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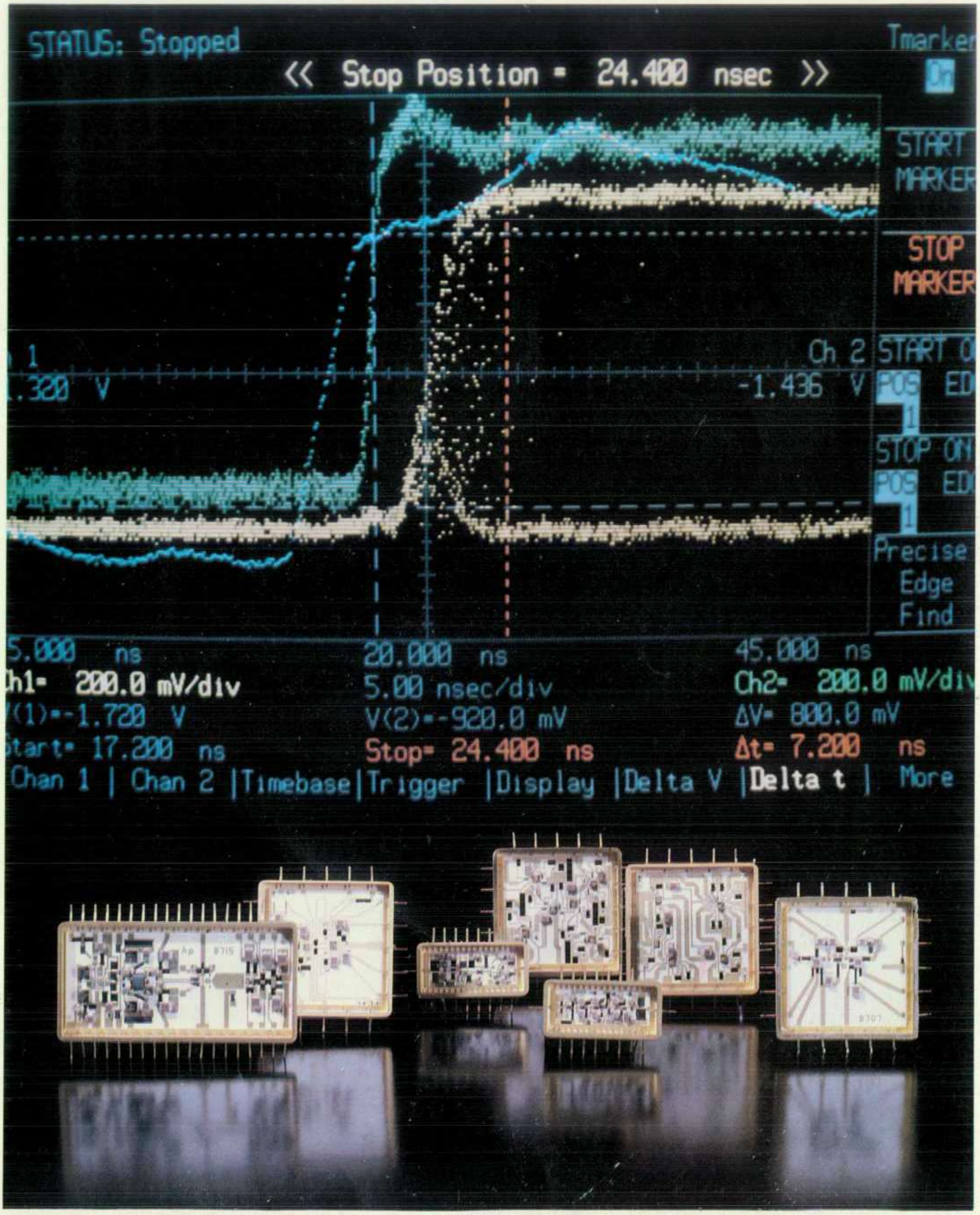


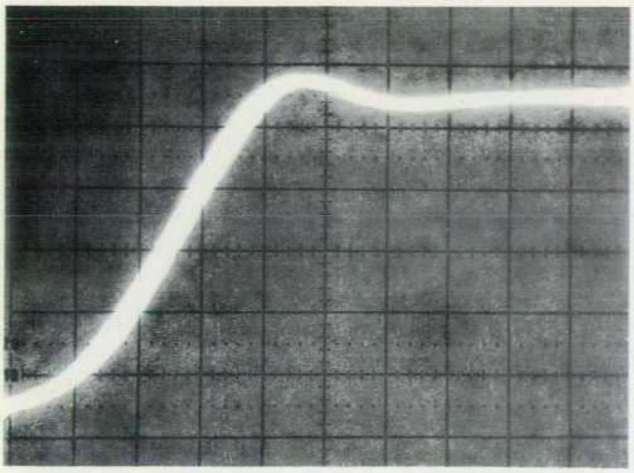


Fig. 15. *Reconstructed sample step response has a rise time of 130 ps. Time scale: 50 ps/div.*

input and output voltages. If the sampling efficiency is not exactly equal to 100%, then the first sample taken after a step change in the input signal will not be correct, but subsequent samples will measure the difference between the input and the output and reduce the error to zero. To minimize this error on the first sample, the sampling efficiency must be as close to 100% as possible.

