A Predictable Subnanosecond Step Generator

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***Abstract*—Determination of the response of a time domain instrument to a voltage step is preferable to determination in terms of its response to sine waves. Unfortunately the output waveshape of a voltage or current step generator cannot be evaluated as easily as that of a sine wave source. Consequently, investigators rely (or should rely) upon waveform predictability rather than waveform measurement when employing step generators in system characterization. One form of a predictable step generator is discussed that is useful in the subnanosecond to tens of nanoseconds time region after the step edge. A practical realization of this form is given that has predictability to within 1 percent in that time region from 350 picoseconds to 6 nanoseconds after an 80-picosecond rise-time step edge.**

Introduction

ENGINEERS presently make a great number of waveform measurements on systems of various kinds. Computers, telemetry equipment, and nuclear event counters are three examples of present day systems. A significant factor in the measurement of waveforms in such equipment is that they operate basically in the time rather than the frequency domain. The measurements performed to establish proper design or function are, therefore, also basically time domain tests, even though some of the waveforms are repetitive.

Two of the instruments used to make these time domain tests are the oscilloscope and the Y-T recorder. Both examples are designed with the ultimate goals of clean linear transient response in mind. Great pains are taken to insure time domain response fidelity. But—and this is an important but—the instrument's response error is absolutely definable only in terms of the frequency domain, not the time domain. A manufacturer may quote specifications for the step response of an instrument, but can guarantee the specifications only in terms of that instrument's response to one particular type of step generator.

Unfortunately, there is no such thing as a standard step generator or a standard oscilloscope. Thus the engineer may find discrepancies between time domain measurements made on his system by instruments produced by different manufacturers or even by different types of instruments produced by the same manufacturer.

It is important for the time domain engineer to realize that the step response of his measuring instrument is checked against the output waveform of a step generator and that this waveform cannot be rigorously measured and described as a function of amplitude versus time. As a matter of integrity, therefore, the instrument manufacturers must go to great pains to be sure that a step generator with an output that is predictable, if not measurable, is used for checking his manufactured product.

For time domains extending from several nanoseconds after the step edge, the form of step generator in common use as a pseudostandard is the current switch. A known predictable current that has been flowing into a resistive load is suddenly interrupted. After a period of time when the switching transients have died down, the voltage across the load resistor is found to be close to zero. In practical cases, the capacitances and storage effects of the current switching element limit the predictability of the step in the time domain extending from tenths of a nanosecond after the edge. This paper proposes a simple step generator to more adequately cover this shorter time domain.

Manuscript received June 28, 1968. This paper was presented at the 1968 Conference on Precision Electromagnetic Measurements, Boulder, Colo.

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Terms Used

The following abbreviations are used in this discussion.

I—current
V—voltage
TD—tunnel diode
I_p—TD peak current
I_v—TD valley current
V_p—TD peak voltage
V_{on}—TD ON or high-state voltage
R_{TD}—forward resistance of a tunnel diode
Z_0—characteristic impedance of a transmission line
T_R—rise time
T_L—propagation time of a transmission line of length L.

The Step Generator

The basic form of the step generator is very simple. A tunnel diode is inserted in series with the center conductor of a length of precision coaxial line. See Fig. 1.

The tunnel diode is mounted in a manner that keeps its lead inductance and shunt capacitance to a minimum. The transmission line is constructed in a manner that assures a constant Z_0 on either side of the diode. Assume for the moment that the line is lossless and that the diode is biased in its low-voltage state. If the bias on the diode is now very slowly increased, eventually a point will be reached where the current through it will exceed the peak current value and switching will occur. During this switching, the current flowing through the diode will be transferred to charging the shunt capacitance of the junction and to driving the losses present in the diode itself and the external load.

