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Balanced Probe Extends High-Frequency Measurements

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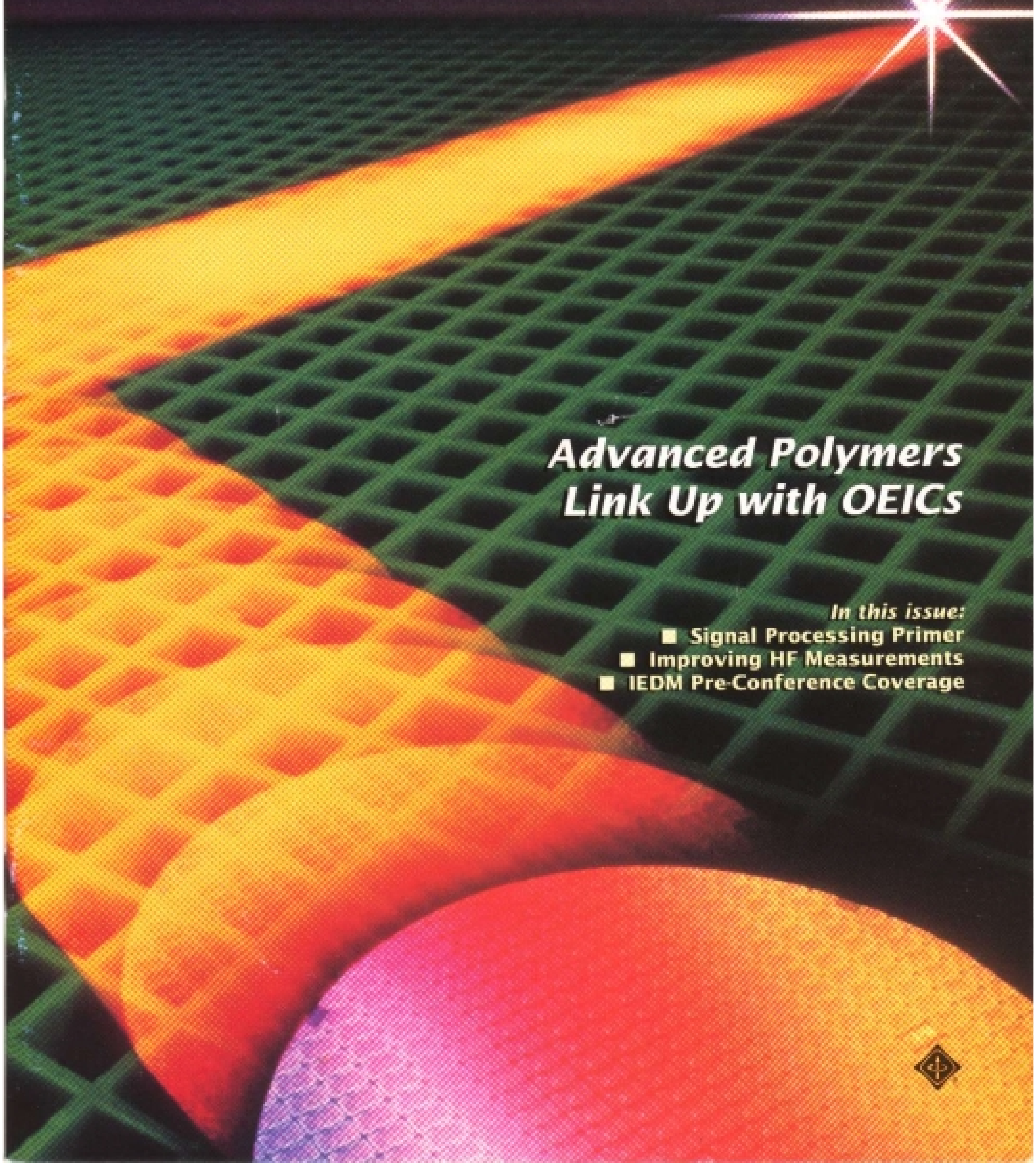

