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A New Pulse Generator with Very Fast Rise Time

THE development of faster and faster circuitry in computer and other work is heavily dependent on the availability of means for generating and displaying the fast waveforms that such circuits employ. One tool that has been of great importance in fast circuit work is the -hp- Sampling Oscilloscope described earlier[1,2]. This instrument displays voltage changes faster than 10^{-9} second and has a high sensitivity of 1 millivolt. With its aid much fruitful development effort has been conducted by many groups.

SEE ALSO:
Measuring Stray L and C, — p. 6

Now, fast circuit investigations are further assisted by a versatile new pulse generator which provides pulses as short as 1 nanosecond (10^{-9} second). The pulses are provided at a high signal level of 10 volts across 50 ohms and at repetition rates of up to 1 megacycle. Despite its high speed, the instrument is a true general-purpose generator with selectable pulse polarity, a calibrated pulse width control, pulse baseline set at ground, an output attenuator control, a matched source impedance, flexible input triggering, and continuously-variable trigger advance. Physically, the instrument has a small size as a result of being transistorized, and is rated to operate in ambient temperatures up to 55°C.

The new pulse generator, when combined

1. Roderick Carlson, "A Versatile New DC-500 MC Oscilloscope with High Sensitivity and Dual Channel Display," Hewlett-Packard Journal, Vol. 11, No. 5-7, Jan.-Mar., 1960.
2. Roderick Carlson, "The Kilomegacycle Sampling Oscilloscope," Hewlett-Packard Journal, Vol. 13, No. 7, March, 1962.

Fig. 1. *New -hp- Model 215A Pulse Generator (in center) provides pulses as short as 1 nanosecond for general-purpose testing. Pulses are provided at high level and from direct-coupled 50-ohm source for simplicity of external use.*

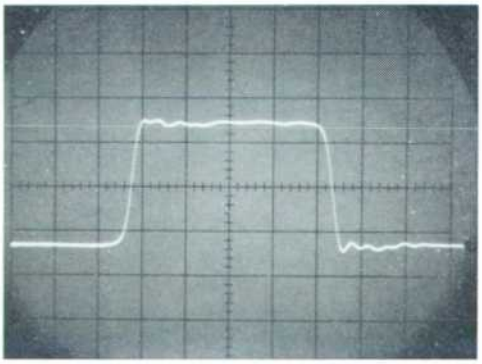


Fig. 2. *Oscillogram showing typical quality of fast pulse provided by new generator. Width of pulse shown is 10 nanoseconds, rise time is less than 1 nanosecond, and overshoot less than 5%. Amplitude of pulse shown is 10 volts across external 50 ohms.*

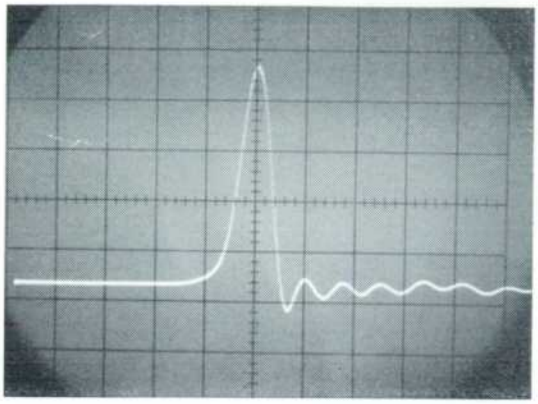


Fig. 3. *Typical ultra-short pulse of under 1 nanosecond provided by new generator. Pulse amplitude is 4 volts.*

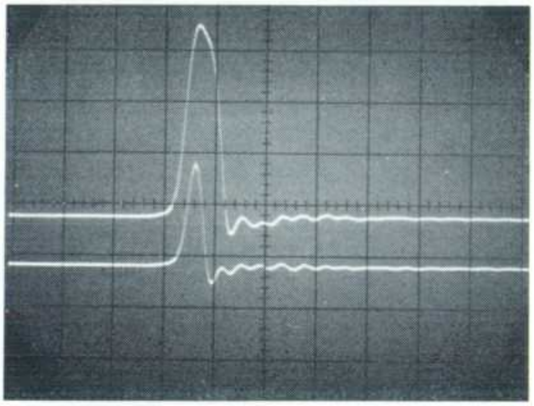


Fig. 4. *Two-exposure oscillogram showing typical pulse widths and amplitudes obtainable in ultra-short pulse region. Upper trace (a) shows 2-nanosecond pulse at 10 volts; lower trace (b) is 1 nanosecond pulse at about half of amplitude of (a).*

with the Sampling Oscilloscope mentioned above, comprises a complete fast-circuit testing system for the usual stimulus-response type of test. It is a system that is useful even with equipment having clock frequencies in the VHF region, since the new pulse generator contains a countdown circuit that will synchronize on frequencies up to 100 megacycles. The generator pulse output then occurs at a submultiple rate below 1.3 megacycles. The Sampling Oscilloscope will also synchronize on VHF clock frequencies or from the pulse generator's sync pulse.

