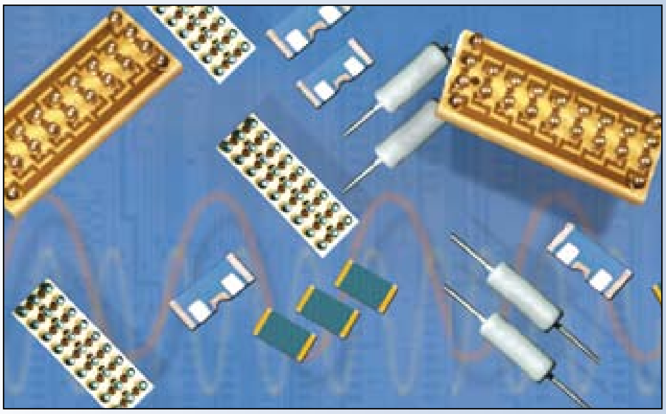
Fixed Resistors

DIGITAL DATA TERMINATIONS

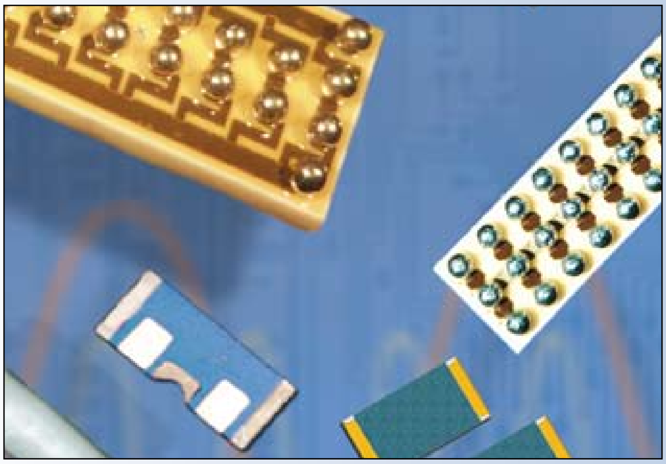
A Comparison of Resistive Terminations for High Speed Digital Data - Application Note



Introduction

Multi-gigabit per second data rates are now commonplace in the worlds of telecommunications, computing and data networking. As digital data rates move beyond 1-Gbit/s, digital designers wrestle with a new list of design problems such as transmission line reflections and signal distortion due to poorly selected transmission line terminators. By properly choosing a termination matching the characteristic impedance (Zo) of the transmission line, the energy in a digital transmission line signal can be turned into heat before it reflects and interferes 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 Zo 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 selected type of termination is crucial to the signal integrity of high speed digital design.

In ideal designs, parasitic capacitance and inductance can kill an otherwise well thought-out high speed design.

The rise time of the digital signals required to transmit data at multi-gigabit rates is now under 100ps. 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 can 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-100ps 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!

$$f_{knee} = \frac{0.5}{t_r} \tag{1}$$

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

$$l_{electrical} < \frac{T_{rise}}{6} \tag{2}$$

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[1] (ε_{eff}) of the dielectric material used in the transmission line [2]:

$$v_p = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{3}$$

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):

$$l_{electrical} = \frac{l_{physical}}{v_p} \tag{4}$$

Example:
Consider a 10cm long transmission line using microstrip construction on 0.062" thick FR-4 board material. 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).