The immediate external load, of course, consists of

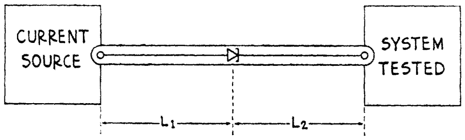


Fig. 1. Basic TD step generator analysis.

the transmission line; the diode sees an effective resistance of $2Z_0$ for a period of time. When the diode switches to its high state, a negative step of voltage equal to $\frac{1}{2}V_{on} - V_p$ propagates to the right.

A positive step of the same value propagates to the left. The final load, or system under test, may be located on either side of the TD. The current source for the TD is located on the opposite side.

When the TD fires, a positive step is sent toward the current source. Since the Z_0 of the line is constant, no reflections are sent back toward the tunnel diode until the wave reaches the current source. If this source has an impedance equal to Z_0, then no reflection occurs. In the practical case, let us assume

$$Z \text{ source} \neq Z_0.$$

A reflection then occurs at this time, equal to the transit time between the diode and the source (T_{L_1}). This reflection reaches the diode and propagates through its low impedance toward the system at a time equal to $2T_{L_1}$. A step of voltage thus propagates toward the system; a negative step in this example, it is free of aberrations except for effects caused by the inductance and capacitance of the diode and mount for a period of time equal to $2T_{L_1}$. If the input impedance of the system is not Z_0, a reflection will occur at the time the step arrives. This reflected energy travels back toward the tunnel diode; since the TD mount may be considered a discontinuity, a rereflection occurs from this point. If T_{L_2} is longer than T_{L_1}, this rereflection cannot cause an aberration in the $2T_{L_1}$ time region after the step. In practical cases, the rereflection is usually very small, measured in hundredths of a percent of the original step amplitude so that L_2 may be made much shorter than L_1, which has certain advantages in counteracting transmission line loss effects.

This form of step generator has been around for some time in the form of the mercury switch charge line pulser. The improvements in performance gained by using the tunnel diode could be had by producing a mercury switch or reed of equivalent size.

Sources of Aberrations

Four sources of transient aberrations are identifiable:

1) tunnel diode imperfections, including method of connection into the transmission line
2) the tunnel diode drive current waveform
3) transmission line Z_0 aberrations
4) transmission line loss effects.

Fortunately, for the majority of systems, the first source of distortion is not terribly important if reasonable precautions and the best available diodes are used. The effects caused by a typical high-speed pill package tunnel diode mounted in a 14-mm transmission system (ID of outer conductor = 14 mm) do not extend below frequencies in the vicinity of 9 GHz. See the Appendix.

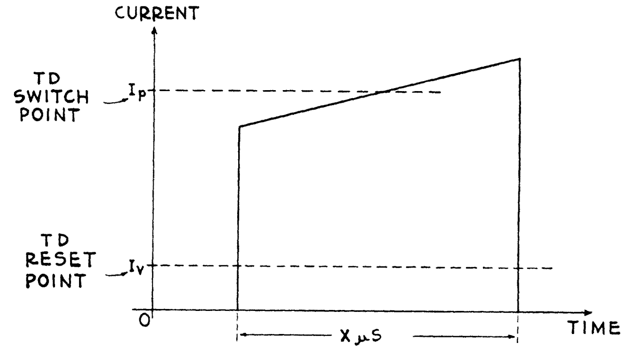


Fig. 2. Tunnel diode bias drive waveform.

Tunnel diodes are subject to thermal time constant effects, which become significant in the microsecond and submicrosecond time domains after switching to the high state. The effect of the heating of the junction when the diode is in the high state will be a decrease in the V_{on} of the device, resulting in pulse droop. Such effects may usually be ignored when operating in the nanosecond regions.

Unfortunately, the second source of transient aberration, the TD current drive source, is a direct contributor to distortion of the step, especially in this system. Any change in drive current is seen as a change in voltage across the Z_{in} of the system tested. Also, the dc component of the TD drive current appears as a voltage drop across the system resistance.