PULSE CHARACTERISTICS

The pulse provided by the new generator is a high quality pulse, and one that does not deteriorate with changes in pulse width, amplitude or repetition rate. The quality of a typical pulse is shown in the oscillogram of Fig. 2. Rise time is less than 1 nanosecond, overshoot is less than 5%, and fall time is less than 1 nanosecond. Preshoot, rounding, and other characteristics are also controlled and stated in the instrument's specifications. In addition, the circuit design is such that no combination of control settings can produce a duty factor above that safe for the circuit components.

A point of special interest to those working with high speed circuitry is that the rise time of less than 1 nanosecond specified for the pulse is for a pulse of full amplitude, i.e., 20 volts open circuit or 10 volts across 50 ohms. The pulse width, however, has been designed to be adjustable down to 0 nanoseconds. This makes the generator able to provide *very short pulses of less than 1 nanosecond overall width (50% points)* by reducing the pulse width so that the pulse fall time begins before the rise is completed. When full pulse amplitude is not needed, this technique can be of substantial value. A pulse of less than 1 nanosecond, for example, can typically be obtained at an amplitude of 5 volts or so across 50 ohms. For many applications this is of great value. Figs. 3 and 4 show typical examples of such very short pulses obtainable from the generator.

The generator is not limited to operating into loads of 50 or more ohms, since it is also capable of delivering a 400 milliampere pulse into a short circuit. The generator source impedance is held to within approximately 1% of 50 ohms so that reflections caused by load mismatch are absorbed almost completely by the generator.

The high resolution of the oscillograms in Figs. 2 to 4 shows that jitter in the generated pulses is unobservably small compared even to these very short pulses. Specified values for jitter are less than 50 x 10^{-12} seconds between the trigger

Fig. 5. *Panel view of new -hp- Model 215A Pulse Generator.*

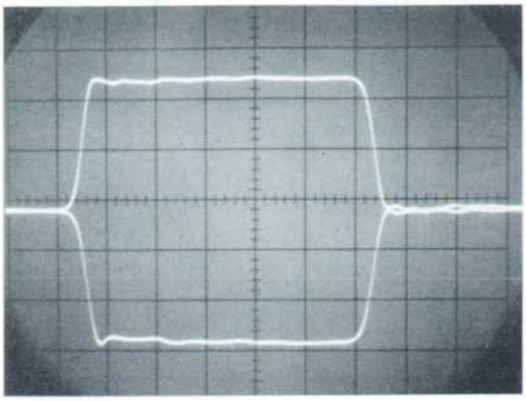


Fig. 6. Two-exposure oscillogram showing retention of baseline with either polarity output pulse.

and the main pulse leading edge, and less than 50×10^{-12} second between the leading and trailing edges of the main pulse. Typical performance for these quantities has been less than half the specified maxima.

The pulse train is provided through a dc-coupled output system so that the pulse baseline does not vary with pulse amplitude, duty cycle, polarity or load impedance. Thus, when testing fast devices such as diodes and transistors in circuits that use no blocking capacitor, the bias levels will not be disturbed by adjustment of the pulse values. The pulse baseline is at ground potential for both positive- and negative-going pulses.

Considerable current from external bias sources can be passed back through the generator without consequent damage, the maximum being $\frac{1}{2}$ watt or 100 ma as determined by the dissipation rating of the generator output resistors. Bias currents of the levels usually encountered when driving external semiconductor circuits have little or no effect on the generator. Thus, external bias currents of from 4 to 15 ma, corresponding to the minimum and maximum settings of the output attenuator, can be accepted by the generator without observable effect. Larger bias currents alter the flatness of the pulse but do not slow the rise time. For applications requiring high dc offset in the tested circuit, a blocking capacitor in a 50-ohm coaxial section has been designed as an optional accessory.

CIRCUIT DESCRIPTION

Conventional techniques for generating pulses with nanosecond rise times are not flexible enough for a general purpose pulse generator. The difficulty lies in maintaining constant pulse height, along with prescribed rise and fall times, while pulse width is varied. The problem is solved in the Model 215A by deriving a pulse from two very fast current steps, one positive and one negative, generated in separate channels. The fast rise times of these steps, and hence of the pulse derived therefrom, results from the use of step-recovery diodes[3] as pulse "sharpeners."

The two current steps are summed in the output circuit where one step serves as the leading edge of the output pulse and the other, occurring later, serves as the trailing edge. The polarity of the first-occurring step determines output pulse polarity, and pulse width is determined by the time difference between the two steps. Since the steps are generated in separate channels, pulse width has no effect on pulse height or rise and fall times.