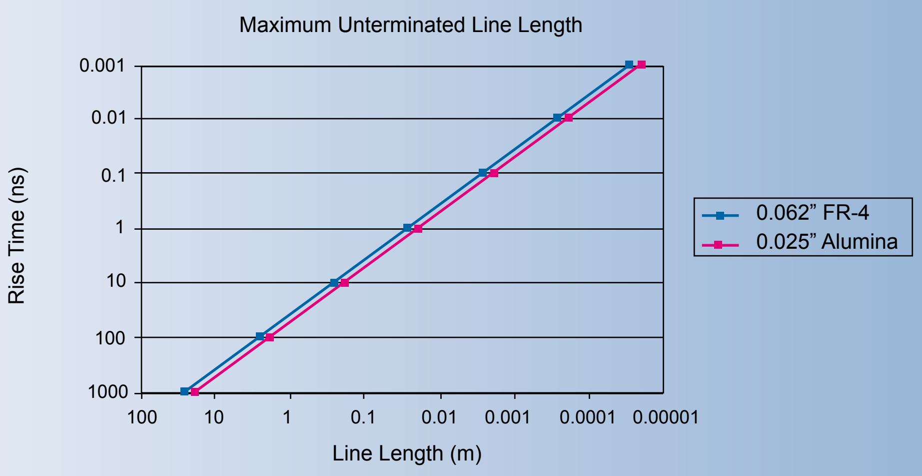


Fig. 1. Maximum physical lengths of unterminated transmission lines

from equation (3): $v_p = \frac{3x10^8 m/s}{\sqrt{3.4}} = 163x10^6 m/s$

The electrical length ($l_{electrical}$) of this line is then calculated from equation (4):

$l_{electrical} = \frac{0.1m}{163x10^6 m/s} = 613 ps$ in electrical length.

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

$$613\text{ps} > \frac{100\text{ps}}{6}$$

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, Fig. 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. 100*ps* rise times require more circuit board traces to be considered for reflections according to the above rule of thumb. 1/6 of the electrical length of a 100*ps* rise time requires that lines physically longer than about 3mm 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 eroneously, considered to be a lumped element with no reactive properties. But in real 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 Fig. 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 Fig. 3. In addition, a thin film microwave calibration reference resistor was measured for comparison to the DUTs. Eye diagrams at a signaling rate of 1Gbit/s for the reference resistor and DUTs are shown in Fig. 3a through 3e.

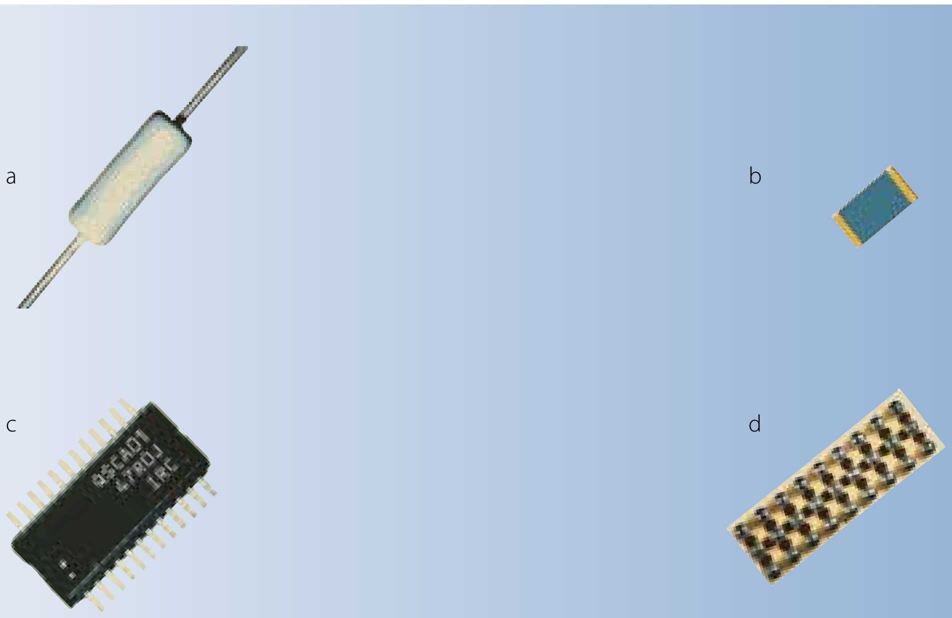


Fig.2. Tested terminators. (a) Axial leaded resistor. (b) 0603 chip. (c) QSOP. (d) BGA.

