

VHF Pulse Techniques and Logical Circuitry*

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Summary—Techniques and components for use in systems handling pulses of 10-millimicrosecond width have been investigated. Bandwidth requirements have led to the use of secondary emission pentodes in amplifier service. The limitations of time delay in feedback type circuitry have made necessary the use of special logical reshaping circuits. A test program on commercially available semiconductor diodes resulted in the selection of high-conductance, gold-bonded junction diodes for use in switching circuits. Multivibrator circuits have been designed for gating and delay functions. Electromagnetic delay lines of both the coaxial and helical-wound types have been used for delay and for pulse generation.

These components have been applied to the design of an arithmetic unit which performs binary addition, multiplication, and dynamic storage at a pulse repetition rate of 50 megacycles per second.

INTRODUCTION

PULSE-CODED information systems have found application in communications, digital computers, and nuclear instrumentation. The desire to handle a maximum amount of information in a minimum amount of time has led to the development of systems using increasingly narrow pulses at increasingly high repetition rates. Resolution of millimicrosecond pulses at low repetition rates has been demonstrated in nuclear instrumentation research.^{1,2} A 50-megacycle per second pulse repetition rate using pulses 10 millimicroseconds wide was considered by the authors to be a practical upper limit on the basis of the available components and the state of measuring techniques. Having established this repetition rate, components and circuits were developed to perform amplification, pulse shaping, and switching. An interesting application is the demonstration that digital computer operations can be performed at a 50-megacycle pulse repetition rate using these components and circuits.

PULSE AMPLIFIERS

The rise time³ in seconds of an uncompensated pentode video amplifier is given by

$$t_r = 2.2RC,$$

where R is the plate load resistance in ohms, and C is the total capacity in farads at the plate. For a 10-millimicrosecond pulse, assuming an allowable rise time of 4.4 millimicroseconds, and a value of C of 10 micromicrofarads, R is found to be 200 ohms. When using an

amplifier to re-establish pulse amplitude and to decrease pulse rise and fall times, the amplifier gain should be of the order of 3 to 5. Postulating a minimum gain, A_0 , of 3 from such a stage the average g_m requirement is given by:

$$g_m = A_0/R = 3/200 = 15,000 \mu\text{mhos}.$$

Using vacuum tubes either clamped on or biased off, signal levels of from 5 to 10 volts are required. Assuming an 8-volt signal level and 200-ohm load resistance the required peak tube current is 40 ma.

Although much progress is being made in the field of high-speed semiconductor devices, there are no available transistors at the time of this writing which will operate at a 50-megacycle per second pulse repetition rate. An examination of available vacuum tubes led to the choice of the Western Electric 417A/5842 triode and the Philips EFP-60 secondary emission pentode. The Western Electric 417A/5842 triode has a g_m of 25,000 μmhos , a plate dissipation of 4 watts, a maximum average plate current of 35 ma, a cathode to grid and heater capacity of 9 micromicrofarads, and a plate to grid and heater capacity of 1.8 micromicrofarads. The Philips EFP-60 secondary emission pentode has a grid to anode transconductance of 25,000 μmhos , a plate dissipation of 2 watts, a dynode dissipation of 1 watt, a maximum average cathode current of 8 ma, and a total input plus output capacity of about 15 micromicrofarads. The EFP-60 has the advantage of having an additional active electrode, the dynode, which allows the tube to be used as a noninverting amplifier with a grid to dynode transconductance of 20,000 μmhos . One may make use of the active electrodes of the EFP-60 to obtain circuits which would require 2 tubes of conventional design.

A noninverting limiter amplifier is shown in Fig. 1. Power supply decoupling and parasitic suppression resistors have been employed, and shunt peaking has been used to decrease the rise time of the signal on the dynode to about 3 millimicroseconds. This amplifier is normally biased below cutoff and is driven positive by pulses fed to its control grid through a dc restorer circuit, which maintains the grid at a constant dc bias voltage. The use of positive pulses, feeding the cutoff grid, has the advantages of elimination of baseline noise and the reduction of average power dissipation. The diode-resistor combination in the cathode circuit of the amplifier allows the tube to draw 10-ma cathode current without degeneration. However, if the tube draws more than 10-ma current, the diode opens and the gain is reduced by a factor of twenty-five. The 10-ma cathode current produces approximately 40 ma of dynode current so that the peak output voltage from the

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¹ I. A. Lewis and F. H. Wells, "Millimicrosecond Pulse Techniques," McGraw-Hill Book Company, Inc., New York, N. Y.; 1954.

² N. F. Moody, G. J. R. MacLusky and M. O. Deighton, "Millimicrosecond pulse techniques," *Electronic Eng.*, vol. 24, pp. 214-219; May, 1952.

³ Committee Personnel, "IRE standards on pulses: methods of measurement of pulse quantities, 1955," *Proc. IRE*, vol. 43, pp. 1610-1616; November, 1955.

