NANOSECOND PULSES:
techniques & applications

By DONALD E. LANCASTER

Some important uses for these ultra-short pulses are in the fields of electro-optics, measurements, and circuit analysis.

A NANOSECOND (10^{-9} second) is but the briefest instant—one billionth of a second or the time it takes light to travel a mere 11.8 inches. In fact, there are more nanoseconds in a second than there are seconds in thirty years. The techniques for electronically generating nanosecond-wide pulses are as bizarre as the pulses are short. One method purposely exceeds the breakdown rating of a transistor. A second method uses special diodes whose recovery times are made quite long. For a third, the spark gap is removed from a dusty shelf, polished up a bit with modern techniques, and given an important and presently unbeatable place in state-of-the-art electronics.

The resulting pulses have now opened up many important new electronic applications, particularly in electro-optics, measurements, and circuit analysis. Other important areas are in the fields of radar and microwave studies, transmission-line testing, and for use as electronic shutters.

Applications

An injection diode laser consists of a *p-n* semiconductor junction that emits coherent light when it is pulsed with a short, high-current impulse. Operation often takes place at supercool temperatures with emission normally being in the near-infrared region. Nanosecond techniques are called upon to provide the required power pulses. These lasers are of value in film-exposure tests, high-frequency communications, and optical-response testing.

Light modulators usually consist of a capacitor with a transparent dielectric of KDP or some similar material. As the applied voltage is varied, the plane of polarization of the cell changes. By combining one of these with a polarizing filter, an electrically variable diaphragm results in which the brightness (actually the attenuation) of the transmitted light is a function of the applied voltage. If an electro-optic modulator is powered by a nanosecond pulse, a shutter open for one nanosecond results. This is of tremendous importance in high-speed photography.

Typical modulator units are called "Pockels cells." These have a capacitance of around 1000 picofarads and require several hundred volts to operate properly. To charge a 1000-pf. capacitor to 100 volts in 0.1 nanosecond requires 1000 amperes of current. This is why there is such a demand for extremely high-current nanosecond pulses. Actually, the modulator itself dissipates very little power and only requires the extreme currents to charge or discharge its own capacitance during the turn-on and turn-off transitions.

Other forms of electro-optic modulators are beginning to demand more and more from the nanosecond sources. Typical applications are extreme bandwidth communications links using c.w. lasers and other similar laboratory devices.

There are some rather elaborate mathematical proofs that can demonstrate that the response of any linear network to any arbitrary input signal can be exactly determined if the *impulse response* is known. An impulse is defined as a pulse of zero width, infinite amplitude, and unity area. Obviously, these do not exist in the real world, but for many applications, the nanosecond pulses form an excellent approximation. By pulsing a network with a nanosecond pulse, its impulsive response may be measured. Then, by using a mathematic technique called "convolution," the response of the network to an arbitrary input may be precisely determined. This is a very important new circuit-analysis tool.

A less elegant and more practical application of impulsive testing is *time-domain reflectometry*. It is important in v.h.f. and microwave work, particularly for measuring and evaluating transmission lines and other distributed networks. As an example, an unknown transmission line could be connected to a generator that produces a step input with a nanosecond rise time and the other end of the cable could be terminated in a known impedance. The voltage at the input to the cable is then monitored by a sampling oscilloscope. The time it will take the first reflection to return will equal twice the electrical length of the cable. The amplitude and polarity of the return will indicate the characteristic impedance of the cable, and the rate the returns diminish tells the attenuation of the cable. Any noise will indicate cable faults and discontinuities; the time delay between discontinuities and the input will show the exact location of the fault.

If 100-picosecond (100×10^{-12} sec.) risetimes are available, discontinuities only 1.18" apart can be resolved and separately evaluated. Large-scale models may be used to resolve smaller prototype distances.

The nanosecond pulses are now finding their way into radar. In a normal pulse radar, a one-nanosecond pulse could, in theory, give a one-foot resolution at close range. This should prove important in applications such as highway safety radars, and measuring devices for high temperature, fast moving, radioactive, or otherwise untouchable objects.