If the system has sufficient dynamic range to handle the dc voltage, then only the former problem is significant. If it does not have the range, then wide-band attenuators may be inserted between the step generator and the system or a resistor may be inserted in shunt with the system to provide a path for a direct current to balance out the tunnel diode bias. Either method is undesirable because each destroys a degree of the predictability of the step by introducing unknown attenuation effects between the switch and the system under test.

The drive current variation problem exists in all cases. A method of bias drive found preferable to the author is that of a dc step generator, which is adjusted to bias the diode to a current just below the peak. Then a slow ramp of current is added to this step. Values are adjusted to allow the tunnel diode to switch state at a point on the drive waveform where only very slow variations are present. See Fig. 2.

The tunnel diode is reset when the drive current drops below I_v. Since only slow and predictable variations of current are present at the time of switching, no high-speed transient aberrations are caused by the bias source.

Unfortunately, a drive waveform of this sort does not produce a jitter-free firing point with respect to the start of the bias step. The trigger for system recognition must be derived from the switching event itself. Only a system with built-in delay lines and trigger pickoff or one that is capable of random signal recognition is capable of using this bias drive method.

One form of step generator that is currently available to industry[1] uses a combination of current removal resistor previously mentioned and a unique system of displacement current injection probes for triggering the TD. This generator places a dc bias pulse on the TD, bringing it up to a bias point near I_p; a fast pulse of current is then injected from two very low capacitance probes to cause the TD to switch. See Fig. 3.

The predictability of the output of this type of step generator is less than that of the system previously described. It can be made to be in the 1 percent ball park for 350-ps T_R systems, however, and is useful for testing the response of a wider range of systems, because of the availability of the pretrigger pulse and the elimination of the TD bias currents from the load.

The third cause of aberration, that of transmission line Z_0 aberrations, is mechanically controllable. The mathematics governing the impedance of transmission lines are well known and no further mention will, therefore, be made here.

The fourth source mentioned is transmission line loss. The most familiar form that this loss exhibits is found in the rolling up of the transmitted pulse. See Fig. 4(a) and (b) (sweep time is 1 ns per division, horizontal). Nahman and Wigington covered this effect thoroughly in the literature.[2,3]

Another form of aberration that is less well known is the rollup seen by a Z_0 generator driving a transmission line. Illustrated in Fig. 5(a) and (b), this rollup starts at the 100 percent level. It is caused by the small reflections from the incremental Z_0 mismatches seen by the step as it traverses down the length of a lossy line. Each incremental length of the line has a small amount of series R that produces an equally small reflection. The total rollup displayed for a whole length of lossy cable is the sum of all these incremental bits, all of which are displaced in time from one another. Fortunately, this effect results in a rollup distortion that is only a small percentage of the incident transmission effect, where all the incremental losses are cumulative rather than dispersed.

It is interesting to note the effect of the 50-ohm termination on the reflected rollup display. The cable used in the illustrating figure is RG 174/U subminax, 110 ns long. The sweep time per division is 100 ns.

Another loss effect is caused by wave transmission through the line with modes other than transverse electromagnetic. If the step edge is fast enough to contain frequency components that will propagate down the line in a waveguide mode, then the presence of transmission discontinuities may excite these modes.