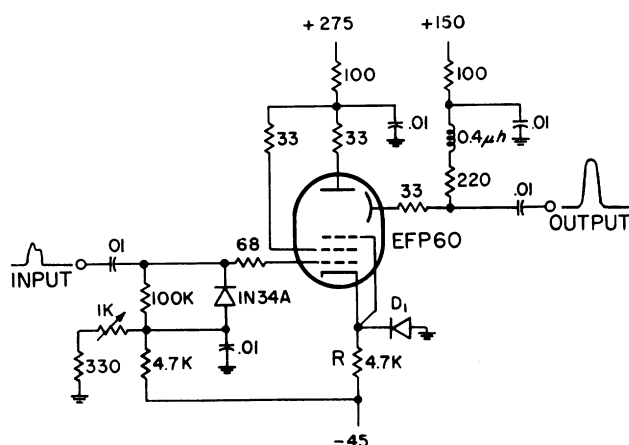


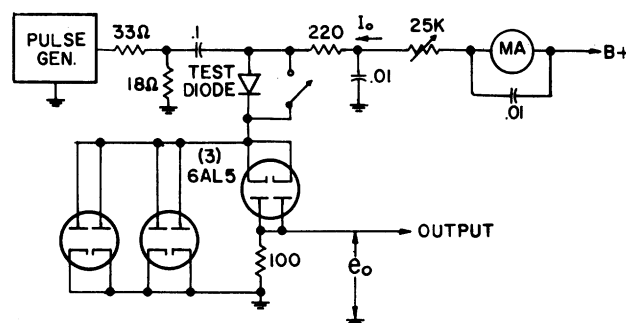
Fig. 1—The limiter amplifier circuit shown above includes decoupling, dc restoration, parasitic suppressors, and shunt peaking. R and D_1 provide limiting of the output pulses and the grid bias is set so that the tube is normally off.

dynode is limited at about 10 volts positive. The output of this amplifier typically drives a 5842 cathode follower which has an output impedance of 40 ohms and which may be used therefore to drive low impedance loads. Cathode follower power requirements are reduced through the use of positive pulses.

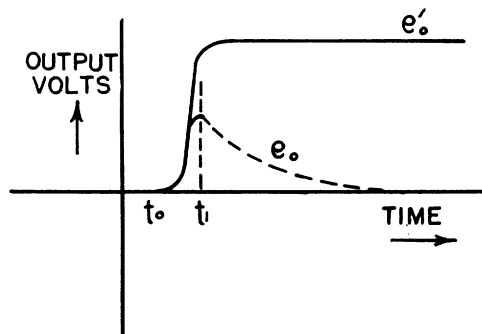
LOGICAL CIRCUITRY

An important property of semiconductor diodes for use in logical circuitry at high pulse repetition rates is their switching speed. Previous experience with germanium diodes at a 1-megacycle repetition rate has shown that they are limited by the magnitude of their "reverse recovery time" effect.⁴⁻⁷ This effect is the tendency for a diode to maintain high reverse conductance upon the application of a reverse bias, following forward diode conduction, and is due to the finite time required to remove the carriers from the conducting diode. The "forward recovery time effect," which is the tendency for the diode to maintain a high forward resistance after application of a forward voltage, is also of significance. At 200-ohm impedance levels it is necessary that the resistance of a diode be large relative to 200 ohms for it to be considered "open"; for it to be considered "closed," it is necessary that the diode resistance be small compared to 200 ohms.

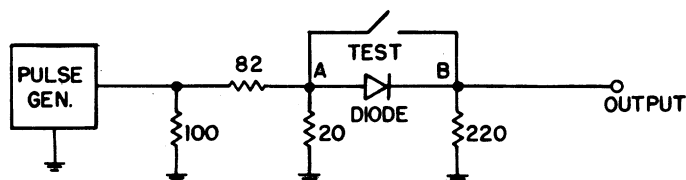
With these criteria in mind, the circuits of Fig. 2 were used to measure recovery times. The pulse generator used is the Spencer-Kennedy Laboratory's Model 503 delay-line pulse generator⁸ which supplies adjustable



(a)—Circuit used to measure "reverse recovery time" effect.



(b)—Typical set of output waveforms, using the circuit of Fig. 2(a), under the conditions of the test diode shorted (e_0') and unshorted (e_0).



(c)—Circuit used to measure "forward recovery time" effect.

Fig. 2.

width pulses having a rise time of less than 1 millimicrosecond at a pulse repetition rate of 120 cycles per second. Referring to the circuit of Fig. 2(a), which is used to measure the "reverse recovery time" effect, the 25 K potentiometer is adjusted to provide the variable forward current I_0 , which passes through the diode under test to ground through the two 6AL5's in parallel. The application of a negative pulse from the pulse generator reverse-biases the diode and a transient appears at the output, the amplitude of which is determined by the back resistance of the test diode as a function of time. By also observing the output voltage transient with the test diode shorted, the dynamic resistance of the test diode may be determined. A typical set of observed output transients is shown in Fig. 2(b).

The diode "forward recovery time effect" or the dynamic forward resistance was observed by using the circuit of Fig. 2(c). By observing the output waveforms with a positive pulse applied to the circuit under the conditions of the test diode shorted and unshorted, the forward resistance of the diode as a function of time can be determined.

