RADAR PULSE MODULATORS

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Any continuous wave (CW) transmitter can generally be used as a pulse transmitter if a *pulse modulator* is added to provide the rapid turn on and turn off. Tube-type amplifiers can be operated with much higher instantaneous powers when they are pulsed. Tubes are primarily limited by their maximum anode dissipation (heat removal); the dissipation can be the result of either modest CW operation or high-power pulse operation. A CW amplifier can be converted for pulse operation by changing the output-matching circuit in order to present a lower load resistance to the tube. Some tubes are available in special pulse-rated versions; they are fitted with high-emission cathodes. Gridded tubes (triodes, tetrodes, and pentodes) can be pulsed by switching the grid bias from negative, for pulse-off, to positive, for pulse-on. The negative bias keeps the tube completely turned off between pulses. Since the grid voltage and current are much smaller than the plate voltage and current, grid control requires only low-power circuitry compared to anode control. At microwave frequencies, magnetrons and klystrons replace gridded tubes. Magnetrons have no control element and therefore require high-power anode pulsers. Klystrons may or may not have a modulating anode ("mod anode") by which the beam current can be cut off. If not, they need high-power pulsers.*

Transistor amplifiers, unlike tube amplifiers, cannot make much of a trade-off between duty cycle and peak power. Transistors suffer one type of breakdown or another when operated much past their maximum continuous ratings. A high-power transistor amplifier for pulse service might differ from a CW amplifier only in that it will dissipate less heat (from the reduced duty cycle) and can therefore get by with a smaller heat sink.

No matter how an amplifier is pulsed, the power supply must furnish high-power pulses with minimum voltage droop. Duty cycles of pulsed transmitters are usually much less than unity so, in addition to at least one switching element, pulse modulators (pulsers) contain some form of energy storage element(s). The simple pulser circuit shown in Figure 25-1 stores energy in a capacitor. In this circuit the tube (magnetron, klystron, or whatever) is shown as requiring negative voltage. Microwave tubes

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*An air traffic control radar might have a peak power output of 2 MW and an efficiency of 50%. A klystron tube in this service could require 50 kV pulses at 80 A.

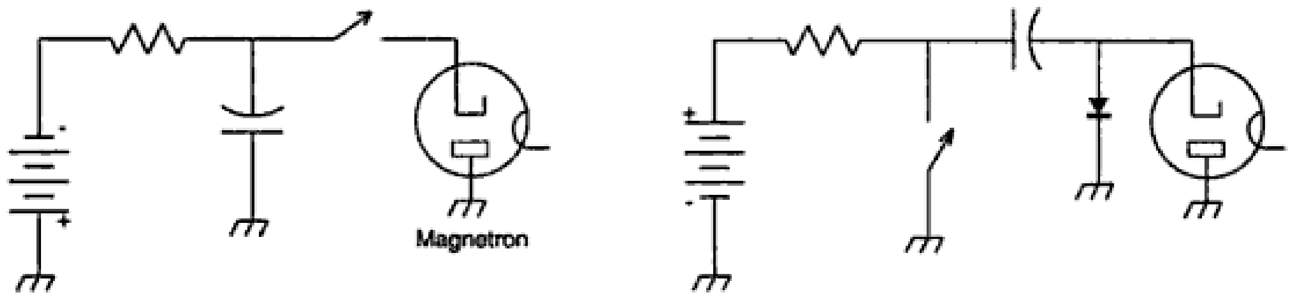


Figure 25-1. Capacitor discharge pulsers.