3. Moll, Krakauer, and Shen, "P-N Junction Charge-Storage Diodes," Proc. I.R.E., Vol. 50, No. 1, Jan., 1962.

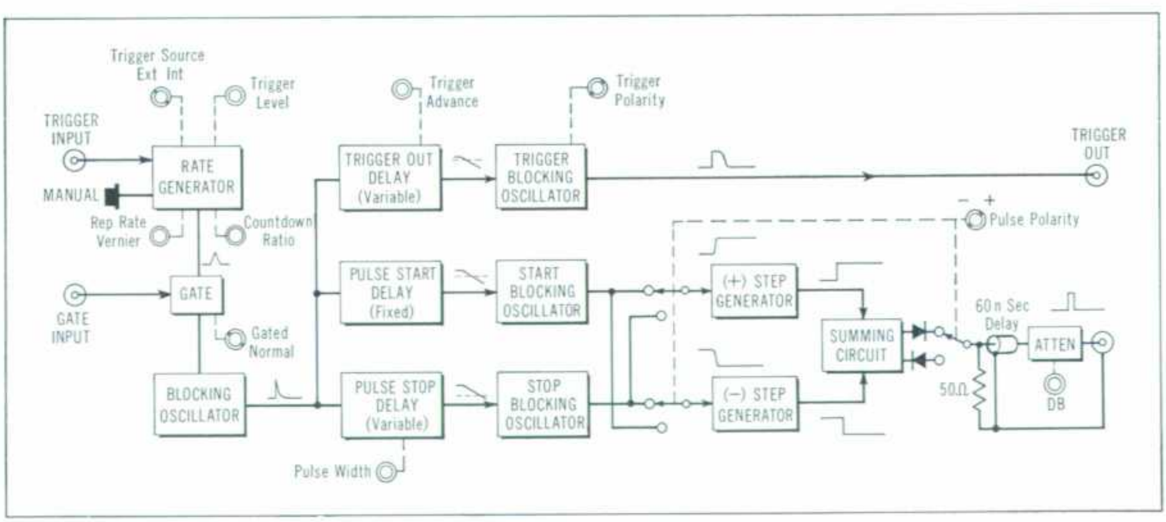
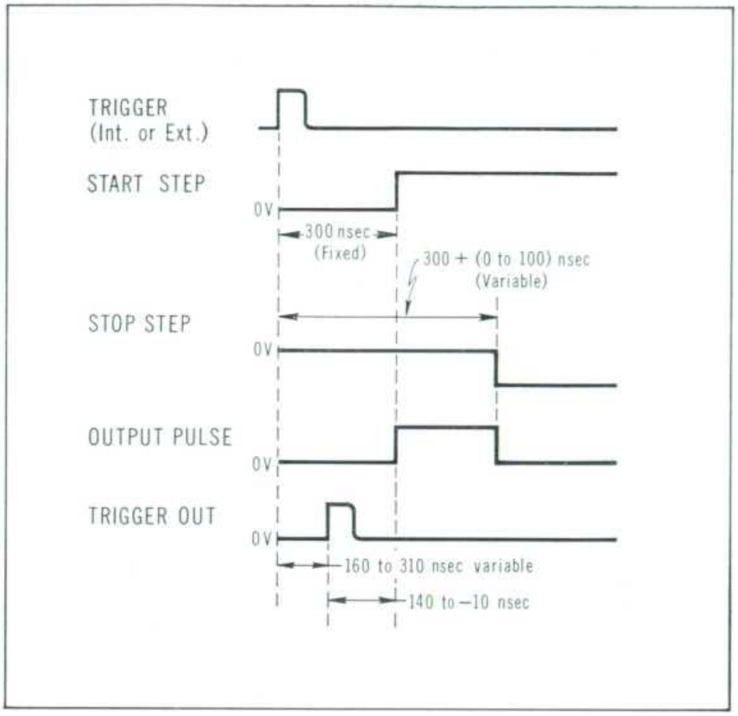


Fig. 7. Basic circuit arrangement of -hp- Model 215A Pulse Generator.



