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High-voltage, full-floating 10-MHz square-wave generator with phase control

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Wherein a fast (50 ns) rise-time high-frequency square-wave generator capable of switching between arbitrary voltages of high potential difference (1000 V or more) is described utilizing solid-state circuitry of low power consumption. Power field effect transistors are used as the active switching element, which afford compact size and simplified circuit construction. With the addition of monostable multivibrators, high-voltage square-wave pulse trains of controllable phase are produced. The generator should find application in a wide variety of situations where fast switching between high voltages is required, such as in time-of-flight, coincidence, and beams-modulation experiments.

INTRODUCTION

There are many applications requiring a fast, high-voltage semiconductor switch. On many occasions, the experimental design of atomic and molecular spectroscopic investigations requires fast, pulsed operation—for example, in correlation with laser shots, in a time-of-flight arrangement, coincidence circuitry, or in a beams-modulation sequence where one or more charged particle beams are modulated to enhance signal-to-noise. The potential differences required in the case of ions typically exceed that for electrons. Owing to the larger ion mass, one requires relatively large acceleration voltages to get the charged particles moving at sufficient velocity to overcome or at least manage any space-charge effects in the beam. To this end, the generation of fast symmetric or asymmetric square pulse trains of arbitrary, variable, and full-floating voltages, with the option of controllable phase between given trains, is highly desirable.

In this article, we present a design for a semiconductor square-waveform generator using power field effect transistors, also known as power MOSFETs, driven by a low impedance, high-speed CMOS integrated circuitry. To date, work has emphasized adequate MOSFET driving techniques[1] to improve circuit stability and linearity over a wide bandwidth. We have avoided these and related obstacles by implementing recently available IC driver chips specifically designed for this purpose (to be discussed). Thus, the complete circuit is simple, fits on a single PC prototype card, and is easily constructed from parts now commercially obtainable.

I. BACKGROUND: HIGH VOLTAGE SWITCHING

A conventional approach to the problem of high-voltage switching employs bipolar transistors, and is depicted in Fig. 1. When a positive TTL logic pulse is applied to the circuit as shown, the base of transistor Q_1 rises (R_b is chosen for sufficient base current) and Q_1 turns on. The input lead to the coupling capacitor, which separates the low- and high-voltage circuit elements, is thus brought high to a logic-1 state. This positive potential pulse is transmitted to the base of Q_2, turning it on. When Q_2 is on, the output is at $-V_{EE}$ (minus the diode drop in Q_2, which is negligible); when Q_2 is off, the output rises to V_{CC}.

Q_2 is a power transistor, which can have as much as 1000 V blocking capability. However, junction and circuit capacitances (typically a few hundred picofarads) will combine with the collector resistance R to limit the speed at which the circuit can swing. Reducing R increases the speed, but also increases the current through Q_2. For high-speed switching (rise times τ less than 1 μs), cumbersome heat-sinking methods which may include paralleling of transistors may become necessary, thus complicating circuit construction and increasing its size and weight. For example, in experiments designed for space exploration, large heavy circuitry with kilowatt power requirements becomes impractical.

To overcome weaknesses in the bipolar transistor circuit thus described, the high-voltage low-current switch shown in Fig. 2 was designed. The absence of any discrete resistors minimizes power requirements, thus reducing size and weight. A logic pulse and its complement enter the low-voltage transistor switches as shown. Transistors $Q_{1\text{-}2}$ operate between rail potentials P_1 which are typically 12 V. Their totem-pole configuration activates a high current driver U_1 which in turn opens or closes the MOSFET gate by bringing it $+12$ V with respect to the source, or equal to the source