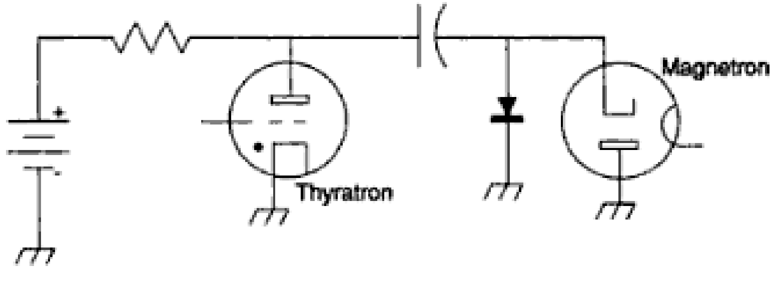
often use a negative supply voltage applied to their cathodes because it is convenient to ground the external heat-dissipating anode. The right-hand version of the circuit allows one side of the switch to be grounded, which is another convenience. The diode provides a charging path for the energy storage capacitor. The circuit of Figure 25-2 uses a thyratron (vacuum tube version of the silicon-controlled rectifier) as the switch.

The simple pulse modulators of Figures 25-1 and 25-2 have two main disadvantages:

1. The voltage droops during the pulse. The droop can be reduced by increasing the size (weight and cost) of the capacitor.
2. Not much of the stored energy is used. Even if a 10% voltage droop is permitted, only 20% of the stored energy is used for each pulse. This might be compared to a car, which would not run well if the fuel tank was less than 80% full.

Despite these drawbacks (they are not really limitations), capacitor banks are often used, as in the 430 MHz pulse transmitter used for ionospheric research at the Arecibo Observatory, because a more efficient circuit, the

Figure 25-2. Thyratron-switched pulser.



line modulator discussed below, does not easily provide the flexibility needed to change the pulse width. A capacitor bank cannot supply longer pulses without increased droop. (Normally inductors are not used as energy storage elements because, compared to capacitors, their maximum energy density is low.)

LINE MODULATORS

A length of transmission line (with the far end open) has capacitance and can therefore store electrostatic energy. When the line is discharged into a resistive load equal to its characteristic impedance, it will supply a perfect rectangular pulse rather than a drooping exponential pulse. The constant pulse amplitude during discharge is maintained by the distributed inductance of the line acting together with the distributed capacitance. In Figure 25-3 the line is a piece of coaxial cable, replacing the energy storage capacitor. As before, the tube is supplied with a negative pulse. A diode provides a path to recharge the line. Often the load has a higher impedance than the characteristic impedance of the line, and a pulse transformer is required.

The line supplies a pulse at half the charging voltage because, during the pulse, the charging voltage evenly divides between the load and the equivalent source resistance. The duration of the pulse is the time taken for the current to make a round trip through the line. At the end of the pulse the line is totally discharged; all the stored energy is delivered on every pulse. Waveforms of the line voltage and current are shown in Figure 25-4.

It is common to use an "artificial transmission line" or pulse-forming network (PFN), which is a ladder network of inductances and capacitances. A four-section network is shown in the modulator circuit of Figure 25-5. The network looks like a low-pass filter, and it is. Its cutoff frequency is given by $\omega^2 = 4/(LC)$. For frequencies well below cutoff, the network behaves like a transmission line with $Z_o = \sqrt{L/C}$. Here L and C are in

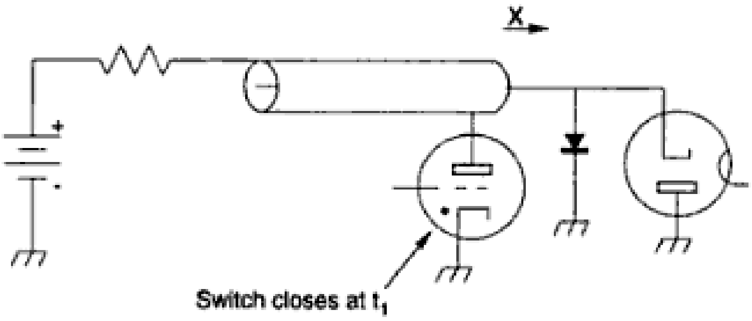


Figure 25-3. Line-type modulator.