Another new application is harmonic generation. Nanosecond pulses invariably have a very high harmonic content. By filtering the desired harmonic, any multiple of an input frequency may be obtained. With this technique, frequency mul-

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tiplication of very high orders is possible. The efficiency is the same as it would be with conventional varactor multipliers, but far fewer stages are normally required. Similar techniques may be utilized to generate test pulses that are only a few cycles long at microwave frequencies.

Conventional Techniques

All the conventional techniques for generating short, high-power pulses are pretty much device-limited to pulses longer than ten nanoseconds. The gas-tube modulator is often used for radar work, but, at best, ionization times of 10 to 40 nanoseconds are available, and the tube simply will not turn on in one nanosecond. Vacuum tubes, in turn, are limited by their poor "on" impedance, their stray capacitances, and their inability to provide a low impedance for negative-going input signals. Some u.h.f. lighthouse and pencil-triode tubes are useful for amplifying nanosecond pulses already generated, but they are largely incapable of generating these pulses by themselves.

Conventional solid-state devices are also limited by present-day technology. The best of power transistors require 20 to 50 nanoseconds to switch any large amounts of power. Lower level logic circuitry can work with 10-nanosecond risetimes but only with limited power capability. Unsaturated logic techniques using u.h.f. transistors now break the nanosecond barrier, but only at very low power levels and supply voltages. The same is true of tunnel diode pulse circuits.

We can arbitrarily draw a line somewhere around 5 nanoseconds. Slower risetimes and wider pulses are obtained by conventional techniques. Faster or narrow pulses require the use of special nanosecond techniques.

Avalanche Transistors

The avalanche turn-on of a transistor is extremely fast and not current dependent. Efficient, powerful nanosecond pulses are easily generated in this manner. Fig. 1A shows the characteristics of a typical diffused silicon transistor. Notice the difference between the breakdown voltages for the zero base-current curve as compared with the other curves. The circuit in Fig. 1B uses this difference to advantage. The circuit is biased to point "A" on the curve of Fig. 1A by the high-voltage collector supply and resistor *R*1. *R*1 also charges *C*1 to the same voltage as point "A" after the power is applied.

If the base of *Q*1 is now pulsed with any reasonably fast waveform, the transistor goes into avalanche conduction and assumes a very low impedance state. (The mechanism is the same as in the four-layer diode or SCR.) As long as *C*1 can supply current through the transistor to the load R_L, the transistor remains in the "on" state. When *C*1 is nearly discharged, the transistor turns "off," *e.g.* returns to a non-conducting state. *R*1 is always made large enough so that it cannot hold the transistor avalanched and after turn-off *R*1 recharges *C*1 slowly, rebiasing the transistor to point "A" to await a new input trigger pulse.

The avalanche current forms an output pulse across R_L. Typical risetimes of one nanosecond are easily achieved. The pulse width is determined by the value of *C*1 and R_L. During the avalanche time, the transistor dissipation is extremely high, but the long duty cycle between pulses averages out the *total* dissipation to a value within the transistor's rating.

If a flat-topped output pulse is needed, the capacitor may be replaced by an open-circuited transmission line. This is shown in Fig. 1C. The transmission line will provide a constant avalanche current for a time equal to its electrical length. This is around 1.6 nanoseconds per foot for most coax. Now the output is a rectangular pulse equal to the electrical length of the cable and has a steep rise, a flat top, and an abrupt fall time.

Most diffused silicon transistors can operate in avalanche mode. The 2N706 is an inexpensive transistor that will produce a one nanosecond rise and fall time with 20 volts of output into a 50-ohm load, giving a peak pulse power of 8 watts. To stay within the 300-milliwatt rating of the device, a duty cycle of 24:1 or less must be adhered to. In the interest of safety margins, 100:1 is a more realistic figure. If the pulse width is 10 nanoseconds (as would be the case with a six-foot length of coax used as a delay cable), the maximum permissible repetition rate would be once each microsecond, or one megacycle. The width of the pulse is determined by the delay or width cable, and can range from 1 to 500 nanoseconds. "Trombone" adjustable-length transmission lines can give continuous adjustment of pulse width.