Advanced Polymers Link Up with OEICs

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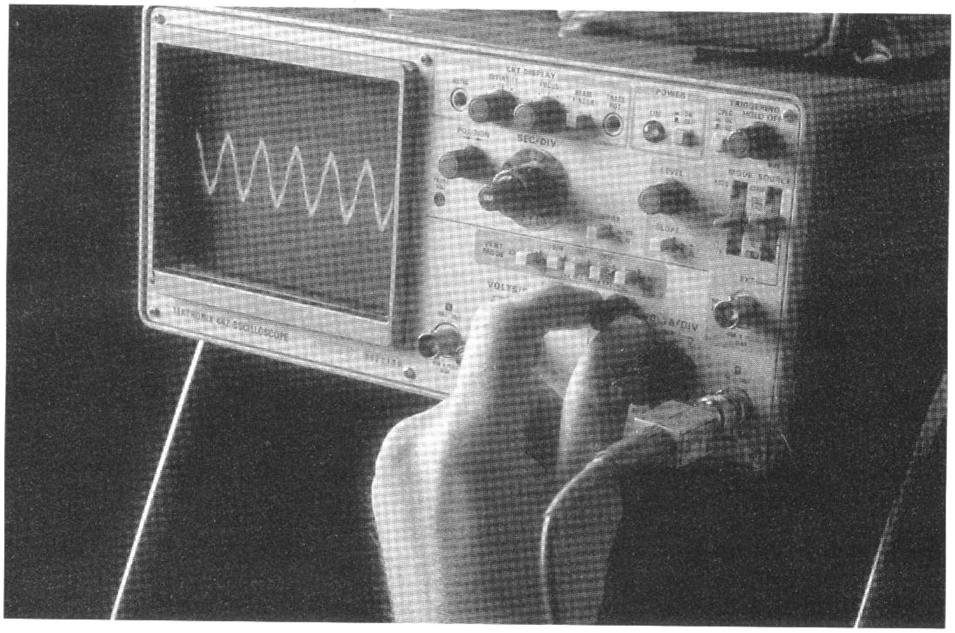

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Coaxial type for 1-500 MHz overcomes the limitations of conventional probes, active and passive

Douglas C. Smith

Making accurate signal and noise measurements at ever higher frequencies becomes more critical for today's complex devices and systems. Many of the standard approaches to making high frequency measurements in design verification, debugging, and the manufacturing of integrated circuits can yield surprisingly large errors that lead to incorrect decisions about the design. This article addresses some of the errors associated with traditional oscilloscope measurements using conventional probes, and offers an improved method of making measurements on electronic circuits of all kinds.

Overview

The conventional 10X high-impedance passive probe and oscilloscope arrangement for performing signal and noise voltage meas-

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Table 1
Inductive voltage drop

Risetime	Induced Voltage
1 ns	1200 mv
2 ns	600 mv
3 ns	400 mv
4 ns	300 mv
5 ns	240 mv
6 ns	200 mv
10 ns	120 mv

urements is inexpensive, rugged, readily available, and works well in many measurement settings. However, today's high speed electronic circuits have strained the capabilities of the traditional setup. Above 50 MHz, the 10X probe can severely distort the waveform. It can also significantly affect the response of the measuring equipment. Thus, when the signal contains frequency components above 50 MHz, an alternative measurement technique is required to ensure accurate results.

Measurement Pitfalls

The main causes of high frequency measurement errors with a 10X passive probe are related to its input impedance and the typical use of a ground lead. Such probes typically have an input impedance of 10 megohms in parallel with 10 pF. At 100 MHz, 10 pF of capacitance has a reactance of only 160 ohms! This presents significant loading on most circuits. If the input impedance (of a "high" impedance probe) is relatively low, and the ground lead has significant reactance, there will be serious measurement problems.

Figure 1 shows the calculated input impedance of a 10X high impedance passive probe with a 15 cm ground lead, a typical length supplied with such probes [1]. This arrangement exhibits a classic series resonance consisting of the probe's input capacitance and the inductance of its ground lead. Such a configuration acts like a notch filter, and connecting the probe to a malfunctioning circuit will oftentimes bring it into normal operation. This result is the inverse of what might be expected. One explanation is that the "notch filter effect" of the probe filters out any offending noise.