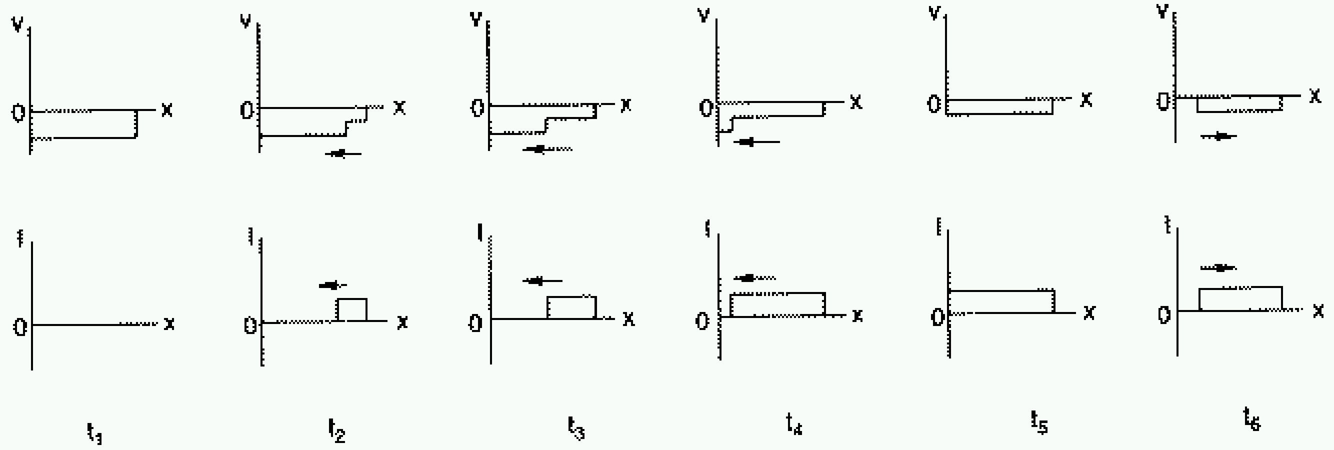


Figure 25-4. Line modulator waveforms.

henries and farads rather than henries per meter and farads per meter, as in the distributed element transmission line. The one-way time delay on this lumped line is $\sqrt{LC}$ seconds per section.

Let us consider a numerical example. A lumped line, as an approximation to a distributed line, does not require a great number of sections to produce a fairly rectangular pulse. Let us use four sections, as in Figure 25-5. Suppose we need a $1\,\mu$s pulse at 10 kV and 10 A. The voltage and current require that $Z_0 = \sqrt{L/C} = 1000$ ohms. The desired $1\,\mu$s of delay in a round-trip through four sections requires that $8\sqrt{LC} = 10^{-6}$. These impedance and time delay equations are satisifed by $L = 125\,\mu$H and $C = 125$ pF. We can verify that the energy stored in the line is indeed equal to the energy delivered by the pulse. The latter is just $(IV)\tau = 10\times10{,}000\times10^{-6} = 0.1$ J. The former, remembering that we must charge the line to 20,000 V, is $CV^2/2 = 4(125\times10^{-12})\times20{,}000^2/2$, which is also 0.1 J.

As often happens in filter design, these are not particularly practical values; real inductors of $125\,\mu$H may well have distributed capacitances that are not negligible compared with 125 pF. We can build the line for a lower impedance and use a pulse transformer between the line and the magnetron. If we lower the line impedance to 100 ohms, the L- and C-