Special avalanche transistors which have been optimized for avalanche operation are also available. Cost ranges from $10 to $40 each. Using these special transistors, 500-watt, 2-nanosecond-wide pulses can be easily produced across very low impedance loads.

It is very important to keep the leads extremely short on all nanosecond circuits as the lead inductance can interfere seriously with the fast risetimes. Because of this, strip-line and other v.h.f. techniques are generally used for this type of circuit.

The avalanche technique is presently limited to risetimes of 1 nanosecond or more and pulse powers of less than half a kilowatt, but it has advantages of moderately low cost and simplicity combined with low jitter and high repetition rate.

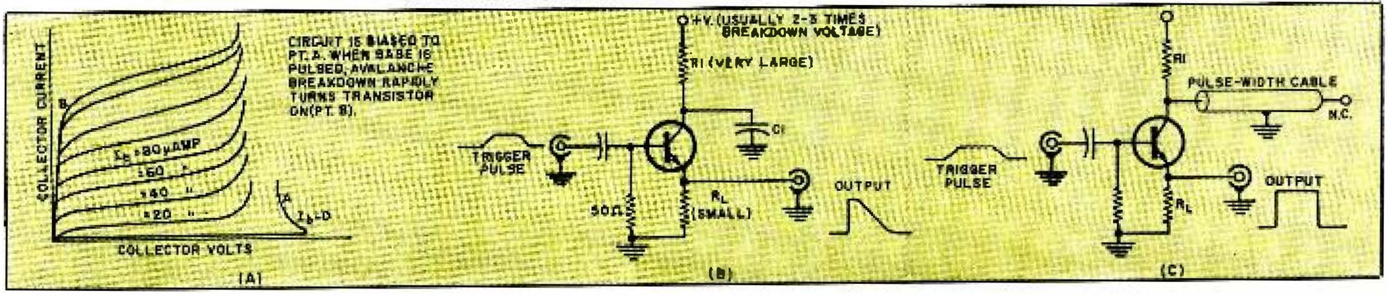
Step-Recovery Diodes

A new class of diodes makes possible the fastest pulses and waveforms available today, but is currently limited to pulses less than 30 volts in amplitude and pulse powers well under 100 watts. Pulse widths as short as 50 *picoseconds* (1/20 nanosecond) are obtainable using these devices.

Any semiconductor diode has a storage time based on the finite mobilities of carriers in the semiconductor material. If the forward bias on a diode is suddenly reversed, the diode will continue conducting for a storage (reverse recovery) time determined by the diode itself and the amount of forward current that was present before the turn-off. In normal high-speed diodes, it is highly desirable to reduce the storage time to as low a value as possible. In a step-recovery diode, the opposite is the case. The storage time is made quite long, but the diode is designed so that *the diode ceases conduction very abruptly at the end of the storage time*, producing a turn-off waveform that is extremely steep. This abrupt cessation is called the *transition time*. Presently available diodes have transition times as short as 50 picoseconds.

Fig. 2A shows the important differences between an ordi-

Fig. 1. (A) Avalanche biasing. (B) C1 produces fast-rising current pulse. (C) Transmission line produces rectangular pulse.