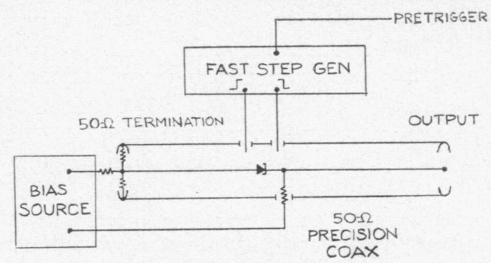
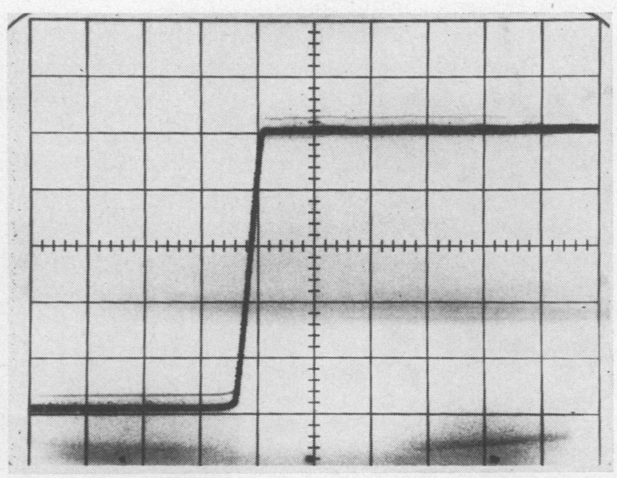
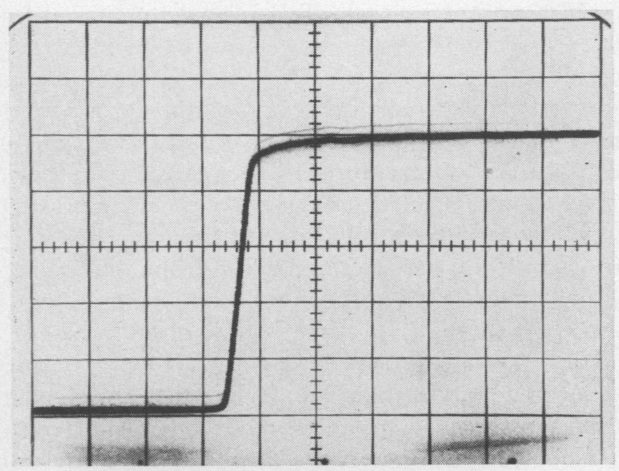


Fig. 3. Commercial step generator.



(a)



(b)

Fig. 4. (a) Voltage step. (b) Voltage step as distorted by series transmission line.

Effects of Sources of Aberration on Step

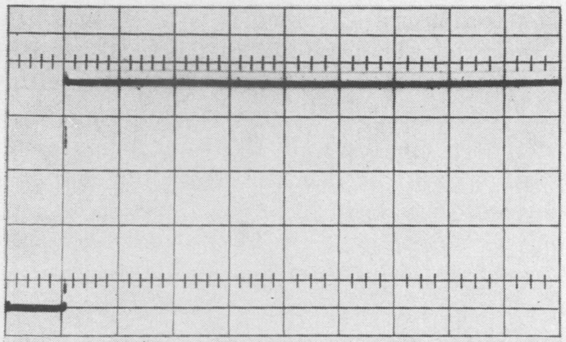
The effects of the aberration sources are almost intuitive, except, perhaps, for the ones for the reverse rollup and Z_0 variations of the transmission line.

1) The tunnel diode imperfections show themselves

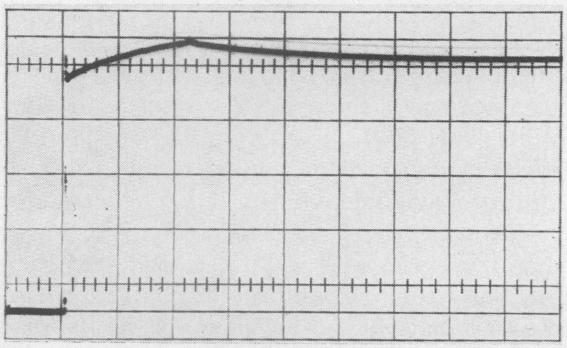
[1] Tektronix type 284.

[2] R. L. Wigington and N. S. Nahman, "Transient analysis of coaxial cables considering skin effect," *Proc. IRE*, vol. 45, pp. 166–174, February 1957.

[3] N. S. Nahman, "A discussion on the transient analysis of coaxial cables considering high frequency losses," *IRE Trans. Circuit Theory*, vol. CT-9, pp. 144–152, June 1962.