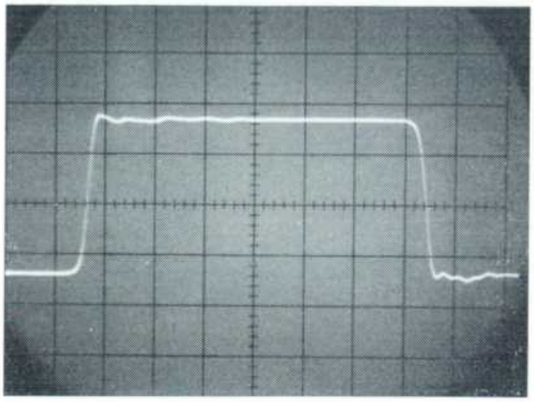


Fig. 9 (above). *Two-exposure oscillogram of generator pulses at prf's of 100 kc and 1 Mc shows freedom of output pulse shape from repetition rate effects.*

Fig. 8 (at left). *Time relations in circuit operation of generator.*

The overall block diagram is shown in Fig. 7. The sync and rate circuit generates pulses which initiate action in the other circuits. This circuit operates as a free-running, tunnel diode-transistor relaxation oscillator at rep rates from 100 to 10^6 pps. Alternatively, it can function as a trigger circuit in synchronism with an external source, or on a one-shot basis in response to a front panel push-button. For count-down operation, the oscillator runs free but the external signal is added to its timing waveform for synchronization. This circuit counts down by as much as 100:1 and syncs at some submultiple of frequencies as high as 100 Mc.

Gating of the output pulses is obtained by passing the sync generator pulses through a gate which is opened or closed by a voltage on its other input. In this way, trains of pulses may be generated in response to an external gating pulse.

Each trigger pulse passing through the gate fires a blocking oscillator which in turn starts three voltage ramps in three separate channels. Each ramp triggers a separate blocking oscillator when the ramp reaches a reference level, resulting in delayed trigger pulses in each channel. The delay times are individually selected by adjustment of the voltages from which the ramps start.

The first ramp to reach its reference level is normally the "trigger out" ramp. Its blocking oscillator generates the 50 ns wide advanced trigger pulse. The second ramp triggers the "pulse start" blocking oscillator. The resulting pulse is routed via the pulse polarity relay to either the positive or negative output step generator. If sent to the positive generator, for example, the pulse initiates a positive step.

Lastly, the "pulse stop" ramp reaches its reference level, firing its blocking oscillator and turning on the other step generator. This step cancels the first step and terminates the pulse. The series diode, connected between the current summing point and the output, disconnects the output as soon as the voltage at the summing point reverses polarity, allowing the steps to be turned off individually (in correct order) without causing an extra output pulse.

As shown by the waveforms in Fig. 8, pulse width is determined by the delay difference between the "start" (fixed delay) and "stop" (variable delay) channels. The potentiometer which varies the ramp starting voltage for the "stop" channel carries the Pulse Width dial.

The generator's 50 ohm output impedance is achieved in an unusual manner with the help of the 60 nsec delay cable shown on the diagram. The output stage previous to the series diode has varying internal impedances during its cycle of operation and by itself does not represent a 50 ohm source. Since the delay line is 60 ns long, any pulse reflected by external circuits arrives back at the output stage at least 120 ns after the pulse started. The series diode will have been back-biased by this time so that the reflected pulse sees only the 50 ohm shunt resistor and is completely absorbed by it. Thus, no further reflection occurs at the output stage and the generator appears to have a true 50 ohm source impedance. A 3-ft. length of well-matched coaxial cable is supplied with each pulse generator, extending the true 50 ohm source impedance to the circuit under test.

The fast rise time and large pulse amplitude of this generator open the way to new kinds of measurements. Waveforms obtained from circuits driven by the 215A pulse generator, when viewed on a sufficiently fast oscilloscope, contain a wealth of information in the observable time differences between parts of the waveform. For instance, the very small inductance of the leads of a capacitor shows up as a distinct spike, as described in the article on page 6. Measurements of fast transistor beta, f_T, stored charge and other semiconductor properties are obvious applications.

Other applications include the testing of nuclear counting systems, klystron modulation, determination of magnetic switching flux, and harmonic generation. Furthermore, a whole new class of measurements, that of time domain reflectometry[4], is now possible and leads towards examinations of coaxial cable systems in ways never before possible.

Fig. 10. -hp- Model 185B Sampling Oscilloscope with 0.35-nanosecond rated rise time used to make oscillograms appearing throughout this issue.

ACKNOWLEDGMENTS

The basic concept of the -*hp*- 215A pulse generator originated with Victor Van Duzer. Fred Basham worked out the delay circuitry, Emanuel Candilis developed the sync and rate circuitry and the undersigned developed the output circuit. Mechanical design was by Clifford L. DeLude. Many other members of the Hewlett-Packard Research and Development Laboratories provided helpful suggestions.