Other pigtail effects involve the ground lead of the probe, which can be a source of error from induced voltages. Any voltage that appears across the ground lead from the L·di/dt drop is in series with the desired signal and is often indistinguishable from it, especially if the expected waveshape is not known beforehand. Such an induced voltage is generated by current flowing between the equipment under test and the scope, through the ground lead and probe cable shield. There are many sources of such currents at high frequency, including ground noise from logic circuits, and field induced currents from usually unnoticed electrostatic discharge (ESD) events in the same room.

It does not take much ground-lead current to develop a significant induced voltage. Table 1 shows the voltage developed across 15 cm of 24 gauge wire in free space, for a 10 mA change in current as a function of time [2]. Various logic-gate families can source more than 10 mA in less than 1 ns, so the numbers shown in the table are conservative. Even the output of an HC gate can cause 2 or 3 volts of inductive drop across a 15 cm ground lead! ESD events in the room can induce tens of volts or more on a probe ground lead from several feet away.

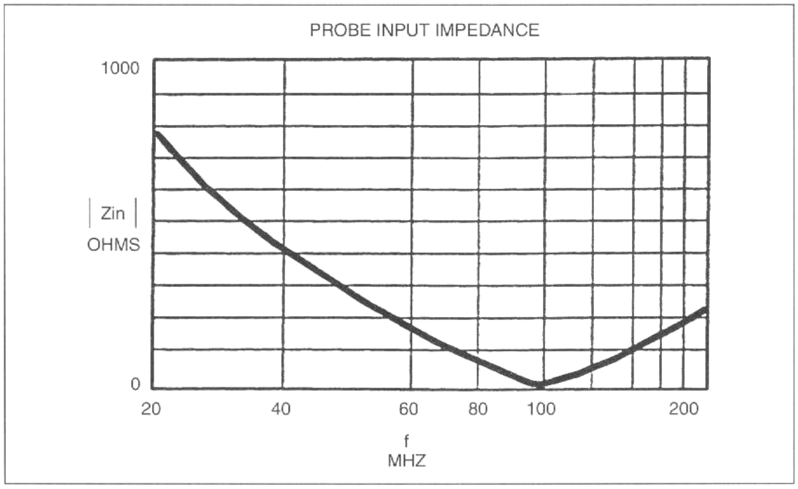
10X Probe Measurements

Figures 2a-c show oscilloscope traces for the output of an HC240 gate (octal inverting buffer) measured in three ways. First, the waveform in Fig. 2a was obtained by connecting a coaxial cable to the 50 ohm input of a scope. 50 ohms is a heavy load for the HC240 buffer, and this causes the signal to have an output amplitude of about 4 volts peak-to-peak. A one volt per division scale is used in Fig. 2a to make the waveform large enough to see the detail near the rising and falling edges.