(a)



(b)

Fig. 5. (a) Voltage step into 50-ohm load. (b) Voltage step into lossy line, viewed at the source.

as overshoot and ringing at the leading edge of the step. Ringing frequency components of a well-designed and constructed system should be above 9 GHz, with the effect of no visible aberration in a 350-ps T_R or slower system (1-GHz 3-dB point).

2) Tunnel diode drive waveforms will result directly in aberrations on the displayed step.

3) Small transmission line Z_0 variations have practically no effect in the area of line between the generator and the system. If a 1 percent Z_0 aberration in the form of a step in impedance is present in this section of the signal path, a reflection ρ of

$$\rho = \frac{Z_{0+1\%} - Z_0}{Z_{0+1\%} + Z_0} = \frac{1\%}{2Z_0 + 1\%} \cong 1/2\%$$

will be sent back toward the generator. The tunnel diode, if a low forward R type is used, will cause a rereflection ρ of 2 percent ($R_{\text{TD}}=2$ ohms in a 50-ohm system) or less to an incident wave. The rereflection from the 0.5 percent developed will thus be 0.5 percent $\times 2$ percent $=0.01$ percent.

For the same reasons, it can be seen that the system tested can have an impedance that does not match the Z_0 of the line without severe problems, even if the line between the step generator and the system is very short. This fact has definite advantages when incident transmission losses are considered.

Transmission line Z_0 variations between the tunnel diode and the current source show up directly as transient aberrations and are very important. A 4 percent Z_0 variation in this region would cause a 2 percent aberration in the step. When the TD switches, a negative step propagates toward the system. A positive step goes toward the current source. If a positive change in Z_0 occurs, a positive reflection is seen a double transit time later at the tunnel diode, which reflection subtracts from the amplitude of the negative step.

The result is an apparent reversal of what is normally seen in time domain reflectometry[4] caused, of course, by the different polarities of the incident waves traveling to the load and to the current source, respectively.

4) Transmission line losses affect the incident wave. The system under test should, therefore, be as closely connected to the step generator as possible. Reflected rollup caused by losses in the L_1 section of line cause overshoot effects in the displayed step; the inversion of the expected result again comes from the different polarity of the steps in the L_1 and L_2 lines. The step seen by the system under test starts out at the correct amplitude and then decays. Fortunately, the effect is small, usually showing up as small fractions of a percent in the time domain extending to a few nanoseconds after the step edge.

Checking Aberrations to Predict Step Response

Checks are possible on the different sources of step aberration.

1) The tunnel diode may be examined in several different ways. Sample tunnel diodes may be purposely burned out by forward current overload in order to obtain mechanical samples to check outer package capacitance. Diodes that have failed in normal use can be used for this test, if the cost of this procedure scares the user. Inductance can be checked without destruction, as can forward resistance and inner junction capacitance. Predictions of ringing time constants may be made from these tests. Perhaps spectrum analysis of a sine-wave-driven TD can yield results.

The thermal time constants may be measured by observation on a well-calibrated sampling or real-time oscilloscope.

2) The tunnel diode bias generator can be designed and built to produce waveforms with no high-speed events in the region of TD switching.

3) and 4) The transmission line can be checked by means of insertion loss measurements[2,3] and time domain reflectometry methods[4] for incident losses, reverse rollup effects, and Z_0 variations.

Measurements Made on a Practical System

Fig. 6 shows the connections made for test of a practical system for transient aberrations.

The mechanical assembly diagram for the TD mount is shown in Fig. 7.

[4] Type 1S2 Sampling Unit Instruction Manual, Tektronix, Inc., sec. 2, 1966.