The sampling efficiency depends on the load capacitance. If there were other parasitic capacitances in parallel with the load capacitor, such as the input capacitance of an amplifier needed to boost the output signal to a sufficient level to be digitized, then the sampling efficiency would not be 100%. Therefore, the postsampler amplifier must have zero input capacitance. In fact, if there are any variances in the load capacitance because of thick-film process variations, the input capacitance of the postamplifier might have to be negative to compensate for other parasitics. The design of the postsampler amplifier is therefore not a trivial matter, especially since its output must settle and be digitized at high rates (40 MHz in the HP 54100A/D).

Fig. 12 illustrates the postamplifier used in the HP 54100A/D. A source follower input stage is used with bootstrapping to reduce the effect of gate drain capacitance. In a normal case, the positive feedback to the drain is 100% (i.e., the drain voltage change is forced to be equal to the gate voltage change). Then the effective load capacitance of the FET is zero. The 100Ω resistor in the drain circuit can be trimmed, allowing the ±0.2-pF input capacitance to compensate for variances in the total holding capacitance according to:

$$C_{in} = C_{gd} (1 - A_{fb}),$$

where A_{fb} is the positive feedback gain and C_{gd} is the gate-to-drain capacitance of the FET.

If A_{fb} is greater than unity, the input capacitance of the amplifier can be negative. This does not cause a stability problem, however, because the holding capacitor makes the total capacitance of the node to ground positive.

Altogether the sampler serves to measure the instantaneous value of an input signal and hold this value to be digitized at a 40-MHz rate. Fig. 13 shows a ramp type input to the sampler, and the output of the postamplifier held in steps 25 ns apart.

Fig. 14 illustrates a step-like input to the sampler and the output of the postamplifier for three settings of the FET drain resistance. Fig. 15 is a reconstructed image of the sampler step response to an HP tunnel diode step generator. The rise time of this sampler is about 130 ps, indicating a bandwidth of about 2.7 GHz.

High-Performance Probe System for a 1-GHz Digitizing Oscilloscope

by Kenneth Rush, William H. Escovitz, and Arnold S. Berger

A TYPICAL SYSTEM to be measured by an oscilloscope usually contains not just one class of signal, but several classes. Making signals from these different classes available to the measuring oscilloscope is the goal of the probing system for the HP 54100A/D Digitizing Oscilloscope.

The probing system consists of the following products:

- The HP 54001A 1-GHz Miniature Active Probe
- The HP 54002A 50Ω Input Pod
- The HP 54003A 1-MΩ Probe
- The HP 54300A Probe Multiplexer.

Circuits that are sensitive to capacitive loading are usually fast circuits having low resistances. For this class, the probe capacitance dominates the design trade-offs. Fast circuits, say ECL 100K, also demand a high-bandwidth probe to preserve the shape and timing of the signal sent to the oscilloscope. The HP 54001A Miniature Active Probe is the optimum probe for this class of signals. This probe's pole-zero cancellation technique results in an extremely small probe tip with low capacitance (2 pF), medium resistance (10 kΩ), and extremely high bandwidth (1 GHz). In size and bandwidth, the HP 54001A is an improvement

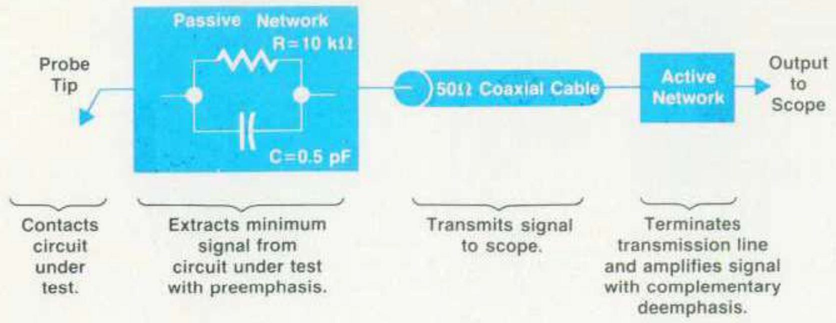


Fig. 1. *Block diagram of the HP 54001A Miniature Active Probe.*

over previous active probes.

A large class of signals exists in a 50Ω environment of coaxial connectors. The requirements of 50Ω terminated coaxial signals cannot be met easily by other probing solutions, so the HP 54002A was designed to cover this class. The HP 54002A offers low insertion loss and good termination.

Circuits that are sensitive to resistive loading (i.e., having resistances above a kilohm) are usually slow circuits and are not so sensitive to capacitive loading. A probe can be optimized for this class of circuits by keeping the probe resistance high at the expense of probe capacitance. Such is the case with the HP 54003A. The HP 54003A probe offers equivalent performance to conventional oscilloscope probes, high resistance (1 MΩ), moderate capacitance (8 pF), and relatively high bandwidth (300 MHz) for requirements where resistive loading is more important than capacitive loading.