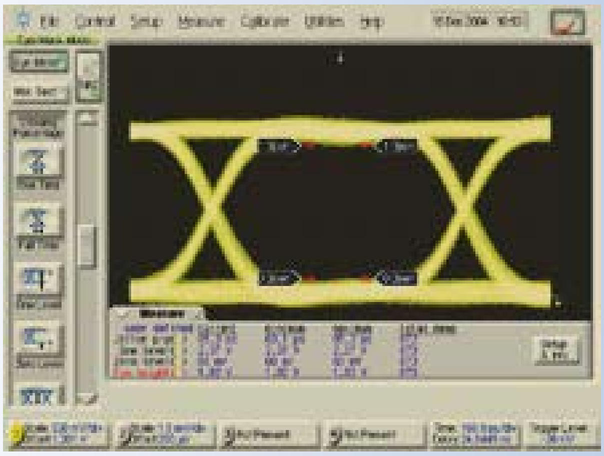


Fig. 3a. Reference resistor.

Fig. 3b. Axial leaded RN55.

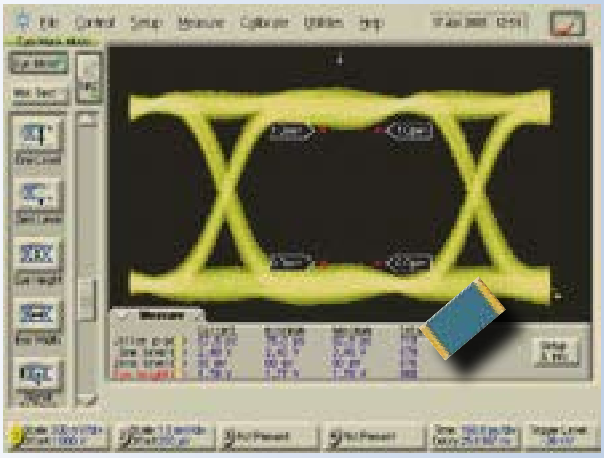


Fig. 3c. 0603 chip.

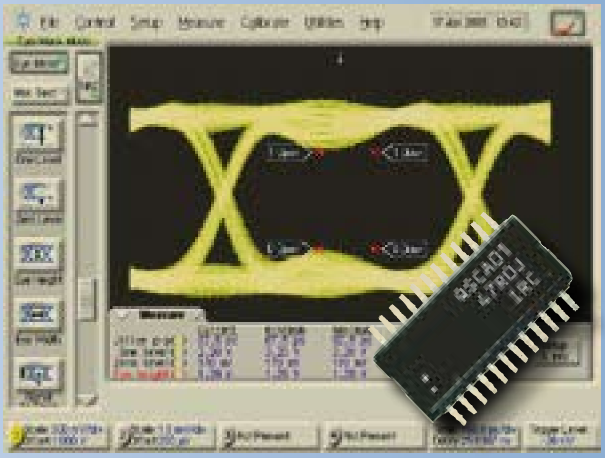


Fig. 3d. QSOP.

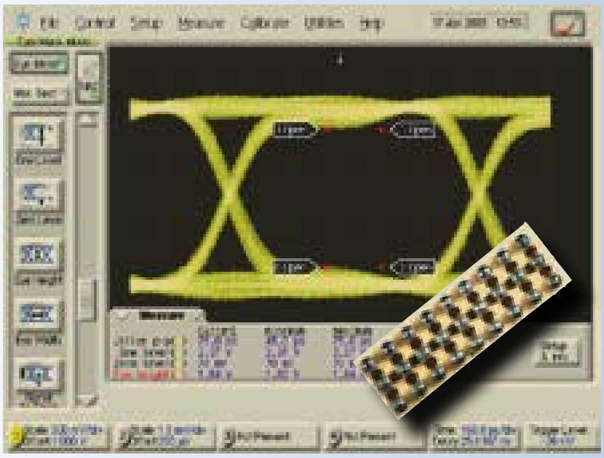


Fig. 3e. BGA.

A summary of the eye diagram measurements is shown in Fig. 5. The BGA array shows the best performance – nearly as good as the reference in terms of eye 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% and36% respectively and overshoot of 24% and 10% respectively.

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

Fig. 5. Eye diagram measurement summary.

The impedance response of the reference resistor and each of the DUTs to a 100ps rise time pulse are shown in Figs. 7a through 7e 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 packaged array is the best performer with only 2 ohms change in impedance due to the 100ps 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 100ps rise time pulse. Using equation (5) the amount of reflection (Γ) present at the terminator due to impedance mismatch with the transmission line at the pulse edge can be found:

$$\Gamma = \frac{Z - Zo}{Z + Zo} \tag{5}$$

where Z = the maximum impedance of the DUT and Zo = the characteristic impedance of the transmission line. Fig. 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 reflection.