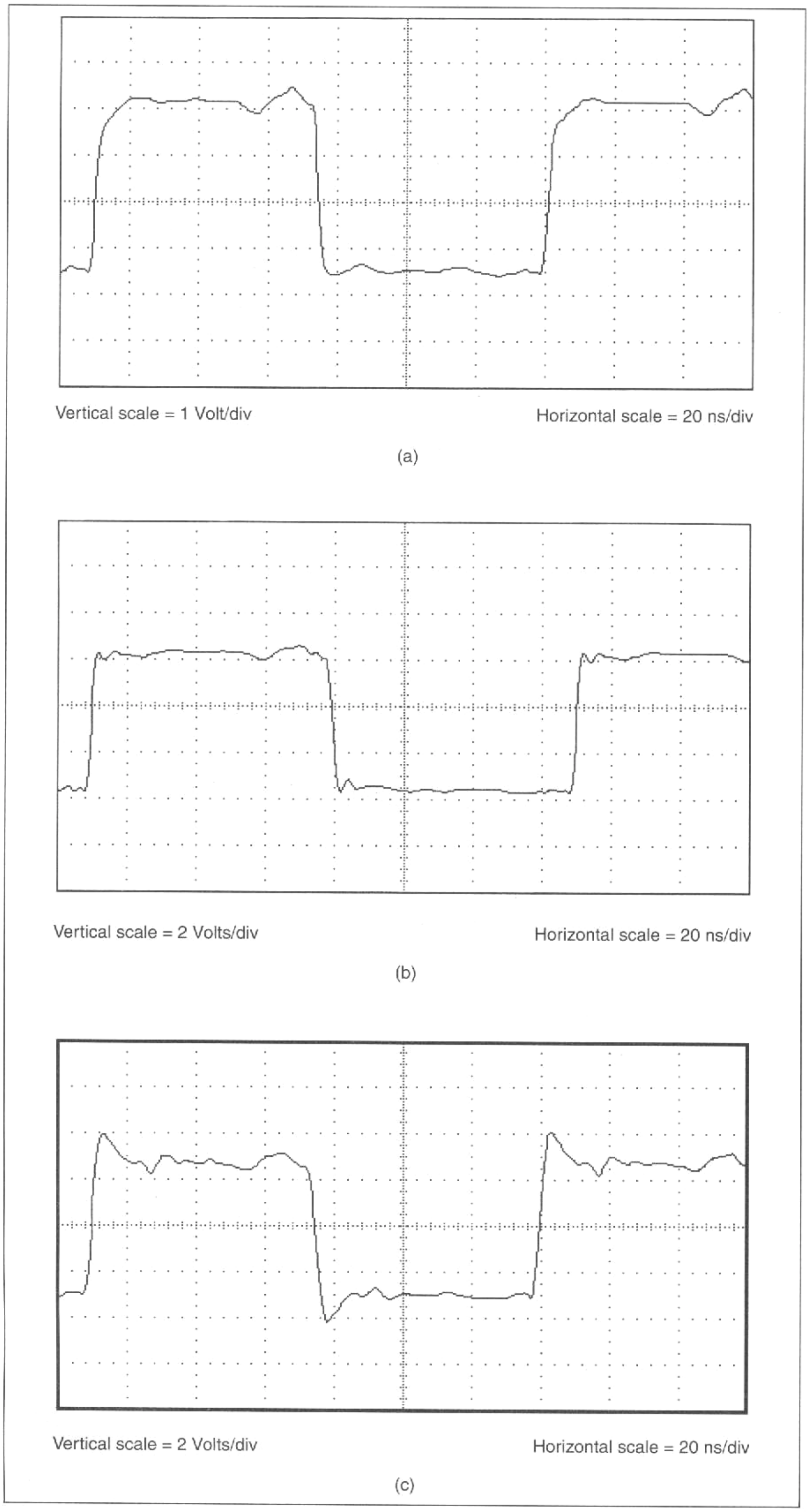
The bumps in the waveform are generated by parasitics in the HC240 and its circuit board, such as ground bounce. Since the 50 ohm cable is terminated with its characteristic impedance, it does not contribute to the bumps in the waveshape of Fig. 2a. Due to heavy loading by the 50 ohm termination, this is not a practical method of measuring most signals.

Figure 2b shows the output of the buffer when loaded with 1500 ohms by a method which will be described shortly. A 2 volt per division scale is used to scale the size of the waveform similar to that in Fig. 2a for comparing the features of the waveform. In this figure, the amplitude is slightly more than 5.5 volts because the buffer is being powered from 4 AA cells through a series diode. The risetime is sharper because the load is more reasonable, and there is no overshoot. The bumps in the waveform, as with the 50 ohm measurement, are due to parasitics in the HC240 and its circuit.

Figure 2c shows the output of the HC240 as measured with a common 10X high impedance passive probe with a 15 cm ground lead. Note the significant overshoot on the waveform, which is not present in Figs. 2a or 2b. For a noise measurement waveform, one would not usually be aware of such a significant error in the peak-to-peak measured voltage since the shape of the wave-



1. 10X high-Z passive probe input impedance.



2. (a) HC240 output into 50 ohms; (b) HC240 output into 1500 ohms; (c) HC240 output as viewed by 10X high Z passive probe.