The idea that allows these products to make a significant contribution is a system of interchangeable pods and a method of multiplexing the outputs of the pods into an oscilloscope. The HP 54300A Probe Multiplexer allows these probes to form a measurement solution. Now signals from several classes of circuits can be brought together and measured in one system. Low-speed, high-resistance operational-amplifier signals can be measured by the HP 54003A and multiplexed with high-speed ECL signals measured by the HP 54001A. Amplifier outputs in 50Ω coax can now be measured in the same system as the low-power CMOS used to program the amplifier gain.

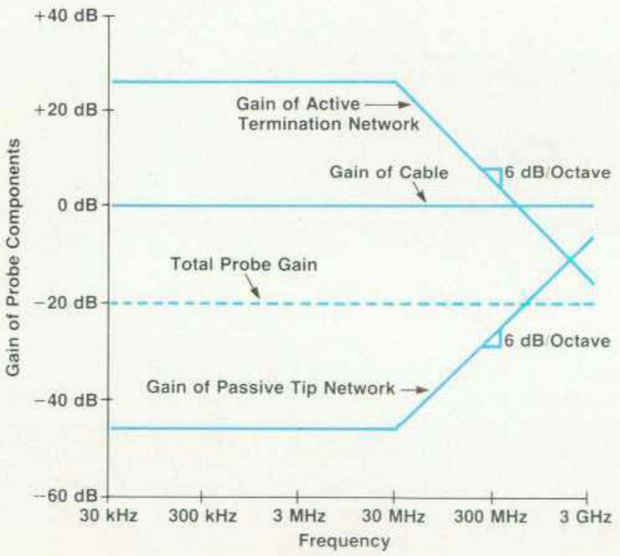


Fig. 2. *Gain of HP 54001A probe components versus frequency.*

Miniature Active Probe

Careful consideration of noise, bandwidth, and loading effects led to some unusual design concepts in the HP 54001A. The single most significant problem in designing an oscilloscope probe is dealing with the cable capacitance. The cable capacitance in a conventional probe is part of a capacitive voltage divider. Hence, the higher the cable capacitance, the higher the probe tip capacitance must be. Historically, designers have used several methods to minimize cable capacitance. One common method is to make the cable short, since capacitance is proportional to length. Unfortunately, this leads to probes that are often too short to bridge the gap between the circuit under test and the oscilloscope. Another method is to make the cable have very high impedance. If we could realize a 150Ω cable, it would have one-third the capacitance of a 50Ω cable. Unfortunately, high-impedance coaxial cable tends to have a large outer diameter. Carrying both of these techniques to their extremes—maintaining sufficient length to be useful, and maintaining a small diameter cable—yields the HP 54003A, which is similar to the HP 10017A passive probe, having a tip capacitance of about 8 pF.

Other techniques have been used to reduce tip capacitance, but they usually have severe drawbacks. First, plac-

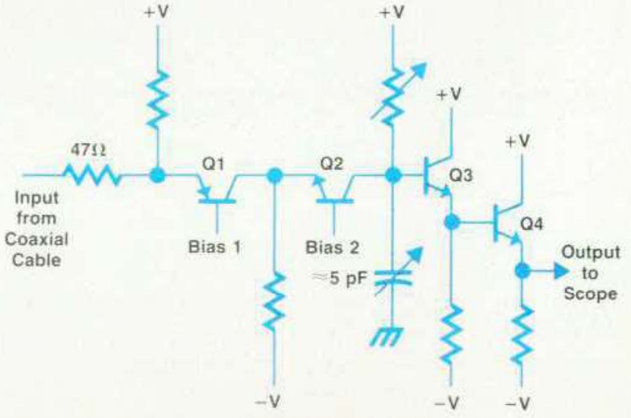


Fig. 3. *Simplified schematic of the active network in the HP 54001A Miniature Active Probe.*

ing an amplifier near the probe tip to drive the cable capacitance eliminates the tip impedance's dependence on cable properties, but power must be supplied to the amplifier, and it takes up space, making the probe tip large. Second, the cable could be considered as a transmission line and terminated as such as in resistive divider probes. However, this leads to probes with very low resistance at the probe tip—500Ω for a 10:1, 50Ω probe such as the HP 10020A.

Obviously a new approach was needed to produce the ideal probe for high-speed logic. To achieve higher bandwidth in a longer probe requires low-loss, high-quality coaxial cable terminated in a 50Ω impedance. The small tip size restraint requires a passive tip. The requirement of high resistance forces us to introduce gain into the system to terminate the cable in 50Ω. One approach might be to use a resistive divider probe with a high division ratio, followed by an amplifier to make up the gain loss. This poses two problems. First, gain at very high frequencies (>300 MHz) is not easy to get, and if we could get it, the gain would add noise to the system. However, if we are willing to remove more signal from the circuit under test using slight capacitive loading, we will not be attenuating the signal as much at high frequencies. Thus, less gain is required. This is the method used in the HP 54001A probe.