⁴ J. H. Wright, "Transient Response Limitations of Various Semiconductor Diodes," Natl. Bur. Standards Rep., No. 3638; July 15, 1954.

⁵ T. E. Firlie, M. E. McMahon, and J. F. Roach, "Recovery Time Measurements of Point-Contact Germanium Diodes," Hughes Aircraft Co. Rep., Res. and Dev. Labs.; June, 1954.

⁶ R. H. Kingston, "Switching time in junction diodes and junction transistors," Proc. IRE, vol. 42, pp. 829-834; May, 1954.

⁷ M. C. Waltz, "On some transients in the pulse response of point-contact germanium diodes," Proc. IRE, vol. 40, pp. 1483-1487; November, 1952.

⁸ R. L. Garwin, "A pulse generator for the millimicrosecond range," Rev. of Sci. Instr., vol. 21, pp. 903-904; November, 1950.

Many commercial point-contact germanium diodes were found to have satisfactory reverse recovery times when working into a 200-ohm load. The need for a diode with a dynamic forward resistance which is small compared to 200 ohms led to an investigation of junction types, gold-bonded types, and various "high conductance" types of recent origin. In general, it was found that large junction area types were satisfactory in regard to forward resistance, but that their "reverse recovery" characteristics were inferior to the average point-contact diode. The gold-bonded junction types were found to have high forward conductance and, in some cases, satisfactory "reverse recovery" characteristics. Several diode types [e.g. 1N308 (CK741),⁹ T6G, T-1N283] have been found which give satisfactory recovery characteristics with minimum variation of parameters during service.

The requirements for a logical AND circuit using these diodes can best be understood by referring to a standard 2-input AND circuit, as shown in Fig. 3(a). The initial rate of rise when driving a capacitive load is given by

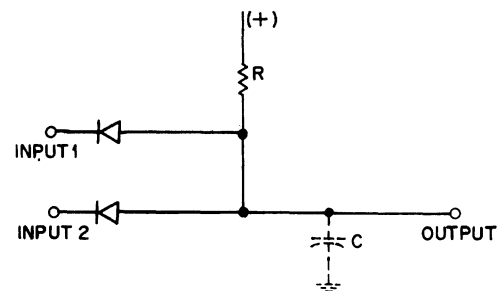
$$de/dt = i/c.$$

For a rate of rise of 2 volts per millimicrosecond with a capacitive load of 10 micromicrofarads (e.g., tube input capacity) a current of 20 ma is necessary. With currents as high as these and 5–10-volt signal levels, the impedances of the sources driving the AND circuit inputs must be kept low in order to eliminate unwanted responses at the output of the AND circuit when fewer than all of the inputs to an AND circuit rise. Driving source impedances can be reduced by using 5842 cathode followers to drive the AND circuit inputs or by the use of the AND circuit design shown in Fig. 3(b). In this circuit the catcher diodes and resistors compensate for the source impedance, and the rise of the output when one leg rises is only a fraction of a volt.

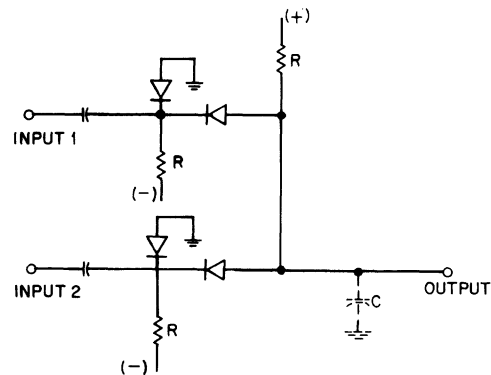
In the case of the OR circuit which is shown in Fig. 3(c), the output rises when either or both inputs rise. The output rise time is a function of the output impedance of the pulse source at the OR circuit input, the forward impedance of the diode, the OR circuit resistor R , and the load impedance. The fall time is determined by the OR circuit resistor R , and the load impedance. Rise and fall times of approximately 5 millimicroseconds are typical for the AND and OR circuits.

PULSE GENERATORS, MULTIVIBRATORS, AND GATES

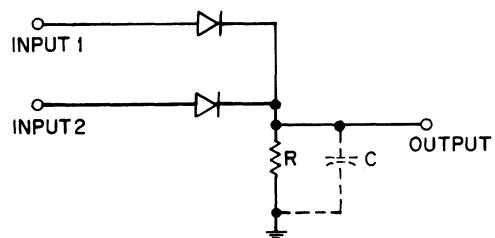
Test work at vhf pulse repetition rates requires pulse generators, multivibrators, and gating circuits as standard test equipment. As outlined above, few components are available with which to construct these circuits. Because of its possibilities for noninverted power-gain with either grid or cathode input terminals (dynode or



(a)—Standard 2-input AND circuit using semiconductor diodes.



(b)—Modified 2-input AND circuit which effectively reduces the driving source impedances.



(c)—Standard 2-input OR circuit.

Fig. 3.