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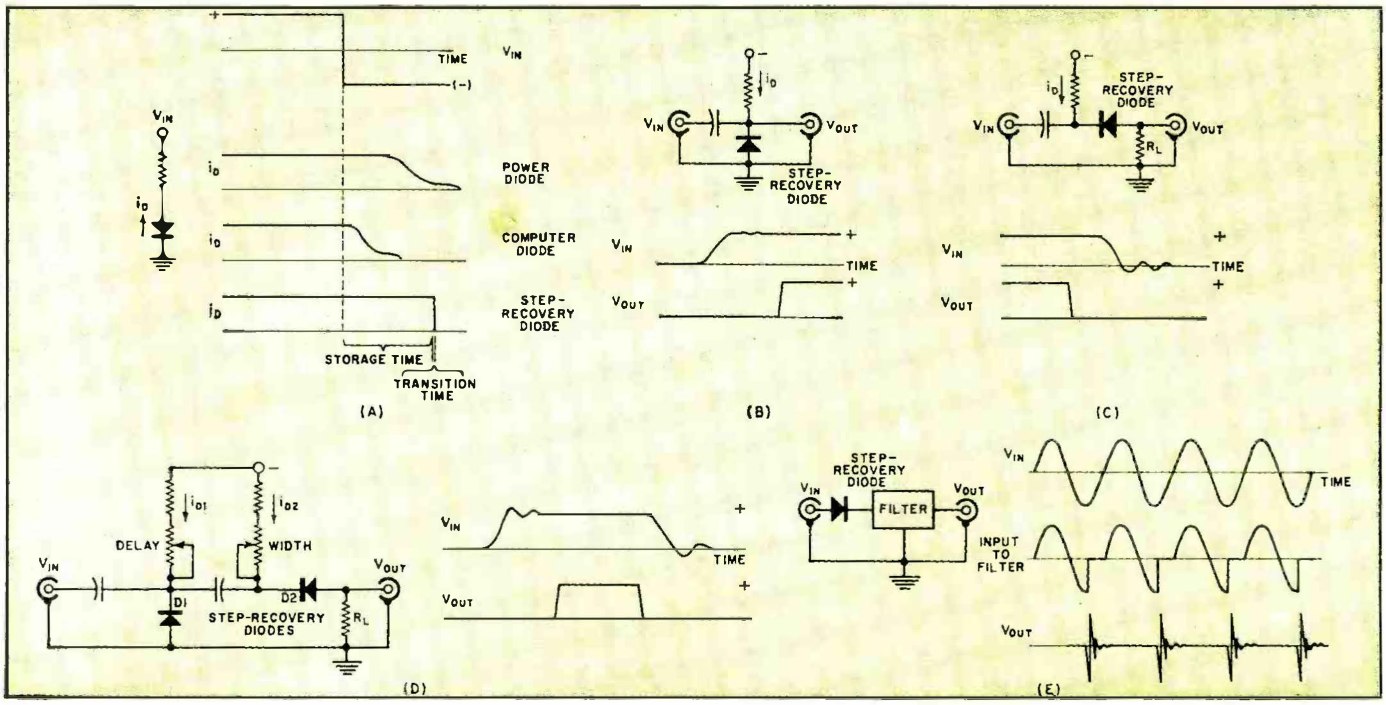

Fig. 2. (A) Recovery-time plots show difference between step-recovery and ordinary diodes. (B) Leading-edge sharpening. (C) Trailing-edge sharpening. (D) Rectangular-pulse generation. (E) High-frequency pulse-train generation.

nary and a step-recovery diode as the two are abruptly reverse-biased, while Fig. 2B shows how a step-recovery diode may be used to steepen the front of a waveform having a poor risetime. In the absence of an input, the diode is normally conducting some forward current, and since it is shunting the output, no input signal will appear at the output.

An input with a risetime of a few nanoseconds (usually generated by conventional transistor circuitry) attempts to turn off the diode, producing a step waveform at the output with a risetime of less than a nanosecond.

Varying the forward current of the diode will, in turn, vary the storage time anywhere from 1 to 500 nanoseconds. The risetime of the input waveform is immaterial as long as the step-recovery diode is adjusted to have a storage time long enough to allow the input to assume a stable value.