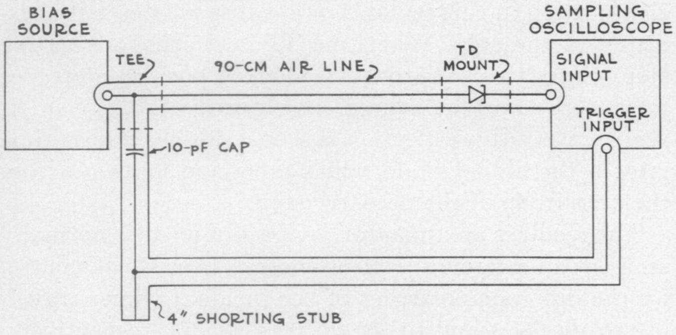


Fig. 6. Practical test system for type S-1 sampler.

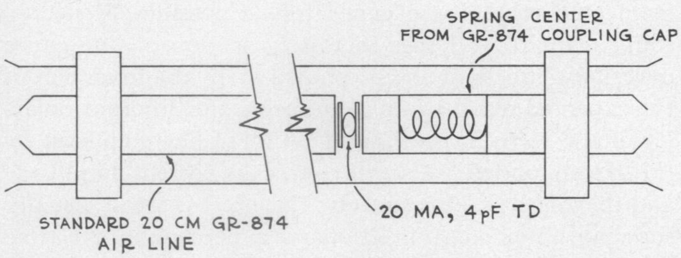
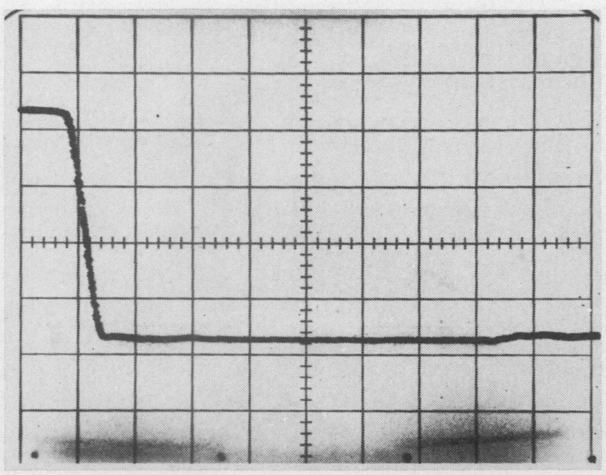
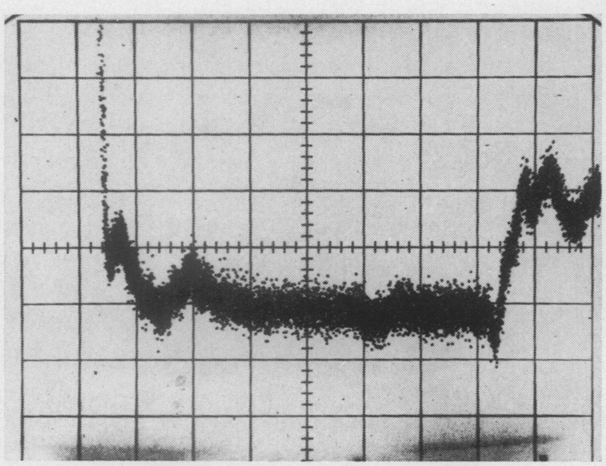


Fig. 7. Tunnel diode mount.



(a)



(b)

Fig. 8. (a) System response—25 percent per division. (b) System response—1 percent per division.

Using techniques discussed in a previous section of this paper, the step generator in this practical example was predicted to have an output waveshape with transient defects limited to below one-half of one percent of the total step amplitude in the time region extending from 350 ps to 6.5 ns after the edge. It should again be emphasized that verification of the step generator's response is not possible; it is only possible to predict what it will do. Thus the transient aberrations present in the waveform photographs are caused almost entirely by defects in the system tested, except in the cases where aberrations are deliberately introduced.