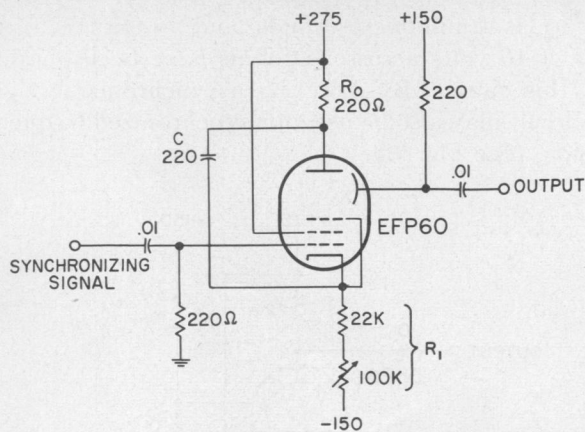
plate output terminals), the EFP-60 has been the preferred tube for use in high-speed regenerative circuits. These circuits are of general interest and are outlined below.

The cathode to plate current gain of a secondary emission pentode is utilized in the plate-cathode coupled multivibrator¹⁰ of Fig. 4.

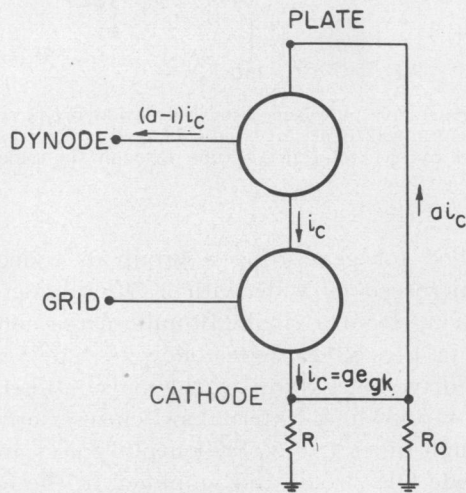
In the astable configuration shown the repetition rate is determined by C , R_0 , R_1 , and the B voltage, while the pulse width is determined by C , R_0 , and the tube characteristics. The grid may be used as a high impedance sync or trigger terminal, while the dynode may be used as an isolated output terminal supplying positive pulses. The condition for regeneration, neglecting stray capacitance, may be derived from the high-frequency equivalent circuit shown in Fig. 4(b) with the requirement that current-gain from cathode-to-plate-to-cathode be greater than one.

¹⁰ F. H. Wells, "Fast pulse circuit techniques for scintillation counters," *Nucleonics*, vol. 10, pp. 28–33; April, 1952.

⁹ No longer in production.

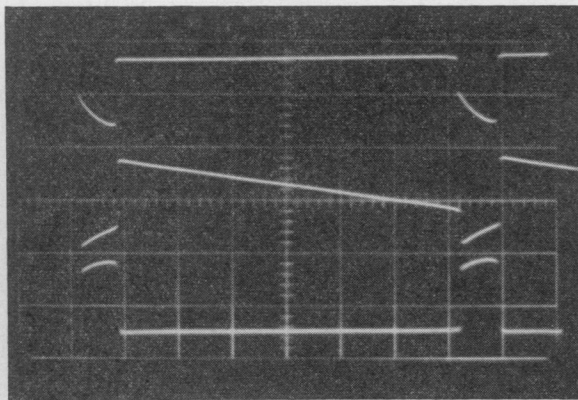


(a)—Plate-cathode coupled multivibrator. In this circuit the secondary-emission current gain of the EFP-60 pentode makes plate-cathode regeneration possible. Repetition rate is varied by means of the 100 K potentiometer.



a = SECONDARY EMISSION CURRENT GAIN
 g = CATHODE-GRID TRANSCONDUCTANCE
 e_{gk} = a.c. GRID-CATHODE VOLTAGE

(b)—High-frequency equivalent circuit of plate-cathode coupled multivibrator circuit.



(c)—The plate, cathode, and dynode waveforms (reading from top to bottom) for the circuit of Fig. 4(a). Sweep speed is 2 microseconds per major division.

Fig. 4.

This gives:

$$a \left(\frac{R}{R + 1/g} \right) > 1 \quad \text{or} \quad (a - 1)Rg > 1,$$

where

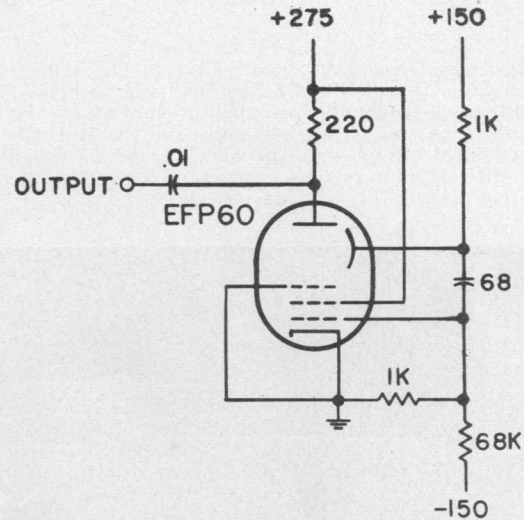
R = total parallel resistance of R_0 and R_1 ,