—Charles O. Forge

4. Halverson, H. "Transmission Line Testing Using The Sampling Oscilloscope" -*hp*- Application Note n. 53.

SPECIFICATIONS

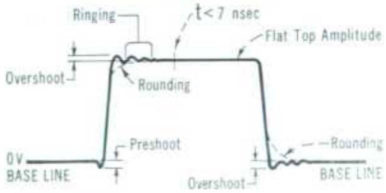
-*hp*- MODEL 215A PULSE GENERATOR

OUTPUT PULSE SPECIFICATIONS*

(specifications apply for all rep rates, all amplitudes, and both polarities):

RISE TIME: less than 1 nsec 10-90%.
FALL TIME: less than 1 nsec 10-90%.
PEAK VOLTAGE: greater than 10v into 50 ohms; greater than 20v open circuit.
POLARITY: positive or negative.
(Leading Edge Only):
OVERSHOOT AND RINGING: less than 5% peak and less than 10% peak-to-peak of pulse amplitude.
CORNER ROUNDING: occurs no sooner than 95% of pulse amplitude.
PRESHOOT: less than 1%.
PERTURBATIONS ON FLAT TOP: less than 2% of pulse amplitude.
TIME TO ACHIEVE FLAT TOP: less than 7 nsec.
(Trailing Edge Only):
OVERSHOOT: less than 5%.
ROUNDING: less than 5%.
TIME TO SETTLE WITHIN 2% OF BASE-LINE: 10 to 25 nsec, varies with width setting.
BASE LINE SHIFT: less than 0.1% under all conditions.
PULSE WIDTH BETWEEN 50% POINTS: continuously adjustable, 0 to 100 nsec. Dial accuracy within ±5% ±3 nsec; width jitter less than 50 psec.

*Measured with -*hp*- 185A/B Scope, 187B Plug-in, 187B-76E Tee Connector with -*hp*- 908A 50-ohm Termination and Weinschel Engineering 30 db pad type 50-30.



ATTENUATOR: 0-12 db in 1 db steps. Absolute accuracy within ±0.1 db.
SOURCE IMPEDANCE: 50 ohms; less than 3% reflection when driven by 1 nsec rise time pulse from external 50-ohm system.

REPETITION RATE, TRIGGER AND TIMING SPECIFICATIONS

INTERNAL REPETITION RATE: less than 100 pps to greater than 10^6 pps in 4 ranges; period jitter less than 3×10^{-3} of period. Vernier provides continuous adjustment of rep rate on each range.
MANUAL: push-button single pulse.
EXTERNAL TRIGGERING: ac coupled input accepts sine waves from 10 cps to 1 mc, pulses from 0 to 1 mc.
TRIGGER LEVEL: trigger level continuously variable, from approximately +8 to −8 volts.
TRIGGER SLOPE: switch selects positive or negative slope.
SENSITIVITY: requires minimum of 1v peak-to-peak; trigger pulses must be at least 30 nsec wide.
INPUT IMPEDANCE: approximately 50 ohms or "High Z" selected by front panel switch; "High Z" is approximately 100k ohms for (−) slope setting and approximately 5k ohms for (+) slope setting.
COUNTDOWN: synchronizes with any frequency up to 100 mc (>2v rms) by counting down to some submultiple less than 1.3 mc; jitter is less than 10% of cycle of external frequency.
EXTERNAL TRIGGER DELAY: delay time between 2 volt, 2 nsec rise time step at trigger input and leading edge of output pulse is fixed at ≈ 300 nsec; jitter is less than 50 psec referred to triggering signal.
EXTERNAL GATING: in "gated" mode, +1 volt gate signal allows pulses to reach output terminal.
TRIGGER OUTPUT PULSE:
WIDTH: 50 nsec ±20% into 50 ohms.
AMPLITUDE: greater than 1v peak into 50 ohms.
RISE TIME: less than 5 nsec.
POLARITY: switch selects positive or negative pulse.
TRIGGER ADVANCE: timing of trigger output pulse is continuously adjustable from 10 nsec delay to 140 nsec advance with respect to leading edge of output pulse; dial accuracy is within ±10% ±5 nsec; jitter is less than 50 picoseconds.
POWER REQUIREMENTS: 115/230 v ±10%, 50-60 cps, 0.7/.35 amp, 60 watts.
DIMENSIONS: 5¼" high, 16¾" wide, 18⅜" deep.
WEIGHT: Net 33 lbs., shipping 49 lbs.
ACCESSORY FURNISHED: -*hp*- 10120A coaxial cable 50 ohms ± ½ ohm, 3 ft. long, BNC to BNC.
PRICE: $1875.00 f.o.b. factory.
Data subject to change without notice

MEASURING SMALL, STRAY L AND C WITH NANOSECOND PULSES

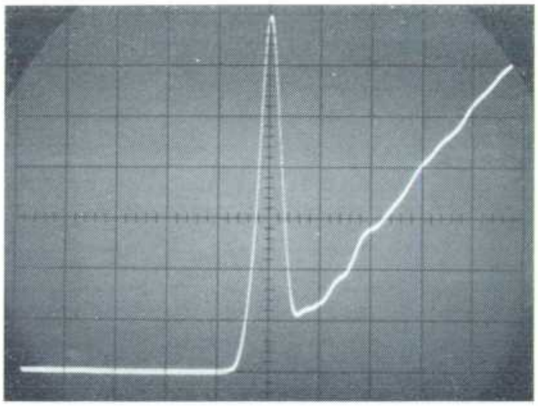


Fig. 1(a) (at left). *Oscillogram showing measurement of small inductance of ¼" leads on 1000-pf capacitor. Vertical scale is calibrated at 1 nanohenry/cm; sweep speed is 2 nsec/cm.*