Fig. 2C shows the opposite circuit. Here a step-recovery diode in series with the output is used to steepen the end of a waveform with a poor fall time. Again the diode is normally conducting heavily, but the input signal now appears simultaneously at the output and tries to stop conduction through the step-recovery diode. The diode continues conducting for the storage time and abruptly ceases conduction, this time *removing* the input signal from the output terminals.

Where rectangular pulses are desired, Figs. 2B and 2C may be combined, as in Fig. 2D. Here the first step-recovery diode steepens the risetime and the second steepens the fall time, leaving a rectangular pulse carved out of the middle of the input waveform. Varying the current through the first diode varies the *time delay* between the input pulse and the start of the output pulse. The current through the second diode controls the *width* of the pulse.

Fig. 2E shows yet another technique. Here a high-frequency sine wave is fed to a step-recovery diode that has a storage time of one-fourth the period of the input wave. The diode produces an abrupt turn-off midway in each negative half cycle. An output filter is added which passes only the steep transition and rejects the fundamental sine wave and the d.c. component. This produces a train of output pulses with extremely fast risetimes and a very high repetition rate. Repetition rates of 100 megacycles are possible, combined with 50 to 100 picosecond risetimes.

These components are somewhat expensive, ranging from a low of $15 to a high of several hundred dollars for the more exotic types. Strip-line and other low-inductance pill packages that minimize the amount of circuit inductance as much as possible are now readily available.

Spark-Gap Nanopulser

The spark gap may seem a crude electronic component, but carefully designed models can produce waveforms with nanosecond risetimes and peak currents of *several thousand amperes*, combined with peak voltages of several kilowatts. The price paid for such extreme power is a very low duty cycle. Normally, only a few pulses per second are possible. Further, there is quite a bit of pulse-to-pulse jitter, and synchronization requires an input that already

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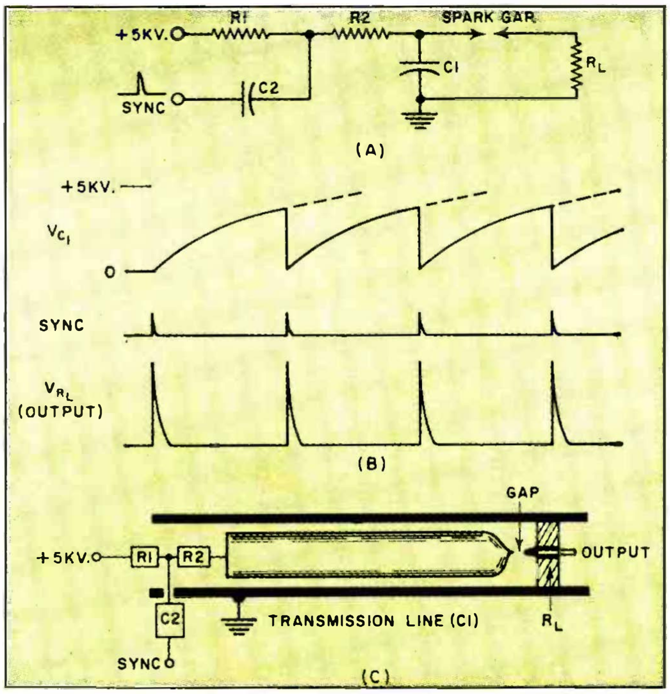
Fig. 3. (A) Spark-gap circuit (B) waveforms, (C) configuration.



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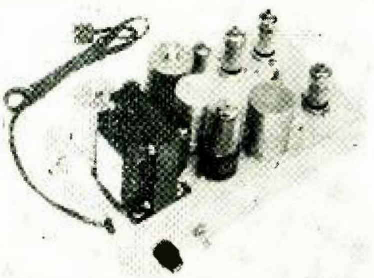

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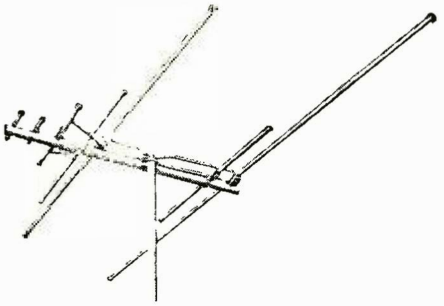