a = secondary emission current gain,

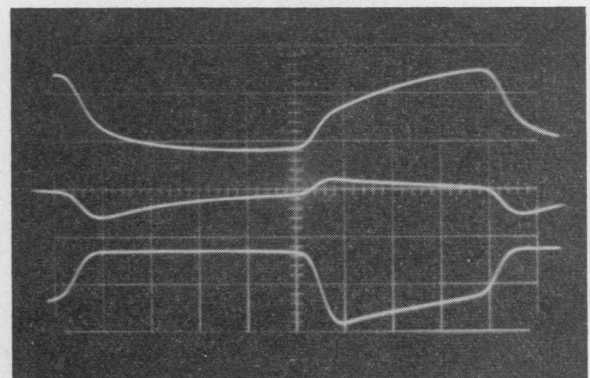
g = cathode-grid transconductance.

For the EFP-60, $a \cong 5$, $g \cong 5000 \mu\text{mhos}$, and therefore regeneration occurs only if $R > 50$ ohms.

The dynode grid multivibrator is shown in Fig. 5.¹¹



(a)—Dynode-grid coupled multivibrator. In this unstable circuit the noninverting voltage amplification characteristic of the secondary emission pentode is used to obtain multivibrator operation.

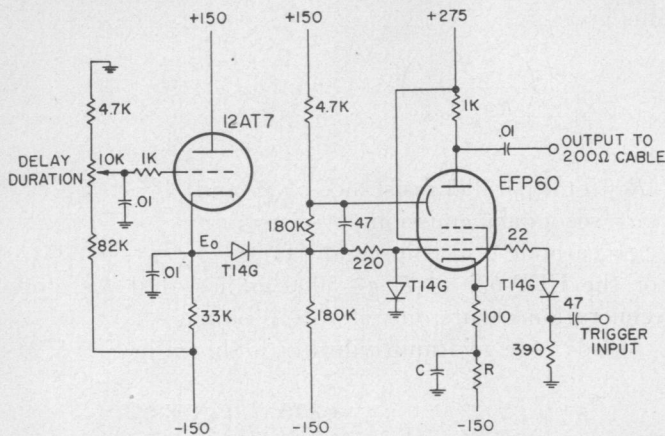


(b)—The dynode, grid, and plate waveforms (top to bottom) for the circuit of Fig. 5(a). Sweep speed is 100 millimicroseconds per major division.

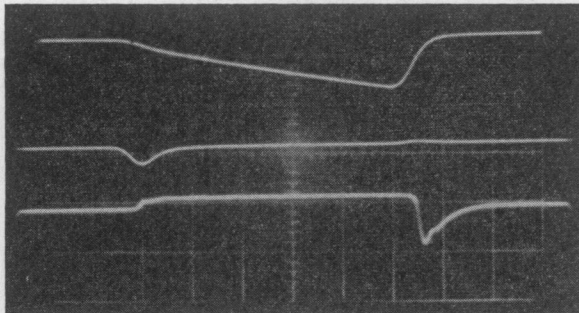
Fig. 5.

A modification of this circuit has been used for synchronized frequency division (see Fig. 9) and time delay. The monostable time delay circuit is shown in Fig. 6. This latter circuit has an "off" period determined by C , E_0 , R , and the grid base of the EFP-60. Supply volt-

¹¹ N. F. Moody, G. J. R. Maclusky, and M. O. Deighton, "Millimicrosecond pulse techniques," *Electronic Eng.*, vol. 24, pp. 214-219; May, 1952.



(a)—Dynode-grid monostable multivibrator. The stable operating condition is with the EFP-60 "on" and with the EFP-60 grid at ground potential. Upon application of a negative trigger pulse the tube cuts off regeneratively and the grid falls to E_0 . EFP-60 remains cutoff until the voltage across C has fallen to a value sufficiently low to allow conduction. At this time the stable operating point is regeneratively re-established.



(b)—The cathode, trigger, and plate waveforms (top to bottom) for the circuit of Fig. 6(a). The cathode and trigger waveforms were obtained by using the Tektronix 531 amplifiers, which have a rise time of 35 millimicroseconds, while the plate waveform was obtained by direct connection to the deflection plates through 200-ohm cable. The sweep speed is 100 millimicroseconds per major division.

Fig. 6.

age variations have only a second order effect on this period, since the EFP-60 is used only to charge C between limits set by E_0 and ground, and since supply voltage changes which produce a change in current through R_1 produce a compensating change in E_0 .

Pulse rise times in the EFP-60 multivibrator circuits are as short as 10 to 15 millimicroseconds and pulse widths may be as short as 25 millimicroseconds. The 4-millimicrosecond transit time of the EFP-60 accounts for part of the rise time when used in regenerative circuitry. Output amplitudes are from 10 to 14 volts across 200 ohms.

Fig. 7 shows a "regenerative pulse generator"¹² which has been used as a source of short pulses. The operation of the circuit is such that pulses are produced having a width determined by circuit bandwidth, and a repetition rate determined by the total delay time. Repetition rates as high as 80 megacycles, pulse widths

as short as 4 millimicroseconds, and amplitudes of the order of 10 volts across 200 ohms have been obtained with this circuit. By injecting a synchronizing signal this circuit may also be used for synchronized frequency division. (See Fig. 9.)