Device	Maximum Impedence Change (Ω)	Reflection (%)
Reference	1	1
Axial Discrete	85	46
0603 Chip Discrete	11	10
QSOP Array	19	16
BGA Array	2	2

Fig. 6. Time Domain Impedance Summary.

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 present reality at high frequencies and fast rise times. In the high frequency lumped element models for the CHC-CC0910B-xx-50R0-x and the PFC-W0603HF-xx-50R0-x, shown in Fig. 4, 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 100ps.

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

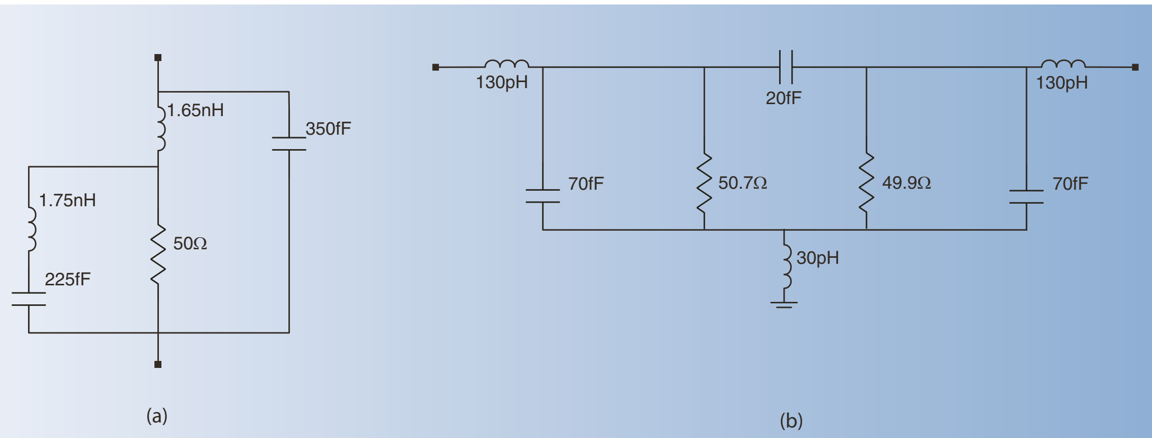


Fig. 4. Lumped Element Models. (a) PFC-W0603HF-xx-50R0-x. (b) CHC-CC0910B-xx-50R0-x.

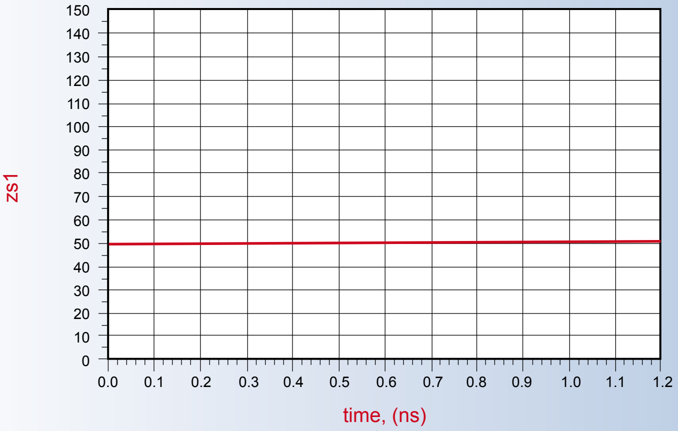


Fig. 7a. Reference resistor.