Fig. 1 illustrates the concept in a block diagram. In the probe tip, a thick-film microcircuit is used to realize an RC passive network. The resistance is a laser-trimmed, thick-film resistor. The capacitance is the front-to-back capacitance of a couple of metal traces on the ceramic substrate and has a value of 0.5 pF.

Fig. 2 illustrates the transmission gain of the passive tip network and the active network gain required to get a total probe gain of −20 dB (10:1). Note the transmission zero caused by the parallel action of the resistance and capacitance in the probe tip. This transmission zero must be cancelled in the active network with a pole at 30 MHz. Below 30 MHz, the passive network has a loss of 46 dB, and the active network must have a gain of 26 dB while the coaxial cable has no loss or gain. Above 30 MHz, the gain of the passive network increases at 6 dB/octave, while the active network gain decreases at 6 dB/octave, yielding a constant −20-dB gain over the frequency range of the probe. The required gain of the active network goes through 0 dB at about 630 MHz.

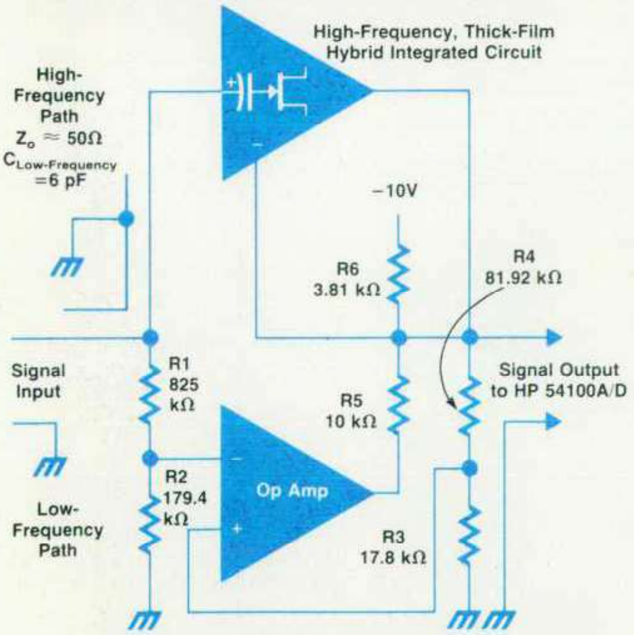


Fig. 4. *Block diagram of the HP 54003A 1-MΩ Probe input pod.*

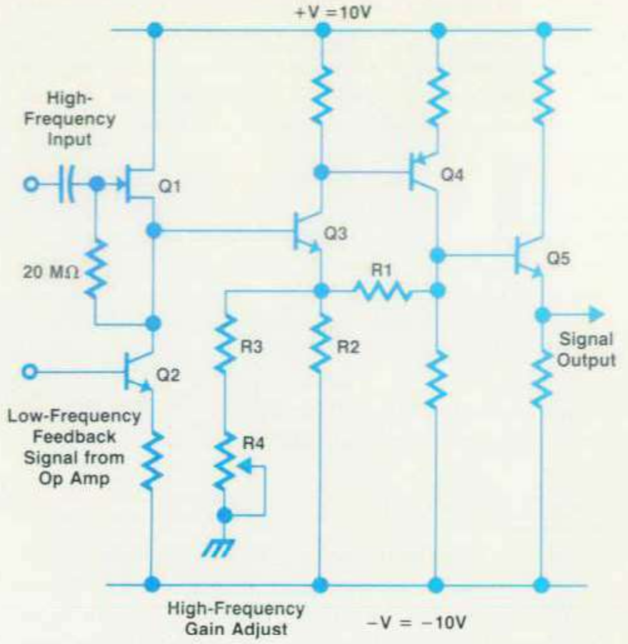


Fig. 5. *Basic circuit of the high-frequency thick-film hybrid for the HP 54003A 1-MΩ Probe input pod.*

The requirements on the active network are rather severe. It must terminate the coaxial cable in its characteristic impedance of 50Ω, boost the signal by 26 dB below 30 MHz, roll off its gain at −6 dB/octave to well past the desired bandwidth of the probe, and drive the 50Ω input of the oscilloscope to a reasonable dynamic range of ±2 V, giving a 20V dynamic range at the probe tip (10:1 probe). Thick-film hybrid microcircuit technology is used to realize the circuit.

Four discrete microwave transistors are used in cascade. Fig. 3 illustrates the circuit. Transistor Q1 and the 47Ω resistor in series with its emitter terminate the coaxial cable in its characteristic impedance. The base bias of Q1 is automatically adjusted with an operational-amplifier feedback circuit to guarantee that the input offset is zero volts. Q2 acts as a buffer to isolate the high impedance at its collector from the low impedance of the active network input. At the collector of Q2 is an RC network that generates the required current-to-voltage conversion of the signal current passing through Q1 and Q2. The resistive and capacitive values are trimmed at calibration to guarantee a match with the passive network to achieve the proper gain at all frequencies. Q3 and Q4 form a cascade of emitter followers to isolate the high-impedance node at the base of Q3 from the low impedance of the output node.