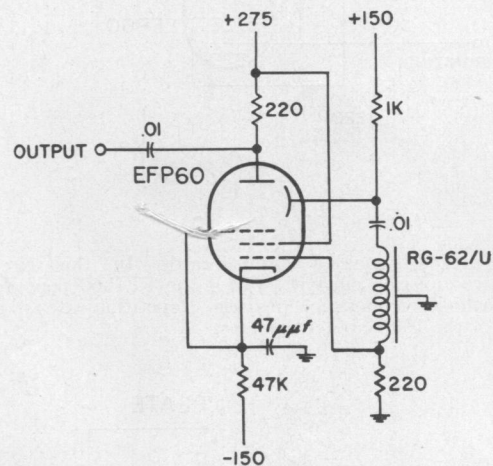


Fig. 7—Regenerative pulse generator. Pulses were produced having a width determined by circuit bandwidth and a repetition rate determined by the total delay time through the tube and the RG-62/U coaxial cable.

A method for generating a group of coded pulses 10 millimicroseconds wide with a 20-millimicrosecond pulse spacing from a single 10-millimicrosecond pulse is shown in Fig. 8. Cathode followers 1 to 5 are successively driven negative by the pulse which travels down the tapped line. External switches set up the current through tubes 1 to 5. The output pulses are mixed in the diode OR circuit and amplified in the following stages.

When working at a 50-megacycle pulse repetition rate synchronized lower frequency pulses are needed for triggering oscilloscopes as well as synchronizing auxiliary circuitry. These pulses are provided by the circuit of Fig. 9, making use of the methods described above.

RESHAPING

As a pulse proceeds through successive stages of circuitry, both its timing and wave-shape deteriorate. In order to compensate for these effects retiming and reshaping circuitry must be provided. The function of the resaper is to produce a retimed fixed amplitude output pulse if, and only if, an input pulse is present at a specified "clock" time. The resaper normally includes input, output and clock terminals, as well as logical circuitry and an amplifying device.

Clock and input timing is set so that the input pulse is at full amplitude at the time of the appearance of the clock pulse. During the coincidence time of the clock and input pulses, circuits are set up which insure the production of a standard output pulse. Since the input, output, and clock pulses are normally of approximately

¹² C. C. Cutler, "The regenerative pulse generator," *PROC. IRE*, vol. 43, pp. 140-148; February, 1955.

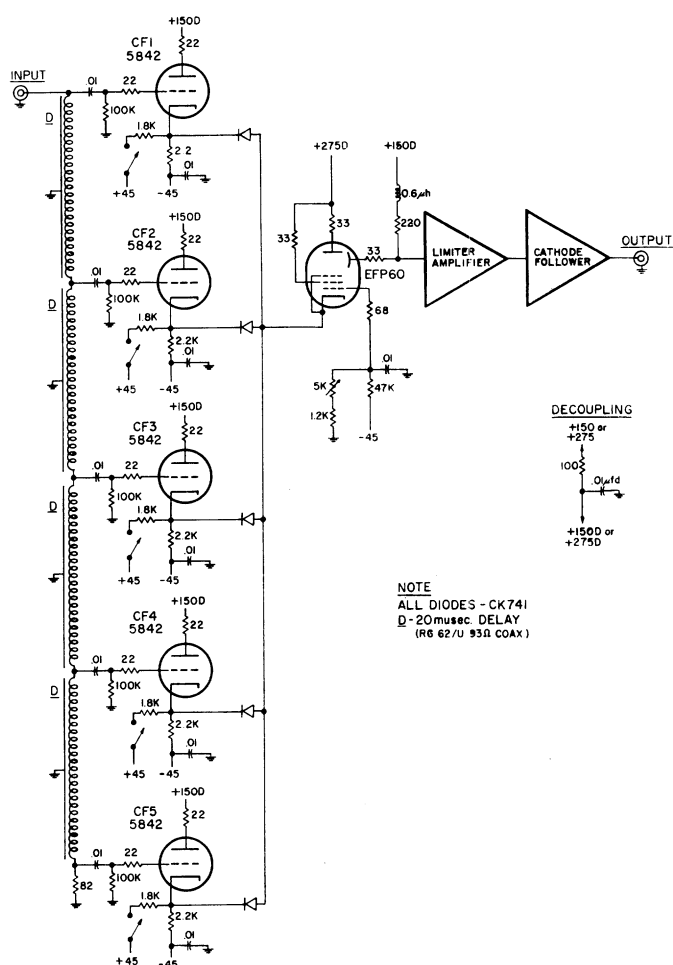


Fig. 8—Circuitry used to generate a group of pulses 10 millimicroseconds wide from a single 10-millimicrosecond pulse.