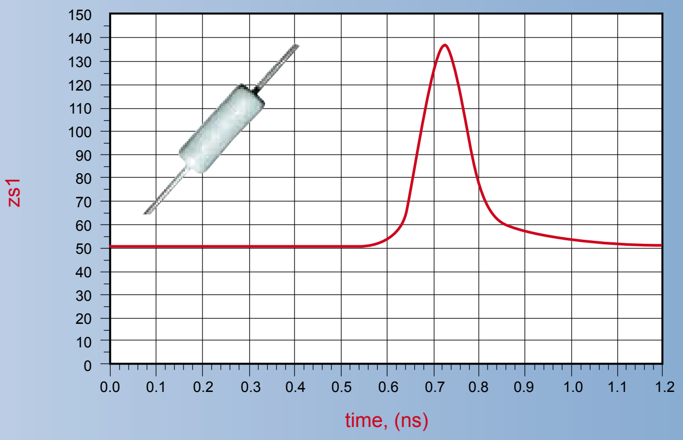


Fig. 7b. Axial-leaded RN55.

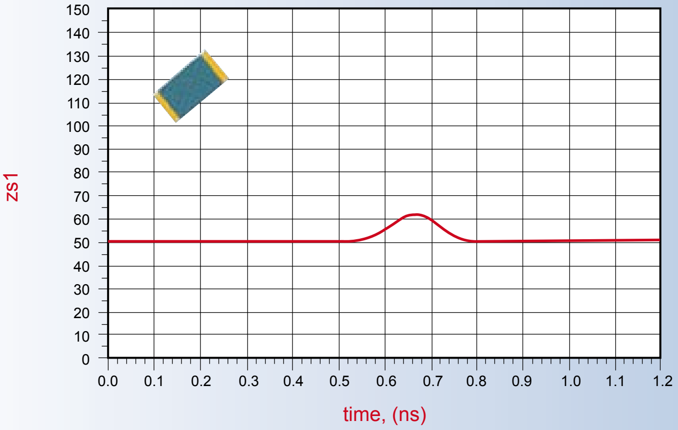


Fig. 7c. PFC 0603 chip.

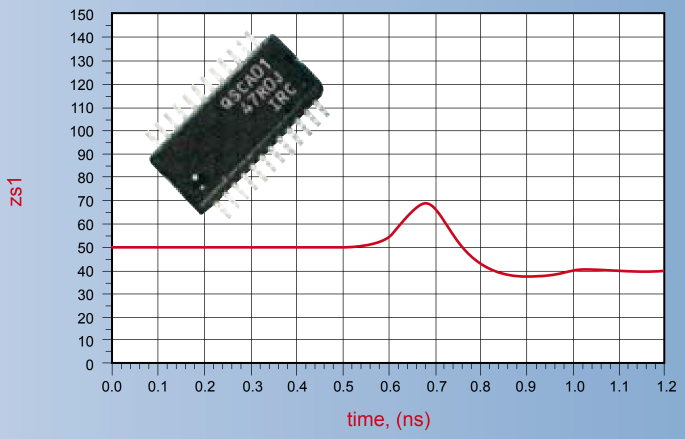


Fig. 7d. QSOP.

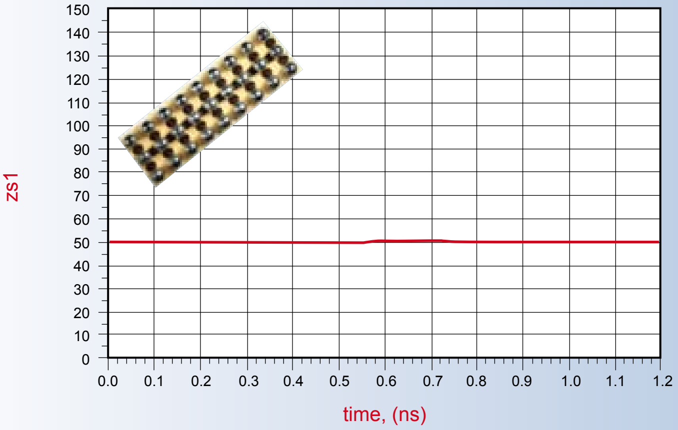


Fig. 7e. BGA.

maintenance of signal integrity as defined by eye closure, overshoot, impedance change and % reflection, the 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, $\varepsilon r=4.6$ and $Zo=50$ ohms, resulting in a velocity of propagation of 165m/s.

REFERENCES

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

[2] K. Demarest, Engineering Electromagnetics. Upper Saddle River, NJ: Prentice Hall, pp.350,645,648.