The overall performance of this probe is limited by the choices of the passive network values. Obviously, if we made the tip resistance extremely high and the tip capacitance extremely low, we would have an extremely small signal to work with, making recovery and measurement of the signal very difficult. The capacitance value chosen yields a total probe tip capacitance of about 2 pF. This gives less than a 3% increase in rise time for a 50Ω, 1-ns-rise-time resistive source. The 10-kΩ resistance gives about 0.5% dc loading error on a 50Ω source. The ultimate bandwidth of this approach is limited primarily by the thick-film active network, and in the case of the HP 54001A probe, this exceeds 1 GHz. The cable losses, primarily caused by skin effect, form a secondary limitation on bandwidth. First-order compensation for these losses is done by an overadjustment of the active network trim capacitor.

1-MΩ Probe

Although the HP 54100A/D is a 1-GHz oscilloscope with 50 internal signal paths, its digital architecture, HP-IB control, and automatic measurement capabilities make it useful at much lower frequencies. To take advantage of this, the HP 54003A 1-MΩ Probe was designed. It is a unity-gain, general-purpose, 300-MHz input buffer amplifier with a 1-MΩ, 10-pF input. It requires an external HP oscilloscope probe. Probes for it include the HP 10017A 1-MΩ, 8-pF miniprobe, the HP 10014A 10-MΩ, 10-pF standard probe, and the HP 10032A 100:1 Probe. Its bandwidth of 300 MHz and its rise time of 1.2 ns are specified both at the BNC input and at the probe tip. It is useful for circuits ranging from high-impedance operational amplifiers to ECL logic circuits to power supplies up to 200V.

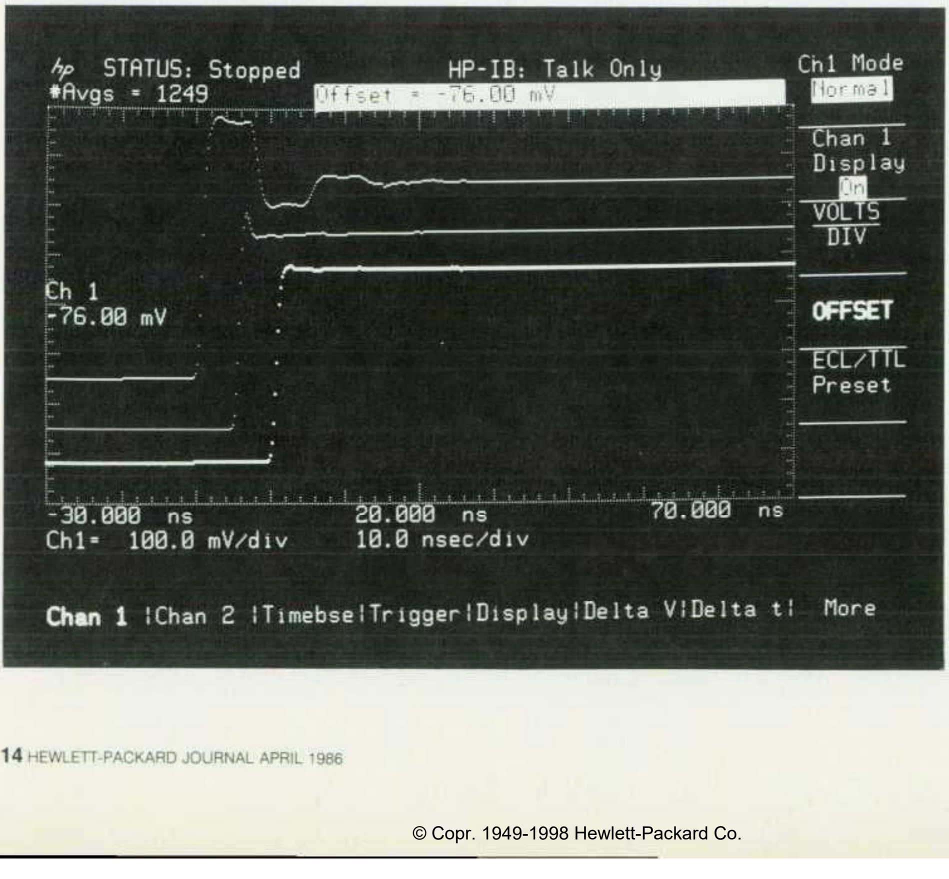
Most oscilloscope amplifiers are preceded by attenuators, which limit the dynamic range that the amplifiers must cover. The HP 54100A/D has 50Ω, 1-GHz attenuators already built into it, so the HP 54003A buffer amplifier must have a large dynamic range. The dynamic range is ±2V, which covers most digital circuit and operational-amplifier applications with a ×10 probe. This is about twice the dynamic range of buffer circuits in active probes and oscilloscope inputs.