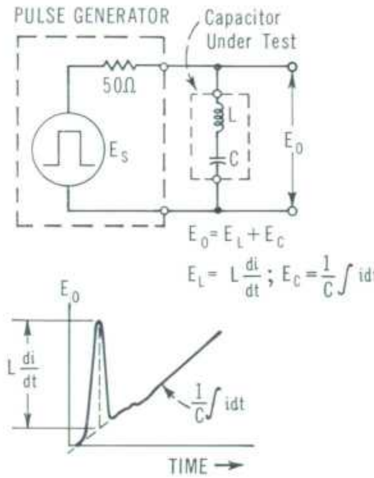


Fig. 1(b) (at right). *Explanatory drawing for Fig. 1(a).*

Transient response measurements made on nanosecond time scales can distinguish the effects caused by stray impedances from the effects caused by the basic circuit elements. Examination of these effects leads to an evaluation of the amount of stray capacitance and inductance associated with a circuit element. These measurements, based on the separation and evaluation of events which are closely spaced in time, have been made possible by the performance capabilities of the -hp- Model 185B sampling oscilloscope and the Model 215A nanosecond pulse generator.

Any physical capacitor has a small amount of inductance in the leads, as shown in the equivalent circuit of Fig. 1. When a high rate of change of current is applied to this capacitor, the total capacitor voltage initially is only the inductive voltage, $L(di/dt)$, provided that the voltage across the capacitance ($\frac{1}{C}\int idt$) has not had time to build up significantly. The height of the initial "spike," as shown in the waveform of Fig. 1, is proportional to the series inductance.

A simplification in measurement results if the rate of change of current is assumed constant, which occurs when the generator behaves as a constant current source. This is the case when the $L(di/dt)$ voltage turns out to be much less than the driving voltage, E_s, and is true for inductances of less than 25 nanohenries driven by 1 nanosecond risetime steps from a 50-ohm source. The oscilloscope vertical deflection may then be calibrated with the $L(di/dt)$ voltage of a known inductor, and the value of other small inductances scaled from their measured $L(di/dt)$ voltages.

The known inductor can be constructed from a measured length of coaxial cable shorted at one end. The cable inductance is calculated from the formula $L = Z_0^2C$, using the known cable characteristic impedance Z_0 and the measured capacitance C. For example, a 50-ohm cable with 2.5 pf/inch distributed capaci-

Fig. 3 (above). *Capacitor (in tee) of Fig. 1(a) and diode (outside) of Fig. 6(a) were placed in -hp- 187B-76E tee for measurement of their lead inductance. Scale of parts can be judged from size of small BNC connectors at ends of tee.*

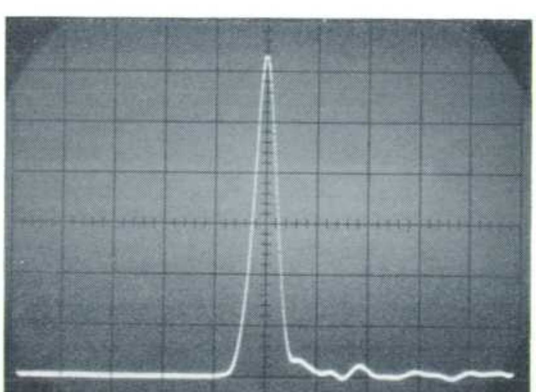


Fig. 2 (at left). *Oscillogram showing how oscilloscope was calibrated for Fig. 1(a) by spike from known length of shorted 50-ohm cable.*

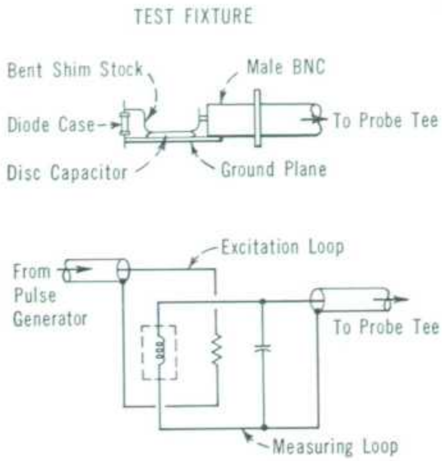
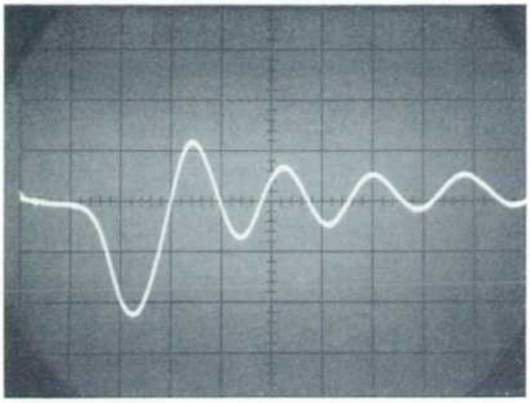