[3] Caldwell B. and Getty D., "Coping with SCSI at Gigahertz Speeds," EDN, July 6, 2000, pp.94,96.

[4] Moretti, G., "Tight Squeeze: RF Design," EDN, November 27, 2003.

DIGITAL DATA TERMINATIONS - Application Note

PN	Resistor Network	Circuit	Package Style	size (mm)	Tolerance +/-%	RoHS	Film Technology	Comments
CHC-CD0910	Yes	Isolated, Bussed	BGA	9.0 x 4.0	1	Yes	Thin film	Ball matrix 9x4 with 1mm pitch
http://www.irctt.com/file.aspx?product_id=89&file_type=datasheet								
CHC-CC0910	Yes	Isolated, Bussed	BGA	9.0 x 3.0	1	Yes	Thin film	Ball matrix 9x3 with 1mm pitch
http://www.irctt.com/file.aspx?product_id=89&file_type=datasheet								
CHC-CD1065	Yes	Isolated, Bussed	BGA	6.4 x 2.5	1	Yes	Thin film	Ball matrix 10x4 with 0.65mm pitch
http://www.irctt.com/file.aspx?product_id=89&file_type=datasheet								
CHC-CD0865	Yes	Isolated, Bussed	BGA	5.1 x 2.5	1	Yes	Thin film	Ball matrix 8x4 with 0.65mm pitch
http://www.irctt.com/file.aspx?product_id=89&file_type=datasheet								
CHC-CB0565	Yes	Isolated, Bussed	BGA	3.2 x 1.2	1	Yes	Thin film	Ball matrix 5x2 with 0.65mm pitch
http://www.irctt.com/file.aspx?product_id=89&file_type=datasheet								
CHC-CC0910L	Yes	Thevenin	BGA	9.0 x 3.0	1	Yes	Thin film	Ball matrix 9x3 with 1mm pitch
http://www.irctt.com/file.aspx?product_id=91&file_type=datasheet								
CHC-CD0927k	Yes	SCSI	BGA	11.4 x 5.1	1	Yes	Thin film	Ball matrix 9x4 with 1.27mm pitch
http://www.irctt.com/file.aspx?product_id=90&file_type=datasheet								
BB1020DT	Yes	SCSI	BGA	11.4 x 5.1	1	No	Thick film	Ball matrix 9x4 with 1.27mm pitch
http://www.bitechnologies.com/pdfs/bga.pdf								
BB1110TB	Yes	Bussed	BGA	9.0 x 3.0	1	No	Thick film	Ball matrix 9x3 with 1mm pitch
http://www.bitechnologies.com/pdfs/bb1110b.pdf								
BB1110B	Yes	Bussed	BGA	9.0 x 3.0	1	No	Thick film	Ball matrix 9x3 with 1mm pitch
http://www.bitechnologies.com/pdfs/bb1110b.pdf								
BB2110DI	Yes	Isolated	BGA	9.0 x 4.0	1	No	Thick film	Ball matrix 9x4 with 1mm pitch
http://www.bitechnologies.com/pdfs/bb1110b.pdf								
PFC-W0402HF	No	Resistor	Chip	1.0 x 0.5	1	Yes	Thin film	6GHZ, mil screening available
http://www.irctt.com/file.aspx?product_id=93&file_type=datasheet								
PFC-W0603HF	No	Resistor	Chip	1.6 x 0.8	1	Yes	Thin film	6GHZ, mil screening available
http://www.irctt.com/file.aspx?product_id=93&file_type=datasheet								
PFC-W0805HF	No	Resistor	Chip	2.1 x 1.3	1	Yes	Thin film	6GHZ, mil screening available
http://www.irctt.com/file.aspx?product_id=93&file_type=datasheet								
PFC-W1206HF	No	Resistor	Chip	3.2 x 1.6	1	Yes	Thin film	6GHZ, mil screening available
http://www.irctt.com/file.aspx?product_id=93&file_type=datasheet								
MWR-MWC01	No	Resistor	Ribbon bond, Flip chip	0.6x0.8	1	Yes	Thin film	40GHZ
http://www.irctt.com/file.aspx?product_id=92&file_type=datasheet								

TT electronics: leading in fixed resistor technology.