array show the worst performance with eye closure of 23% and 36% respectively and overshoot of 24% and 10% respectively.

The impedance response of the reference resistor and each of the DUTs to a 100 ps rise time pulse are shown in Figures 5a through 5e using an Agilent Technologies 8753 vector network analyzer swept to 6 GHz and then converting to time domain using Agilent Advanced Design System Software (ADS).

Again, the BGA is the best performer with only 2 ohms change in impedance due to the 100 ps rising edge and is nearly as good as the reference resistor. The axial leaded resistor is the worst performer, changing from 50 ohms to 135 ohms in impedance due to the 100 ps rise time pulse.
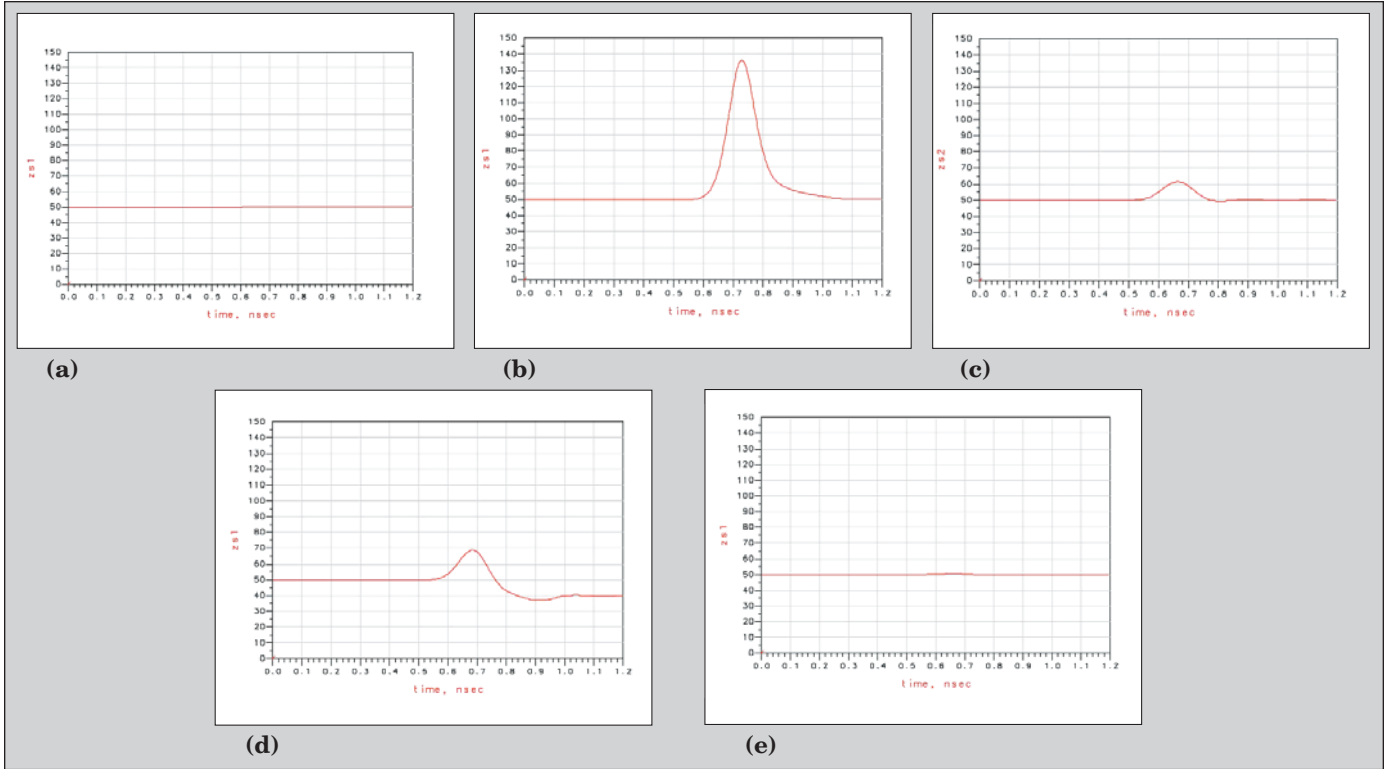
Figure 5 · Impedance reponses of: (a) reference resistor; (b) axial leaded RN55; (c) 0603 chip; (d) QSOP; (e) BGA.

Using equation (8) the amount of reflection (Γ) present at the terminator due to impedance mismatch with the transmission line at the pulse edge can be found:

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} \qquad (8)$$

where Z = the maximum impedance of the DUT and Z_0 = the characteristic impedance of the transmission line. Figure 6 shows the impedance summary for the reference resistor and the 4 DUTs. The summary shows that the axial discrete terminator reflects 46% of the signal back to the source during the pulse edge while the BGA reflects less than 2% of the signal back to the source. The larger the reflected energy, the more likely that the forward travelling wave will be distorted by the relection.