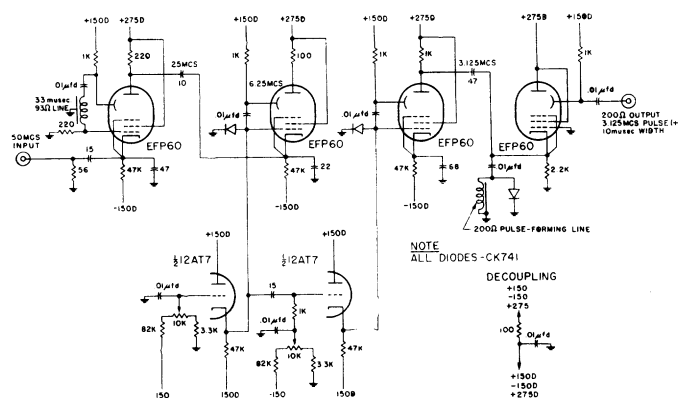
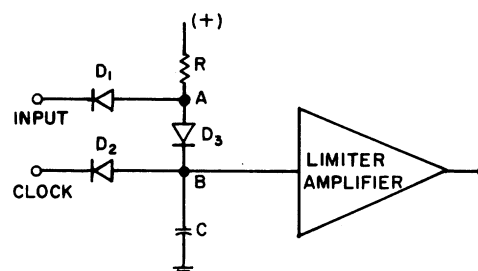


Fig. 9—Multivibrator divider chain used to produce synchronized pulses at a submultiple of the input frequency.

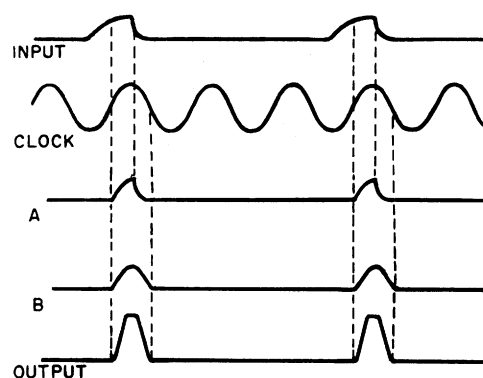
the same width, and since the input pulse must arrive early enough with respect to the clock to insure that the rise of the output is determined by the leading edge of the clock pulse, a hold circuit must be provided to maintain the output until the fall of the clock pulse. A limiting device is generally needed in order to maintain constant amplitude output pulses.

In the microsecond range these requirements can be

met in many ways.¹³⁻¹⁵ For pulses of 10-millimicrosecond width the use of "regenerative broadening"¹⁴ is made impractical by the magnitude of transit time and rise-time delays in available amplifiers. Fig. 10 shows a method of reshaping, adopted here, which avoids the use of "regenerative broadening." The condenser *C* is used for the "hold" operation, while the logical circuitry provides that the rise and fall of the output pulse are timed by the clock.



(a)—Reshaper circuit which eliminates the need for feedback.



(b)—Idealized reshaper waveforms.

Fig. 10.

DELAY LINES

Electromagnetic delay lines have been used to provide a storage medium for use with the pulse circuitry described. Both standard coaxial cables and specially constructed helically-wound lines have been used for this purpose. For delays of from 10 to 100 millimicroseconds, coax cables such as RG62U, RG58U, etc., or special helical lines¹⁶ of the type shown in Fig. 11(a) are satisfactory. For delays greater than 100 millimicroseconds the attenuation limitation becomes more seri-

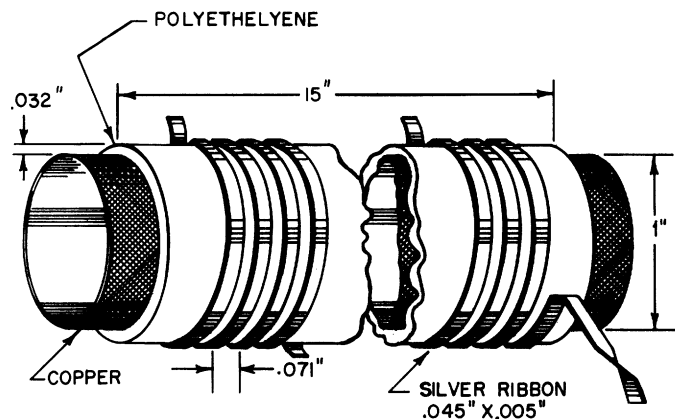
¹³ H. Ross, "Arithmetic element of the IBM type 701 computer," *Proc. IRE*, vol. 41, pp. 1287-1294; October, 1953.

¹⁴ R. D. Elbourn and R. P. Witt, "Dynamic circuit techniques used in SEAC and DYSEAC," *Proc. IRE*, vol. 41, pp. 1380-1387; October, 1953.