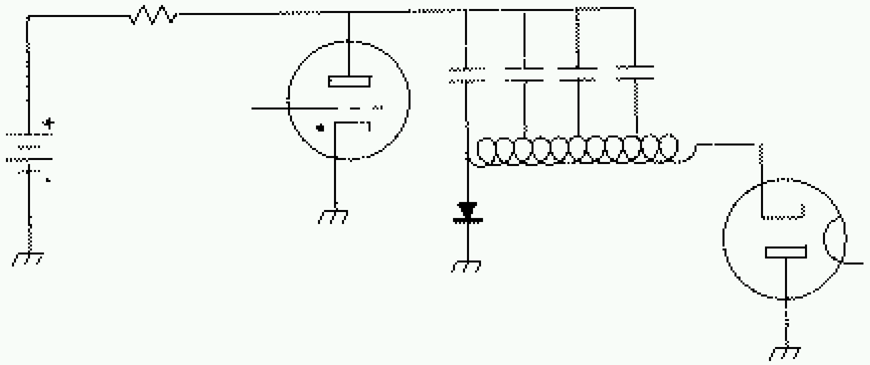


Figure 25-5. Pulser using an artificial transmission line (PFN).

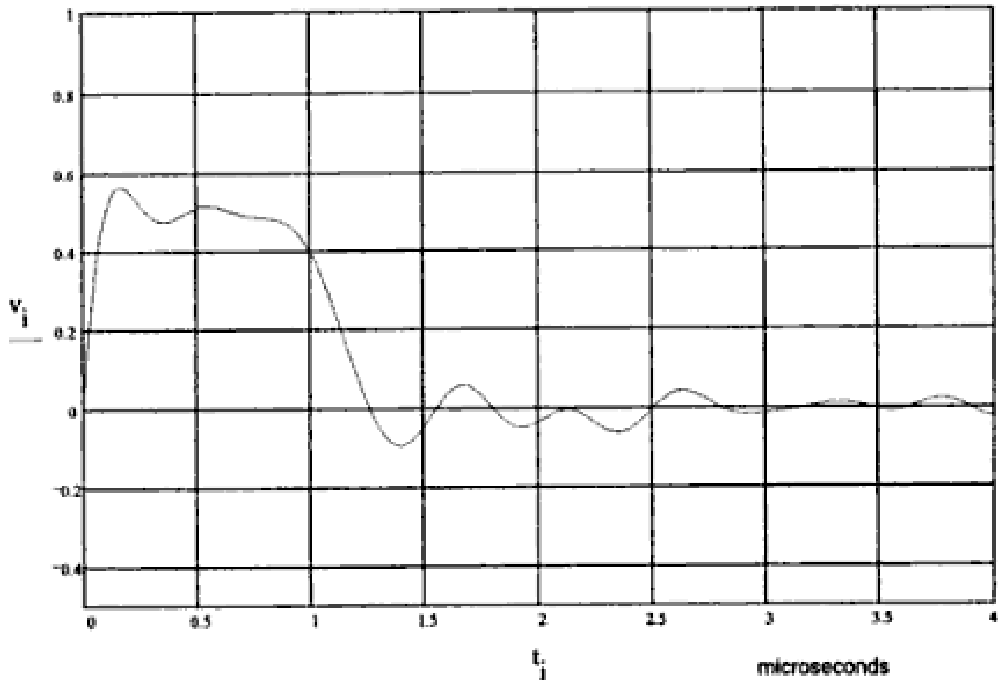


Figure 25-6. Waveform produced by a four-section PFN.

values become 12.5 μH and 1250 pF, respectively, values that are more practical. Using these values in a Spice simulation of the discharge produced the voltage waveform shown in Figure 25-6. The voltage scale is normalized, that is, the capacitors were charged to 1 V so the nominal pulse voltage is 0.5 V. Lines with more sections provide better-shaped pulses.