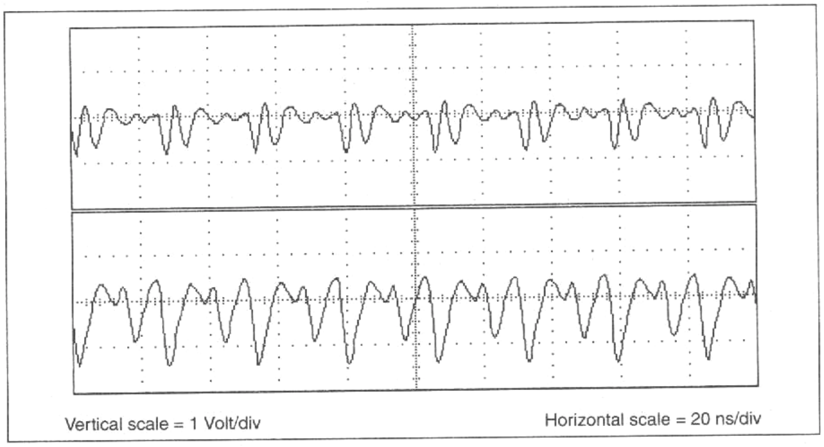
form is not known beforehand. In this case, the peak-to-peak voltage measured is about 45 percent too high (compare Figs. 2b and 2c). This overshoot, caused by a capacitive input impedance and lead inductance, underscores the problem of probes with a capacitive input impedance. That is, they cannot be used to measure the high frequency potential between two nodes much more than an inch apart because of the required lead length to make such a measurement.

Figure 3 shows the results of an even more serious problem. The measurement configuration consisted of shorting the inputs of two 10X high-impedance passive probes with their own 15 cm ground leads and connecting them to the output of an HC240 buffer. The output of the buffer is a slightly rounded 40 MHz squarewave. I call this a "null experiment." Such an experiment is one whose outcome is expected (usually zero), and the extent to which the outcome deviates from the expected value indicates the error in a measurement. Experience has shown that all measurements should be checked by an appropriate null experiment, especially if the result indicates additional cost must be invested into a product.

Note that the channels are displaying a waveform of a few volts, even though the probes are shorted! This display is due to ground lead currents generating an L·di/dt drop across the ground leads. This ground lead voltage appears as an input signal to the probe. An interesting point to notice is that the two waveforms bear little resemblance to each other even though the probes and scope amplifiers are essentially identical. This is because the impedance looking into the shields of the two cables are different. Thus, the shield currents are different and, accordingly, so are the ground lead induced voltages. These voltages can be minimized by twisting the cables together. However, the variability rarely exhibits more than 10 dB of common mode rejection above a few tens of MHz if the two probes are used in an A minus B mode for differential measurements.

The Balanced Coaxial Probe

The balanced coaxial probe sidesteps many of the high frequency problems described above by making a balanced measurement with a resistive probe input impedance. Commercially available active balanced



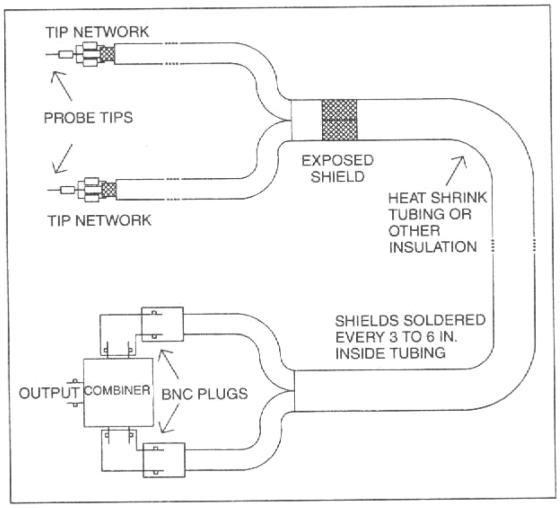
3. Shorted probe responses for two probes.

probes are available, but these are limited in frequency response to about 100 MHz. They also tend to be expensive, have capacitive input impedances, and are sometimes fragile. The balanced coaxial probe is a passive "low" impedance probe that uses a pair of coaxial cables fastened together. It has a typical input impedance of 1000 to 2000 ohms. As mentioned earlier, a standard "high" impedance 10X passive probe has a much lower input impedance than 1000 ohms at frequencies above a few tens of MHz. So, an input impedance of 1000-2000 ohms is not as low as it sounds.