Conclusions and Recommendations

A well matched termination resistor at all frequencies below the knee frequency (f_{knee}) is essential for the prevention and suppression of bit error inducing signal distortion in high speed digital circuits. While it may be tempting to assume that resistive terminators are ideal lumped elements—they are not. They possess inductances and capacitances which are an unintended but

Device	Max. Impedance Change (ohms)	Reflection (%)
Reference	1	1
Axial Discrete	85	46
0603 Chip Discrete	11	10
QSOP Array	19	16
BGA Array	2	2

Figure 6 · Time Domain Impedance Summary.

present reality at high frequencies and fast rise times.

In the high frequency lumped element models for the PFC-W0603HF-xx-50R0-x and the CHC-CC0910B-xx-50R0-x, shown in Figure 7, the reactive properties of the terminators are evident in the small, but still present parasitic capacitances and inductances in the components. Both models are valid for rise times to 100 ps.

Eye diagram and impedance profile time domain data provide a good comparison of the performance of four types of resistive terminators commonly used to terminate transmission lines. A high frequency resistive reference provides a bench mark against which the four different terminators may be compared. In terms of the maintenance of signal integrity as defined by eye closure, overshoot, impedance change and percent reflection the
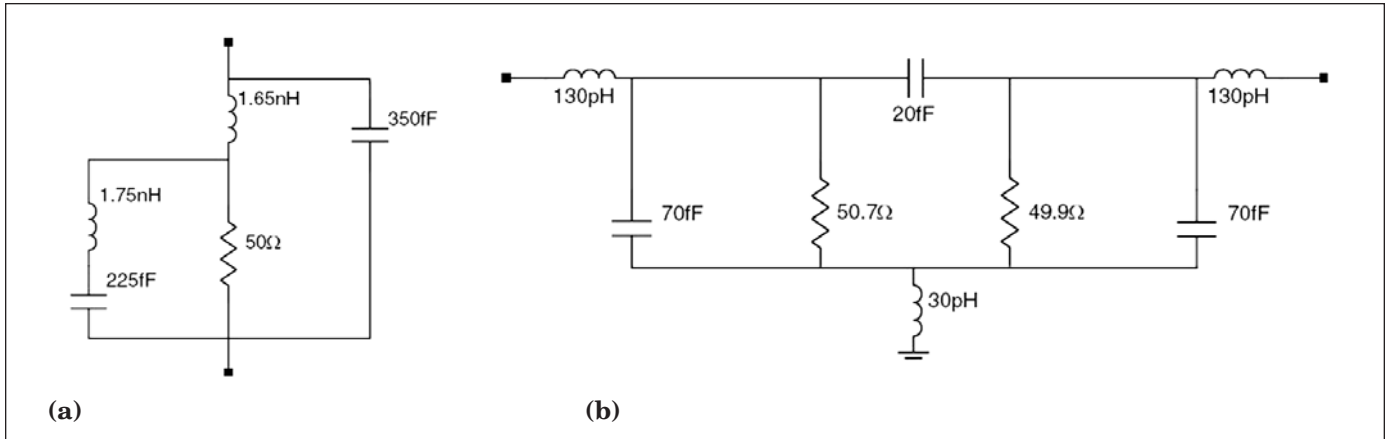
Figure 7 · Lumped element models: (a) PFC-W0603HF-xx-50R0-x; (b) CHC-CC0910B-xx-50R0-x.

terminators are ranked from best to worst as follows:

1. BGA packaged array
2. 0603 Chip
3. Wire bonded QSOP array
4. Axial leaded discrete

Intuitively, this makes sense. The axial discrete and the QSOP both possess unwanted inductance due to leads and bond wires which do not exist in the chip or the BGA. Both unwanted capacitance and unwanted inductance are minimized in the BGA with its downward facing "flip chip" configuration and short conductor to resistor traces. This results in performance nearly as good as the high frequency reference resistor.

Notes

1. The effective dielectric constant applies to quasi-TEM mode transmission lines such as microstrip. The effective dielectric constant of a quasi-TEM mode line can be determined by formulae from electromagnetic texts or from software calculators such as Agilent Technologies' AppCad. In true TEM mode transmission lines such as coaxial cables the effective dielectric constant equals the relative dielectric constant [2].

2. Assumes microstrip design on FR-4 dielectric, ε_r = 4.6 and Z_0 = 50 ohms, resulting in a velocity of propagation of 165 m/s.

References

1. H. Johnson and M. Graham, *High-Speed Digital Design,* Upper Saddle River, NJ: Prentice Hall, pp. 2, 166-167.

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Author Information

Jerry Seams is the Manager of New Business Development for the IRC Advanced Film Division of TT electronics, Corpus Christi, Texas. His current duties include new product development, technical marketing and worldwide responsibility for thin film product training and technical customer support. Prior to his current position, Jerry worked as Applications Manager, Process Engineering Manager, and Applications Engineer as well as Electronic Systems Designer for TRW, Inc. He received his Bachelor of Science degree from Texas Tech University, Lubbock, Texas and his Master of Science in Electrical Engineering from Texas A&M University, Kingsville, Texas.