The line modulator uses all the stored energy on each pulse but, precisely because of this virtue, deserves a more sophisticated charging circuit than the resistor shown in the circuits above. Remember that when a capacitor is charged through any resistive path from empty (no energy) to $CV^2/2$, the resistor will dissipate this same amount of energy, $CV^2/2$. Here the charging resistor, no matter what its value, would dissipate half the power consumed by the radar. The solution to this problem is to charge the line through an inductor instead of a resistor. Figure 25-7 shows the voltage waveform on a capacitor as it is *resonantly charged* through an inductor. The voltage is a sinusoid, building up to a maximum of twice the supply voltage. The modulator can be triggered just as the voltage reaches this maximum. The brief pulse discharges the line, and the charging curve begins anew. It would seem that the pulse repetition frequency is therefore determined rigidly by the charging time but, if a diode is put in series with the inductor, the charging stops at the maximum voltage and the next pulse can occur anytime. The resonantly charged modulator, with the diode and a pulse transformer is shown in Figure 25-8. Note that the primary of the pulse transformer provides a charging path, eliminating the diode originally in parallel with the magnetron. Also

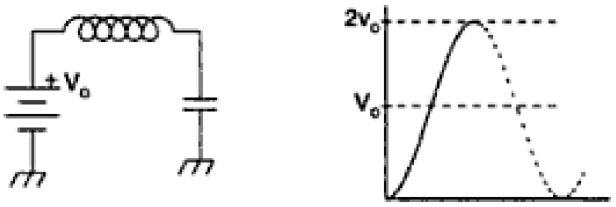


Figure 25-7. Resonant charging.

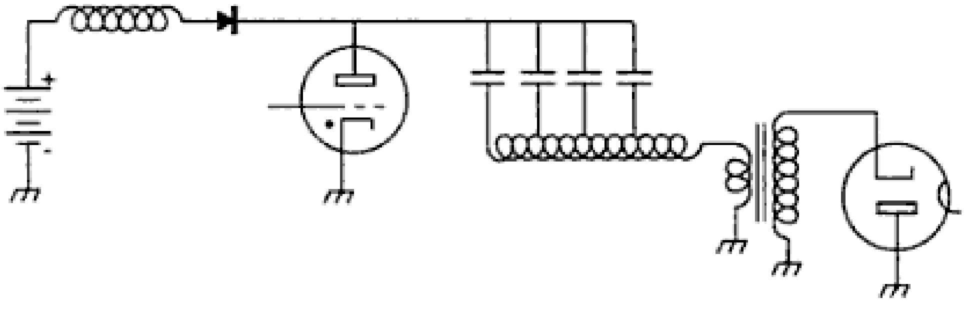


Figure 25-8. Complete pulser circuit.

remember that, because of the resonant charging, the supply voltage needs only to be half of the line charging voltage.

Line modulators present less risk to tubes than partial-discharge capacitor modulators because there is less stored energy available when an arc occurs in the tube.

BIBLIOGRAPHY

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2. M. I. Skolnik (1970), *Radar Handbook.* New York: McGraw-Hill.

PROBLEMS

1. (a) Show that when an uncharged capacitor is brought to potential V by connecting it through a resistor to a voltage source V, the energy supplied by the source is twice the energy deposited in the capacitor (CV^2 rather than $CV^2/2$).

(b) The charging efficiency in Problem 1(a) is only 50%. Find the efficiency when the capacitor initially has a partial charge, that is, when the capacitor is initially charged to a voltage αV, where $\alpha<1$.

2. (a) Find the characteristic impedance of the artificial transmission line shown below. This impedance, Z_0 (which is complex), can be