Triggering for the sampling oscilloscope was accomplished by performing a double differentiation on the bias plus positive TD waveform, insuring that the fast positive edge emanating from the tunnel diode switching event would be the trigger. In Fig. 8(a) and (b) the displayed edge is shown at a sweep rate of 1 ns per division and at a magnification of 25 percent per division and 1 percent per division, respectively. Fig. 9(a) shows the same waveform as Fig. 8(b), except that the joint between the TD mount and the 60-cm airline has been pulled apart, causing a transient aberration to occur about 1 ns after the leading edge. The same is true in Fig. 9(b), except that here the joint between the 60-cm and the 30-cm airlines was pulled apart. Fig. 9(c), on the other hand, shows the effect when one of the connectors between the step generator and the system was pulled almost open.

Fig. 10 shows the response of the commercially available pulser at a vertical resolution of 1 percent per division, indicating that it has good response, despite the design compromises. The sampler output was inverted in this photograph for comparative purposes.

The 3-ns 1.5 percent rollup shown in the photographs is almost entirely caused by the sampler. The 1 percent bump 1.4 ns after the edge is also in the sampler.

Conclusion

Although it is not yet possible to verify the transient behavior of step generators, it is possible to construct a step generator having predictable output to within one percent before and after a subnanosecond transition.

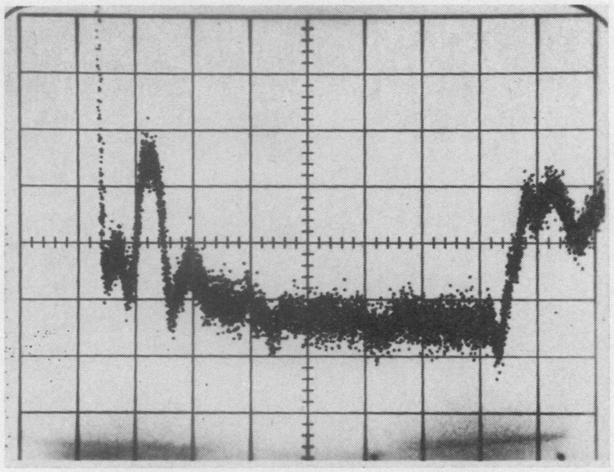
Appendix

An analog computor was used to evaluate the switching characteristics of a typical pill package tunnel diode equivalent circuit. The circuit used is shown in Fig. 11. The equations that describe the operation of this circuit are

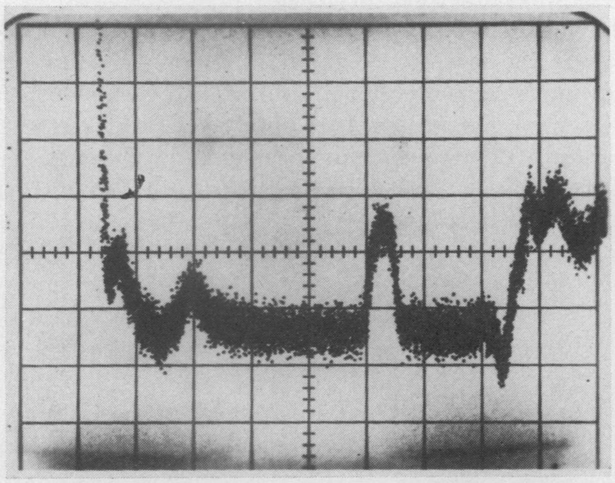
$$e_1 = \frac{1}{C_1}\int (i_1 - i_g - i_2)dt$$

$$i_G = e_1 G$$

$$-i_2 = \frac{1}{L}\int (e_2 - e_1)dt$$



(a)