As shown in Fig. 4, the HP 54003A is a two-path amplifier. Signal components less than about 1 MHz pass through the low-frequency path, an operational-amplifier circuit, then to a low-frequency input of the high-frequency amplifier. The operational amplifier also controls the operating point of the high-frequency amplifier.

Signal components higher than 20 Hz also follow the high-frequency path. There is sufficient overlap of the two circuits' passbands to ensure a smooth total response. Because of the closed-loop design and modern operational-amplifier stability, there is almost no visible drift. Also, the high open-loop gain of operational amplifiers means that 0.1% resistors R1, R2, R3, and R4 accurately and repeatably set the low-frequency gain to:

$$A = \{R2/(R1+R2)\}\{(R3+R4)/R3\}.$$

One adjustment in the high-frequency amplifier sets the high-frequency gain equal to the low-frequency gain so that the overall response is flat. The high-frequency circuit (Fig. 5) is a unity-gain amplifier with input, gain, and output sections. Because the input and output sections are followers with gain less than 1, a gain section is necessary. Transistors Q1 and Q2 make up the input section. FET source follower Q1 is operated at gate-to-source voltage $V_{gs}=0$, maintained by the 20-MΩ gate-to-source resistor. However, the Miller effect between the gate and source causes the input impedance to be much greater than that resistance. The input resistance does not significantly load the 1-MΩ input resistor of the low-frequency operational-amplifier



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Ch1 Mode: Normal
Chan 1 Display: On
Ch 1 -76.00 mV
-30.000 ns
20.000 ns
70.000 ns
Ch1= 100.0 mV/div
10.0 nsec/div

Fig. 6. *Response of the HP 54003A probe input pod with the HP 10100C 50Ω feedthrough terminator and artificially long 600-mm 50Ω cable as a stub, with the HP 10100C directly on the HP 54003A input pod, and with no HP 10100C. The 50Ω feedthrough terminator with stub creates 33% overshoot (top trace). The HP 54003A input line as a stub (middle trace) causes less overshoot because it is fairly short for this bandwidth. Proper use of the HP 54003A is without feedthrough terminator (bottom trace).*

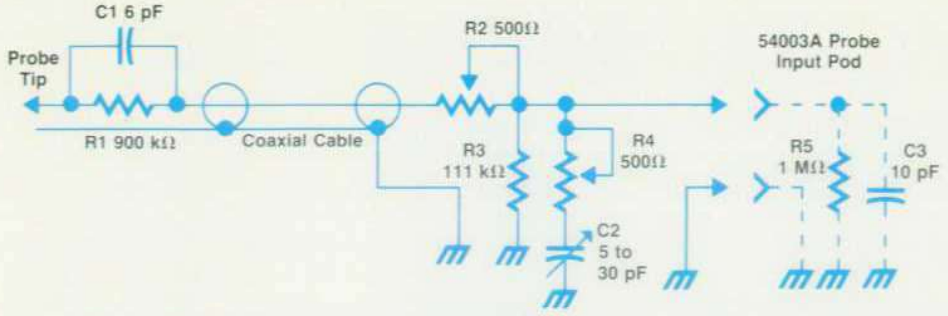


Fig. 7. *Schematic diagram of the HP 54003-61617 1-MΩ, 8-pF, 10:1 oscilloscope probe (same as the HP 10017A).*

circuit. The feedback input from the operational-amplifier circuit maintains the proper current in Q1 and Q2 for FET operation at $V_{gs}=0$ regardless of the input bias level within the ±2V dynamic range and regardless of individual FET variations.

The gain stage is the common-emitter/common-emitter circuit of Q3 and Q4 with voltage series feedback. Resistors R1 through R4 make up the feedback network. R4 is adjusted so that the high-frequency amplifier gain is equal to the low-frequency operational-amplifier circuit gain.

The high-frequency circuit is implemented as a thick-film hybrid. The technology is described in the article on page 33. The short length of chip-to-substrate wire bonds and repeatable geometry of traces minimize variable parasitic impedances at 300 MHz. This produces consistently high-performance circuits.

The HP 54003A input should be driven from a 50Ω source or oscilloscope probe such as the HP 54003-61617 (HP 10017A). Although the input capacitance is about 10 pF, the BNC input connector and the input line look like a 50Ω transmission line terminating at the input capacitance of the high-frequency amplifier, which is only about 2 or 3 pF. Thus, a 50Ω source can drive the input well beyond 300 MHz. It is common to terminate high-impedance inputs with 50Ω feedthrough terminators, such as the HP 10100C, to reduce reflections in high-frequency measurements. However, this causes overshoot with fast rise time signals because of the inevitable stub of BNC connector and buffer amplifier input line. For a long stub, the overshoot is 33%. Instead of a feedthrough termination, it is better to use a ×5 or ×10 50Ω attenuator at the BNC input if the signals are large enough. If the source impedance is close enough to 50Ω, no termination or attenuator is necessary. Fig. 6 shows how the waveform varies for three different terminations. Only analysis of individual cases reveals the best termination, if any, to use with high-impedance inputs. Of course, the HP 54002A 50Ω Input Pod is best for dedicated use in a 50Ω system.