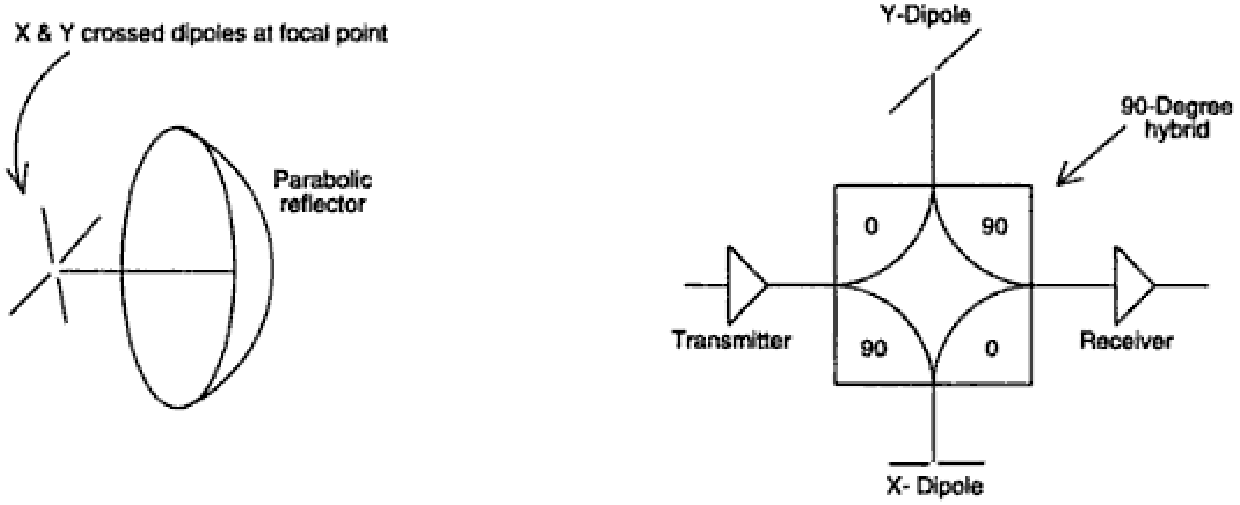

Figure 26-1. A self-duplexing radar using circular polarization.

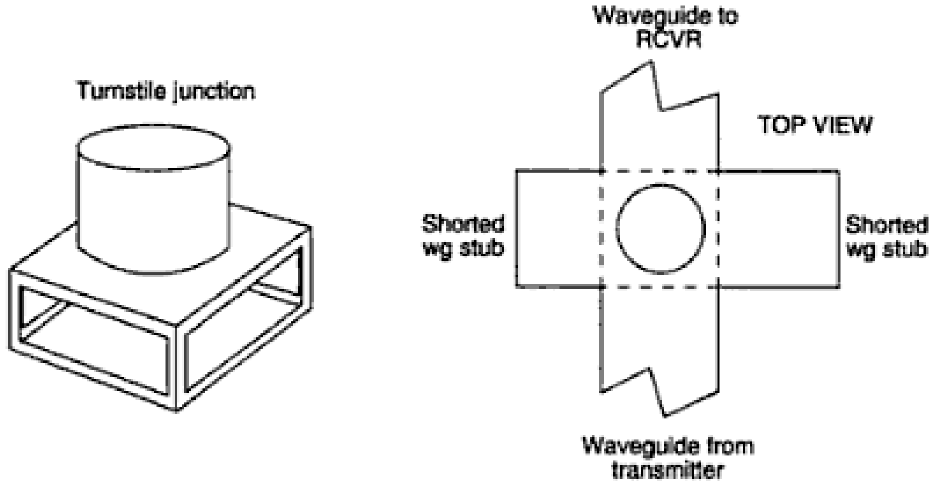

Figure 26-2. A waveguide turnstile junction combines the functions of the hybrid and crossed dipoles.

junction is described in Volumes 8 and 9 of the *Radiation Laboratory Series*. The transmitter and receiver are connected to the remaining rectangular ports (the pair without shorts) while the antenna, usually a feed horn, is connected to the round waveguide.

A true self-duplexing circuit, shown in Figure 26-3, uses a circulator. The circulator has the property that a signal injected at the transmitter port will exit via the antenna port while a signal injected at the antenna port will exit through the receiver port. (If a signal were injected at the receiver port, it would exit through the transmitter port.) This nonreciprocal action depends on transmission through a nonreciprocal medium which, for the circulator, is a ferrite material subjected to the field of a permanent magnet. This elegant TR system is limited by available circulators to powers of tens of kilowatts.