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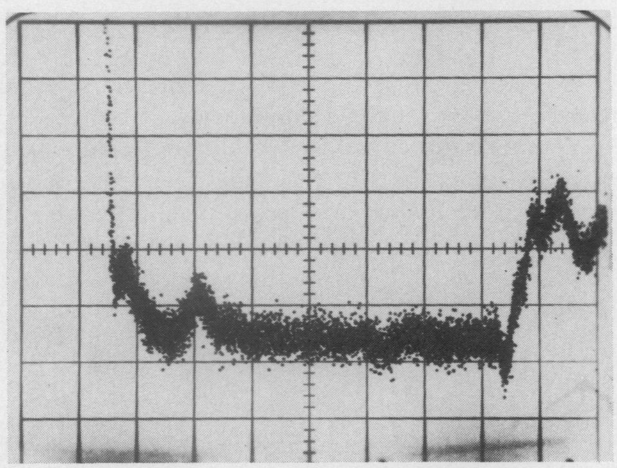

(c)

Fig. 9. System response with inserted aberrations (see text).

$$e_2 = \frac{1}{C_2}\int (i_2 - i_{TD})dt,$$

where

G = external load conductance
C_1 = TD case capacitance
L = TD internal inductance

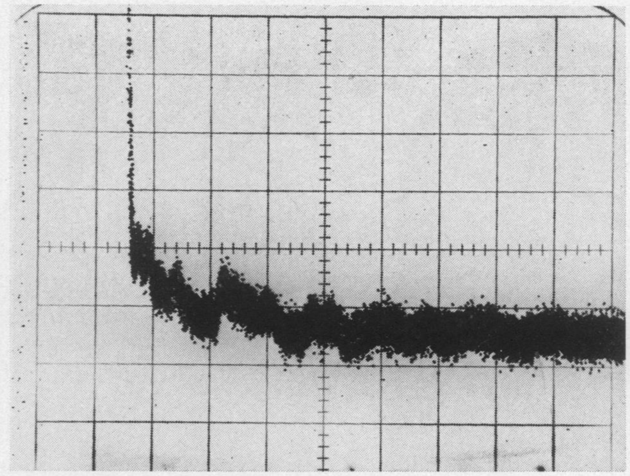

Fig. 10. System response to commerical pulser.

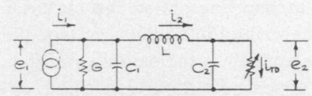

Fig. 11. Tunnel diode equivalent circuit.

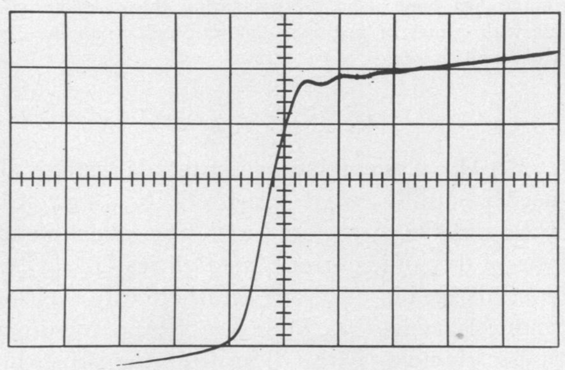

Fig. 12. Computer solution to TD equivalent circuit.

C_2 = capacitance at TD junction
i_{TD} = TD junction current as a function of voltage (basic TD characteristic).

Values that fit a typical high-speed tunnel diode are

$L = 0.1$ nH	$C_2 = 5$ pF	$I_p = 50$ mA
$C_1 = 0.33$ pF	$G = 10^{-2}$	$V_p = 0.5$ volt.

The analog computer solution of e_1 is shown in Fig. 12. The forcing function i_1 was a linear ramp, accounting for the positive slope seen in the waveform. The vertical scaling is 100 mV per major division; horizontal scaling is 50 ps per division.

Physical dimensions of the pill are 0.030 inch in thickness, 0.060 inch in diameter.

Acknowledgment

The author wishes to thank T. Charters and F. Kawabata for their contributions to the pulse generator effort and Mrs. Fern Rowland for preparing the manuscript. Thanks also go to Tektronix, Inc., for enabling the presentation of this paper.