Most high-impedance inputs are used with probes to characterize or troubleshoot circuits. Probes represent the highest-resistance, lowest-capacitance, lowest-disturbance connection to circuits that do not have buffered 50Ω test points. The main probe for the HP 54003A is the HP 54003-61617, which is identical to the HP 10017A Miniature Divider Probe (Fig. 7). It is designed to drive 1-MΩ inputs with approximately 10 pF input capacitance. Up to about 10 MHz, it is a capacitor-compensated 10:1 resistive voltage divider. The divider consists of the parallel combination of R1 and C1 in series with the parallel combination of R3, R4, R5, C2, C3, and the cable capacitance. The R2 and R4 network terminates the characteristic impedance of the cable at very high frequencies, where transmission line effects in the cable become important. The center conductor of the cable is resistive to damp out remaining reflections.

1-MΩ Probe Performance

Fig. 8 is a block diagram of some of the equipment used to characterize the high-frequency performance of the HP 54003A. It produces flat pulses of approximately 1-ns rise time, typical of the fastest pulses the HP 54003A can usefully measure. The pulse flattener is a Schottky diode series clipper. When the HP 8082A output is negative, it is connected to the pulse flattener output through the diode, which is turned on. When the HP 8082A output returns to 0V, it is connected to the flattener output only through the diode capacitance, about 1 pF. The output of the flattener returns rapidly to 0V through the 50Ω output resistor. The small capacitance of the turned-off diode filters the pulse-

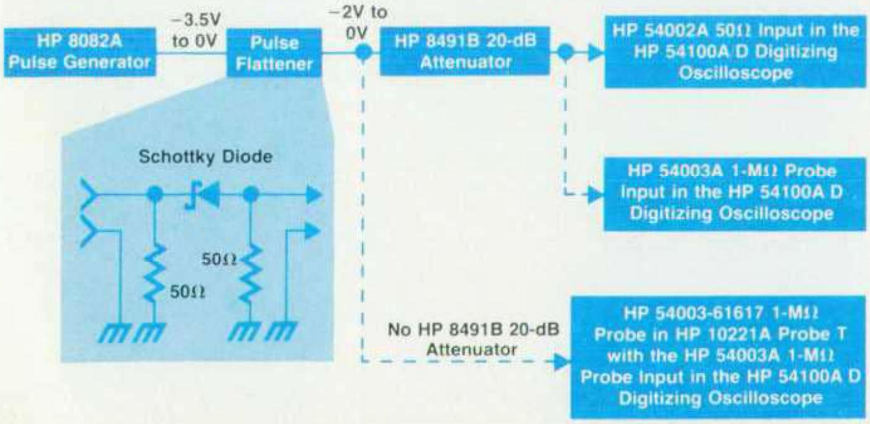
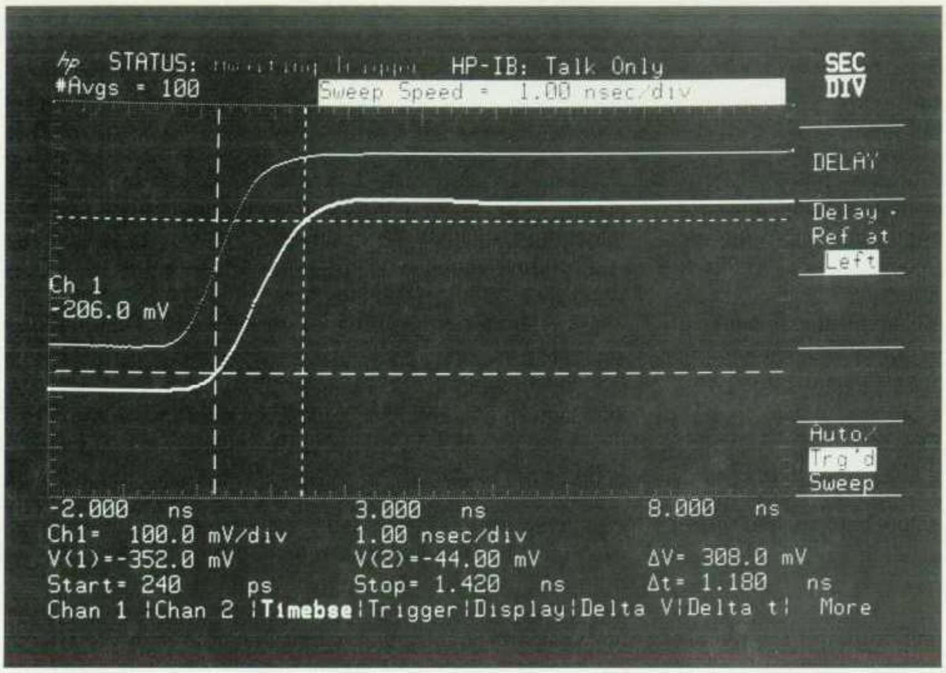