Figure 4 shows the simplified construction of a balanced coaxial probe. Its main features consist of a 180 degree combiner to subtract the signals on the two coaxial cables, a pair of coaxial cables with shields maintained in contact or with an overshield, terminations to match the cable impedances at the probe tip end of the cables, and the probe tip series resistor. This probe can be built with reasonable effort by someone experienced in VHF/UHF rf design techniques. The construction of the 50 ohm terminations and control of parasitic capacitances at the probe tip are the most critical portions of the circuit.

The combiner requires 50 ohm terminations on all its ports. This condition is met by providing 50 ohm terminations at the ends of the coaxial cables. Using a single 50 ohm resistor would not work well, as the inductance of the resistor might become comparable to 50 ohms at a few hundred megahertz. In general, a network of resistors or a disc resistor must be used. If a network of resistors is used, the type of resistors and the geometry of the network are important to meeting the goal of achieving a 50 ohm resistive termination that works to hundreds of megahertz. The impedance of the termination should be measured on a network analyzer to ensure its performance.

From the center conductor of the coax cable ends, where the terminations connect from center conductor to shield, we connect a series-probe tip resistor. The free end of this resistor is the probe tip. The value of this resistor determines the input impedance and attenuation factor of the probe. The calculation of this resistor and its affects on the probe performance will be discussed in the next section.



4. Simplified diagram of a balanced coaxial probe.

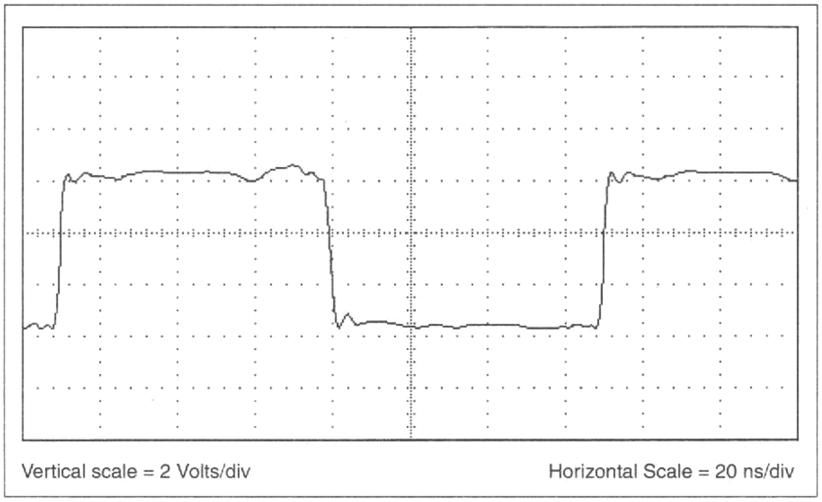
The aforementioned description covers the basics of the probe. In addition, one may find that performance can be improved by further attention to parasitics. For instance, the termination and probe tip resistor could be shielded to prevent proximity of the operator's fingers from affecting probe performance. In any event, the probe must be carefully checked out and calibrated for gain and frequency response. Very small differences between the two halves of the probe will effectively destroy its common mode rejection.

Balanced Probe Performance

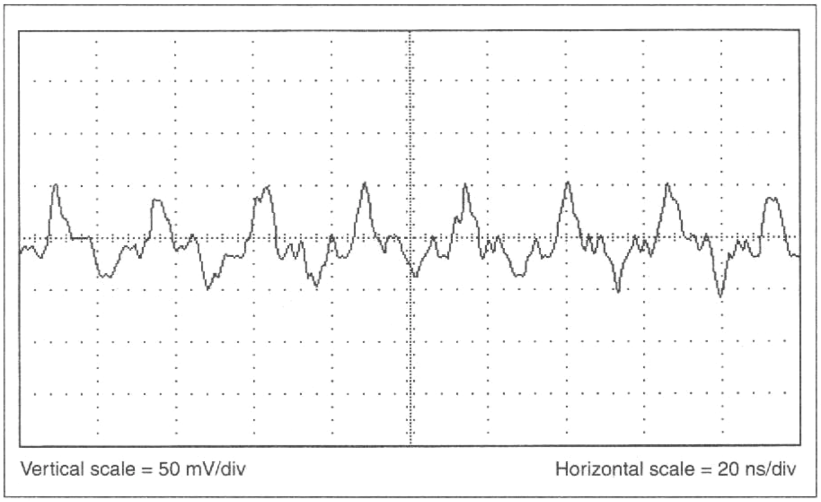
In comparison to commercially active balanced probes, the balanced coaxial probe has a resistive input impedance (no resonances to well beyond 500 MHz); can be built or purchased relatively inexpensively; and has a bandwidth to 500 MHz with an appropriate 180 degree combiner. The frequency range of 1 to 500 MHz can be covered with a single commercially available combiner. Common mode rejection ratios between 30 and 35 dB are typically achieved over the range of 1-500 MHz.