Fig. 4 (at left). *Test fixture and circuit arrangement used for measuring diode case inductance.*

Fig. 5 (at right). *"Ring" induced by arrangement of Fig. 4 in test for comparing inductance of fine wires for diode whisker contacts. Sweep speed is 1 nsec/cm; calculations show measured L of 1.3 nanohenries of which 0.8 nh was estimated for fixture.*



tance gives $L = (50)^2\ (2.5 \times 10^{-12}) =$ 6.25 nanohenries/inch. One inch of this cable, with the far end shorted, was used to obtain the calibrating waveform shown in Fig. 2.

If a more precise determination of circuit inductance is desired, and the circuit under test is in the form of a loop, another method is useful. Either the actual loop, or an exact replica with all series diodes, capacitors, and other elements replaced by equivalent lengths of wire, is assembled. A small ceramic disc capacitor without leads of any kind is soldered into a gap directly in series with this circuit.

A small loop across the 215A output, placed physically adjacent to the circuit, inductively shock excites a resonance around the loop during each pulse. The period T of the resulting "ring" is observed across the capacitor with an -hp- 185B sampling scope. The inductance then can be found from the formula $T = 2\pi\sqrt{LC}$, or $L = T^2/4\pi^2C$. An example is shown in Fig. 5. This works even when the circuit "Q" is so low that the "ring" lasts for only a few cycles, a situation in which grid-dip meters and other methods usually fail to obtain an indication.

If the lead inductance of a circuit element having some resistance is to be measured, such as a forward-conducting semiconductor diode, the resistive drop is subtracted from the total peak voltage, as shown in Fig. 6. The inductance then is proportional to the overshoot, except for the case described in the following.

Some semiconductor diodes generate overshoot within the diode chip. This effect is isolated by the cancellation procedure diagrammed in Fig. 7. (Here, apparently, the B channel is looking at a cable ground; actually, the surge impedance of the cable loop is much larger than the inductive reactance of the dummy case, so that the two "ground" points appear isolated to nanosecond risetime steps). A dummy case with leads shorted internally, or an equivalent length of wire, is placed in series with the measured device. Overshoot from the dummy inductance is subtracted from the total device overshoot when the dual channel oscilloscope is used in the A-B mode, yielding the inherent semiconductor overshoot. The inductive

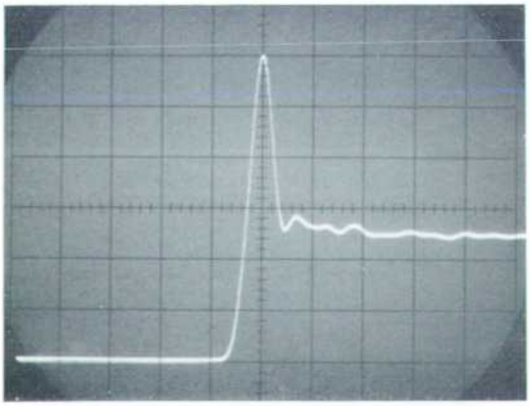


Fig. 6(a). *Oscillogram showing spike in measurement of diode lead inductance.*

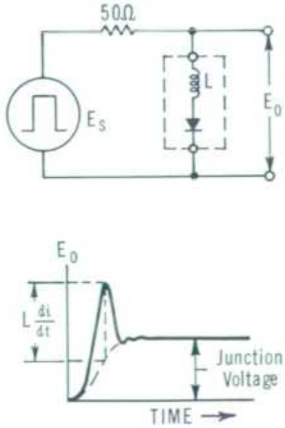


Fig. 6(b). *Explanatory drawing for Fig. 6(a).*

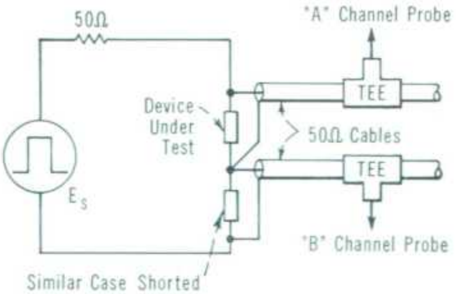


Fig. 7. *Arrangement used to separate inherent device overshoot from lead and case inductive responses. Tees are -hp- 187B-76E's.*