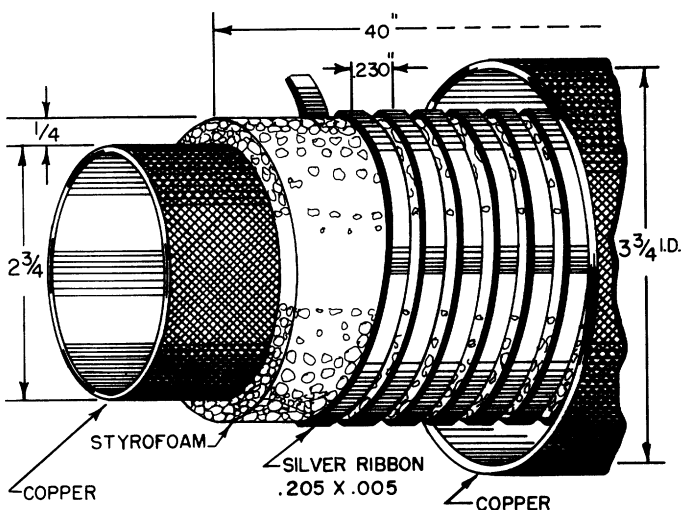
¹⁵ Q. W. Simkins and J. H. Vogelson, "Transistor amplifiers for use in a digital computer," *Proc. IRE*, vol. 44, pp. 43-55; January, 1956.

¹⁶ I. A. Lewis and F. H. Wells, "Millimicrosecond Pulse Techniques," McGraw-Hill Book Co., Inc., New York, N. Y., pp. 42-47; 1954.

ous. Since skin effect attenuation in the frequency range of interest is inversely proportional to wire size, and since characteristic impedance is determined by geometry, the problem is solved for a given impedance by the use of larger diameter coax (e.g., RG-15U), or larger diameter spiral lines. An example of the latter is shown in Fig. 11(b).



(a)—Helical delay line. The measured impedance is 93 ohms and the delay is 84 millimicroseconds. The measured attenuation is approximately 3 db at 70 megacycles.



(b)—Helical delay line. The measured impedance and delay are 200 ohms and 160 millimicroseconds respectively. The large structure is necessary to minimize attenuation due to skin effect.¹⁷ The attenuation measured was 2 db at 100 megacycles per second.

Fig. 11.

CONSTRUCTION AND TESTING

When working with pulses in the millimicrosecond range extreme care is necessary in pulse handling. As a typical example of the problems involved, a standard half-watt composition resistor has a shunt capacity of $\frac{1}{2}$ micromicrofarad, and therefore has a time constant of $R/2000$ millimicroseconds. Therefore, a resistance voltage divider consisting of a 100 K and a 10 K resistor (of the same type) would have an output waveform as shown in Fig. 12 for a step function input. This example

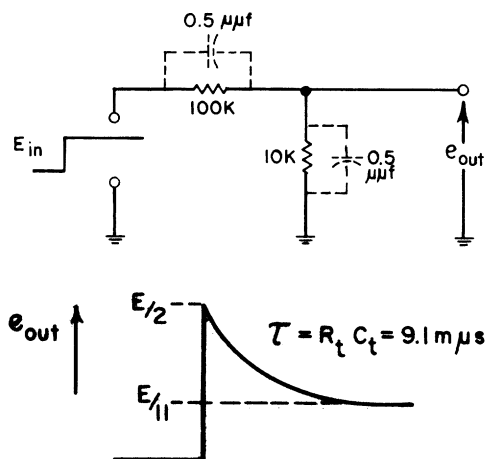


Fig. 12—Resistive voltage divider made up of standard half-watt composition resistors. Output waveform for step function input.

ignores all additional stray capacities but illustrates the fact that one cannot accept the low-frequency values of components when working with pulses in the millimicrosecond range.

A further example is the problem encountered with small values of resistance where a series inductance of 1 millimicrohenry produces a time constant of $1/R$ millimicroseconds. It is desirable that all connections of over a few inches in length be made through terminated coaxial cables.

The Tektronix 517 Oscilloscope, having an inherent rise time of 7 millimicroseconds, is used for test work at low repetition rates. The Tektronix 531, with provision for direct connection to the deflection plates (see Fig. 13)

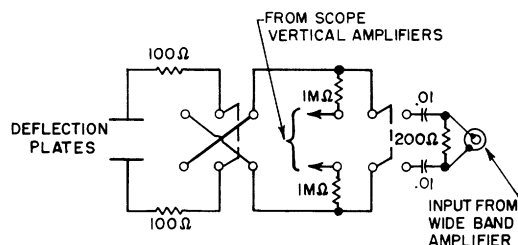


Fig. 13—Switching for oscilloscope deflection plates. The 100-ohm resistors prevent high-frequency ringing by damping the resonant circuit consisting of lead inductance and deflection plate capacity. When the output of the wide band amplifier is to be observed, connection through 1-megohm resistors to the scope vertical amplifiers is maintained in order to utilize the oscilloscope vertical centering control.

is used for observation of high repetition rate phenomena. A cathode follower probe (e.g., Tektronix 517 Probe) driving a wide band distributed amplifier (e.g., Hewlett-Packard 460B or Instruments for Industry 500) is used to drive the scope deflection plates. The measured rise time, when using a cathode follower probe feeding the wide-band amplifier, is 3 millimicroseconds and the deflection sensitivity is approximately 5 volts/cm.

¹⁷ L. H. Thomas, "Propagation in Helical Lines" (unpublished).