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is checked by turning the chroma control slowly counterclockwise. The color should become pale and finally disappear. Since some receivers are equipped with an automatic chroma-control circuit, the rate of fading will depend upon the model under test. Most receivers will hold color sync just before the color disappears, as evidenced by diagonal running of the colors. Both of these conditions indicate normal operation of the color sync circuits. If, however, a slight reduction of the chroma amplitude causes the color to fall out of lock, it indicates that the color synchronization ability of the receiver may be inadequate.

The ten bars of color in the pattern can be checked to see that they "fit" in the proper position. The colors should not lap over the blank spaces between the bars. Improper fit may be caused by incorrect delay in the video amplifier or by incorrect alignment of the band-pass amplifier. Normal receiver overscan may hide some of the bars of the pattern. These can be seen by reducing the raster width. Overscan adjustment of the set can be checked and adjusted by using the crosshatch pattern. Service notes for color receivers usually specify a recommended amount of overscan at the left and right and a different amount of overscan at the top and bottom. The recommended overscan varies in different receiver models. Because the Model 1245 provides a fixed number of 10 vertical and 14 horizontal lines, it is easy to judge the amount of overscan. The crosshatch pattern also permits accurate checks of the horizontal and vertical linearity in both black-and-white and color receivers. Convergence adjustments are made using dots, crosshatch, or vertical or horizontal lines.

This color generator measures only 2⅞" x 8½" x 8⅞", weighs only 3 pounds, and sells for $134.95. ▲

Grand Transformers "Insta-Test" Dielectric Strength Tester

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PATTERNED after a prototype model that has been used in quality control for nearly ten years, a dielectric breakdown checker called the "Insta-Test" dielectric strength tester is being marketed by *Grand Transformers, Inc.* The unit gives both an audio and visual response to a breakdown of windings used in coils, motors, transformers, etc. Six test a.c. voltages may be selected, ranging from 750 volts to 3000 volts. The unit operates from the a.c. line with fused protection.

Two high-voltage probes permit a quick check across any winding. At the potential breakdown point, a buzzer will sound and a red "leakage" lamp will light up if the part or circuit is defective. A check is made by increasing the applied voltage in steps until breakdown occurs.

Safety features of the unit include a grounded line cord, fused primary circuit, molded high-voltage lead plugs, and safety test prods—all to reduce shock hazard.

The tester gives breakdown tests to UL, CSA, and NEMA standards, which are usually at twice the operating voltage plus 1000 volts.

The unit is available from the manufacturer at just under $75. ▲

Nanosecond Pulses

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has a steep wavefront and a large amplitude. Nevertheless, no other technique today can approach the extreme power pulses obtained in nanosecond times but the spark gap.

Fig. 3 shows the details. The circuit is essentially a relaxation oscillation. Resistors $R1$ and $R2$ charge capacitor $C1$ from a high-voltage source until the charge on $C1$ reaches the arc-over potential of the spark gap. The holding voltage of an arc is substantially less than the arc-over potential, and $C1$ will thus discharge itself into the load. When the charge on $C1$ is finally too low to sustain the arc, the conduction abruptly ceases and $R1$ and $R2$ once again start slowly charging $C1$ for a new cycle.

The pulser may be synchronized by a trigger pulse that arrives just before discharge would normally occur. By a careful design, the inductance of the discharge circuit is held to an absolute minimum, permitting extreme risetimes and currents. To insure proper waveforms, the load resistance must be very low. By plating and the use of controlled atmosphere, the effects of burning, aging, and oxidation may be minimized.

A rectangular pulse is produced by using a transmission line instead of a capacitor, just as in Fig. 1C. This time, the transmission line must have an extremely low impedance and is designed as an integral part of the gap itself. ▲

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