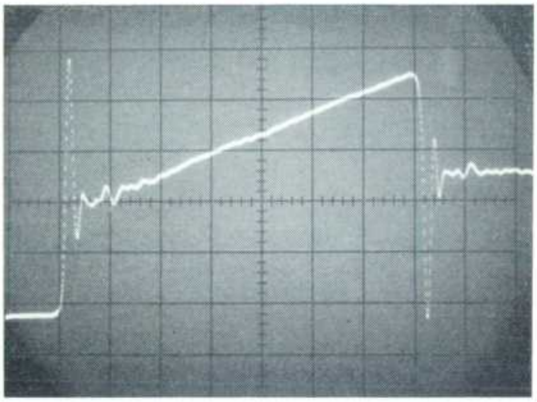
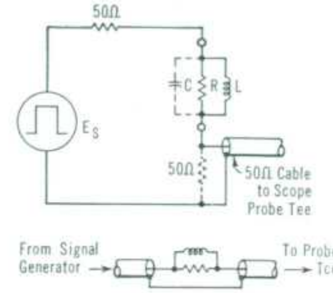


Fig. 8(a) (at left). *Oscillograms showing waveforms in measuring small C shunting 1K and 2.2 µh R-L combination. Sweep speed is 5 nsec/cm.*



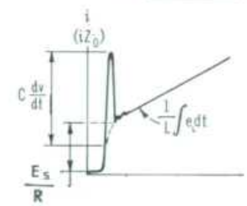


Fig. 8(b) (at right). *Explanatory drawing for Fig. 8(a).*

overshoot is then represented by the B channel.

MEASURING CAPACITANCE

Small, stray capacitance is measured by the dual of the inductance measuring circuit, a series circuit as shown in Fig. 8 rather than a parallel circuit. The measured element is placed in series with the 50-ohm cable and tee feeding the sampling oscilloscope probe. The capacitance couples the initial fast rise of the test pulse directly to the 50-ohm scope cable, as would occur with any other differentiating circuit.

As in the inductive case, the amplitude of the leading edge spike is proportional to the capacitance if the circuit time constant has a value much less than 10^{-9}. This is evidenced by e_{peak} being much less than the driving voltage. In view of the 100-ohm resistance through which the capacitor charges (50 ohms in the generator and 50 ohms in the cable), C should then be less than 10 pf ($C \approx 10^{-9}/100 = 10^{-11}$f) for meaningful results. As shown on the waveform, $i = C\frac{dv}{dt}$ so that $C = \frac{dv/dt}{i}$.

The iR voltage waveform seen by the oscilloscope actually is a representation of the current in the measured element. The very fast rise time of the 215A causes the $C\frac{dv}{dt}$ current to be much greater than the other components of current through the device, enabling measurement of capacitance in the presence of other shunt loadings.

A small, known capacitance can be used to calibrate the vertical oscilloscope display and the effects of other measured capacitances will be proportional. If lower series resistance is desired for measuring larger values of capacitance without increasing the time constant, shunt disc resistors may be put across the cables at the point of insertion of the tested circuit.

This test is useful, for example, in measuring the capacitance across small inductors, resistors, diodes and the like in the presence of other stray elements, as shown in Figs. 9 and 10.

—Charles O. Forge

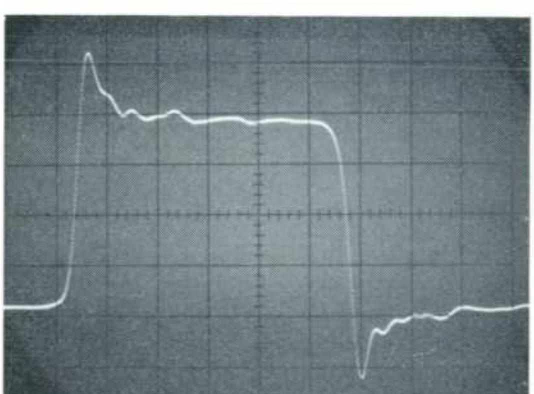


Fig. 9. *Oscillogram showing measurement of stray C shunting resistor.*

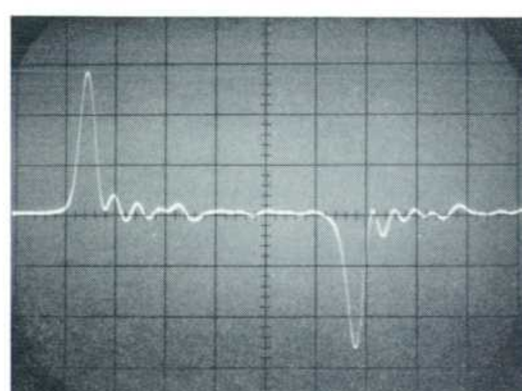


Fig. 10. *Oscillogram showing measurement of stray C shunting semiconductor diode.*