The probe's input impedance is a function of the attenuation factor. If a 475 ohm probe tip resistor is used, the input impedance will be 1000 ohms, centertapped to the probe shield ground (475 + 50 ohm cable in parallel with the 50 ohm terminating resistor). The probe factor will be about 30 dB (32X). Of that, 26 dB (20X) comes from the dividers formed by the tip resistors, terminations, and cable characteristic impedance. About 4 dB of the probe factor is due to the loss of a typical combiner. If 764 ohms of tip resistance is used, a 50X probe will result if the combiner loss is 4 dB.

An input impedance of 1000 ohms centertapped to ground may seem low. However, the impedance is much higher at 100 MHz than that of any probe with 5 or 10 picofarads of input capacitance. In addition, with the exception of resonant circuits, most high frequency circuits (above a few tens of MHz) are of lower impedance. If the power-to-ground impedance of a circuit board is comparable to a probe input impedance of 500 ohms, the circuit board design is probably in real trouble! For instance, this probe



5. HC240 output as viewed with a balanced coaxial probe.



6. Shorted probe response for the balanced coaxial probe.

would not be usable with tuned, resonant circuits and logic gates with low output current. For the vast majority of high frequency voltage measurements, however, the balanced coaxial probe is preferred.

Although a ground lead can be attached to the probe, for most uses it is not necessary. If it is used, any voltage induced across it will be common mode to both channels and will be reduced in the measurement by the common mode rejection of the probe. The only reason to use a ground lead is to reduce a large common mode signal to a value where the differential signal can be measured. For most logic circuits, common mode voltage will not be a problem for this probe. The exposed shield shown in Fig. 4 is used to connect to the chassis of the EUT (equipment under test) for measurements in the presence of ESD, where common mode voltage reaching hundreds of volts can be a problem.

The single output of the combiner can be used with either a scope, to measure signals or the peak value of ground noise for instance, or a spectrum analyzer. When used with a spectrum analyzer, the balanced coaxial probe becomes a powerful EMC, electromagnetic compatibility, troubleshooting tool.

Balanced Probe Measurements

Now consider the same measurements observed previously with a standard scope probe, with comparison to those taken with the balanced coaxial probe. Figure 5 shows the waveform corresponding to Fig. 2c (standard probe with 15 cm ground lead), but measured with the balanced coaxial probe. This probe also used about 15 cm of lead length for the measurement. Notice how clean the waveform is with no overshoot and a fast risetime (about 2 ns, limited by the HC240 buffer). In fact, the waveform looks faster than with the coaxial cable, Figure 2a, because the 50 ohm load imposed on the HC240 output loads it almost beyond its drive capability. The HC240 easily drives the 1500 ohm input impedance of the balanced coaxial probe used. Figure 2b is, in fact, Figure 5.

In Figure 6, the probe tips are shorted together and connected to the output of the HC240 which is producing a slightly rounded square wave at about 40 MHz, corresponding to Fig. 3 using the standard probe. The response to this null experiment is only about a hundred millivolts peak-to-peak instead of the few volts observed before! This illustrates the excellent common mode rejection of this probe and indicates a reasonable measurement in Figure 5.

Conclusions

The balanced coaxial probe is a valuable high frequency measurement tool that avoids the limitations of conventional probes, active and passive. Its resistive input impedance and balanced design are the keys to making clean measurements. In fact, this probe represents an extremely effective method to accurately measure a high frequency voltage between nodes a few inches apart, as the required lead lengths for such measurements cause severe overshoots for "normal" probes with capacitive input impedances.

Douglas C. Smith is a Distinguished Member of Technical Staff at AT&T Bell Laboratories, Middletown, NJ.

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