Fig. 8. *Equipment to produce flat pulses for characterizing oscilloscopes and probes.*



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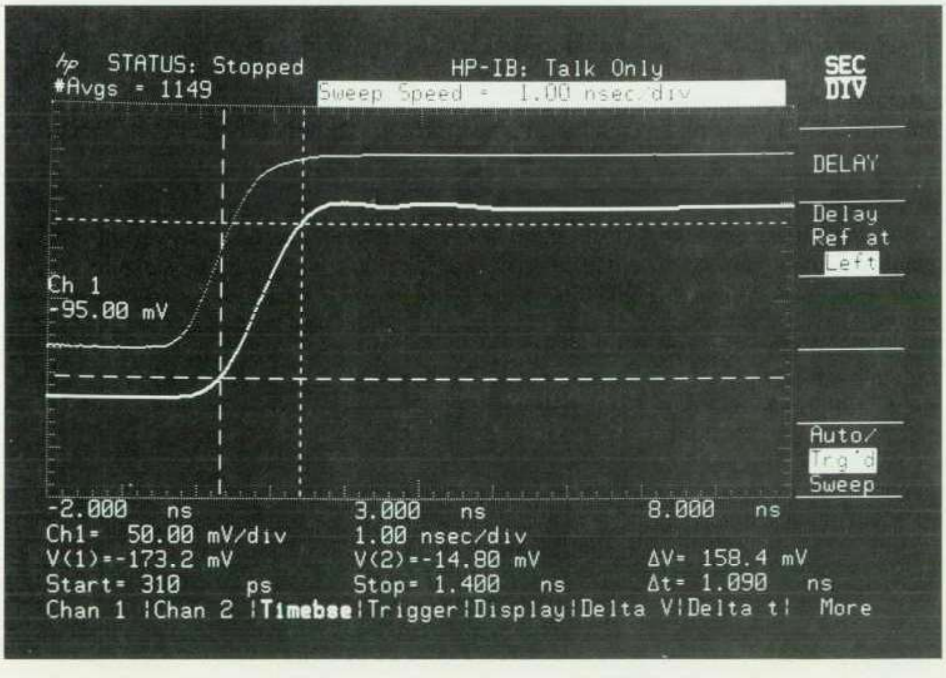
-2.000    ns            3.000    ns            8.000    ns
Ch1=  100.0 mV/div      1.00 nsec/div
V(1)=-352.0 mV          V(2)=-44.00 mV         ΔV= 308.0 mV
Start= 240      ps      Stop= 1.420     ns     Δt= 1.180     ns
```

Fig. 9. *Response of the HP 54100A/D with the HP 54002A 50Ω probe to a 1-ns rise time reference pulse (top trace), compared with the response of the HP 54003A 1-MΩ input pod (bottom trace).*

top aberrations of the pulse generator, which are already small, and the 50Ω output resistor reduces reflections when the diode is off. The 20-dB attenuator is a nearly 50Ω load for the pulse flattener regardless of the device under test. The HP 8082A's amplitude and offset are adjusted to produce the flattest reference pulse near the pulse transition.

Fig. 9 shows the response of the HP 54100A/D with the HP 54002A 50Ω input (top trace, the reference pulse) and the HP 54003A 1-MΩ input (bottom trace). The reference trace has a 1.02-ns rise time and aberrations of about 1% peak-to-peak for the first 10 ns, which require the HP 54100A/D's magnify mode to see. The HP 54003A trace has a rise time of 1.18 ns and about 2% overshoot compared to the reference pulse.

Fig. 10 compares the performance of the HP 54003A and the HP 54003-61617 ×10 miniprobe (bottom trace) with the reference trace. No attenuator is used because the probing tee is already terminated in 50Ω. The rise time with the probe is 1.09 ns and the perturbations are about 3% peak-to-peak. The 1.09-ns rise time of the probe compared to the 1.02-ns rise time of the reference waveform or the 1.18-ns rise time of the HP 54003A itself does not mean that the 1-MΩ probe is exceptionally fast, but only that it can be tuned using its adjustable termination resistors.



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-95.00 mV
-2.000    ns            3.000    ns            8.000    ns
Ch1=  50.00 mV/div      1.00 nsec/div
V(1)=-173.2 mV          V(2)=-14.80 mV         ΔV= 158.4 mV
Start= 310      ps      Stop= 1.400     ns     Δt= 1.090     ns
```

Fig. 10. *Response of the HP 54100A/D with the HP 54002A 50Ω probe to a 1-ns rise time reference pulse (top trace), and the response of the HP 54100A/D with the HP 54003A 1-MΩ probe input pod and the HP 54003-61617 1-MΩ miniprobe (bottom trace).*