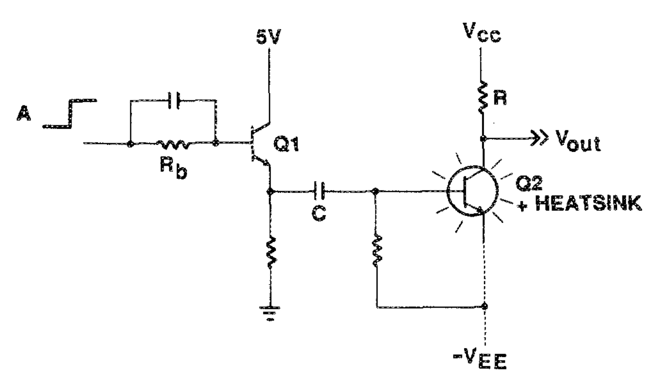

FIG. 1. Conventional bipolar transistor switch. R_b is the base resistor to transistor Q_1, while R is the collector resistor to Q_2. Shown also is a coupling capacitor C, linking the low voltage Q_1 to the high voltage Q_2.

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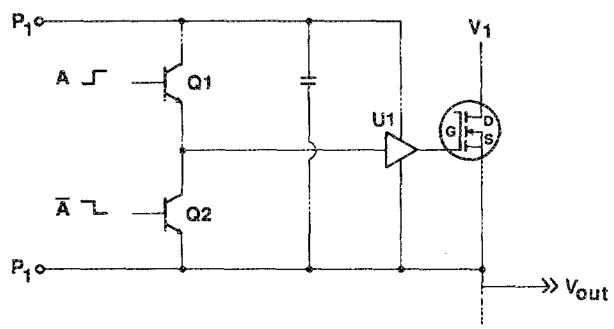

FIG. 2. A power MOSFET switch, whose gate (G), drive (D), and source (S) are shown. The circuit is incomplete, but is used to illustrate MOSFET operation.

potential, respectively. When the gate of the MOSFET is so driven, the switch closes between the drain and the source ($V_D = V_S$), and V_{out} rises to the potential V_1.

Power MOSFETs with a 1000-V blocking capability have recently become available.[2] The advantage of using MOSFETs is that they are voltage driven, whereas transistors are current-driven devices. Switching speed is dependent on charging and discharging the FET device capacitances, and therefore MOSFETs have the potential for faster operation over bipolar transistor circuitry. Also, as the gate is isolated from the source, the drive requirements are independent of the load current. Finally, as FETs are majority-carrier devices, they are less sensitive to nuclear radiations (for example, so-called "single-event upsets") than the minority-carrier transistor devices, which makes them ideal for certain space and nuclear physics applications.

II. DESIGN: HIGH-VOLTAGE SQUARE-WAVE GENERATOR

Our complete circuit design is shown in Fig. 3. A TTL compatible 5-V waveform from a BNC pulse generator[3] is fed into the circuit on the left. This waveform may be a sine wave, symmetric square wave, or asymmetric square wave with the width of a logic 1 pulse not equal to the spacing between pulses (logic 0). Two outputs to the TTL waveform are shown, with one (B) having the capability of adjustable phase with respect to the other (A) by employing a monostable multivibrator. The values of the timing resistor and capacitor are chosen according to the amount of phase control required, which requires knowledge of the type of input (and output) wavetrain desired. For our purposes, we chose $R = 10\ \text{k}\,\Omega$ and $C = 0.01\ \mu\text{F}$ for a value of τ_{delay} between 0 and 100 μs.

The outputs A and B are each directed to a high-voltage circuit, one of which is shown in the diagram. A Schmitt trigger cleans up any noise on the signal, and directs the waveform to a NAND gate which drives the LED of the optoisolators. When a NAND output goes low, current passes through the LED to activate it, thus turning on the transistor switch enclosed in the IC package. The transistor-switch side of the optoisolator, and everything else to the final output, floats on the high voltages that are used in forming the final wavetrain; specifically, P_1 floats on the output voltage and P_2 floats on V_2.

Power rails P_1 and P_2 are +12-V dc floating power supply cards (using an isolation transformer) whose return (ground) float on the source line of the MOSFET. These 12 V are necessary to power the optoisolator switch and a packaged IC noninverting MOSFET driver capable of driving 1000 pF in 30 ns.[4] To guarantee low supply impedance over a wide frequency range, a tantalum capacitor in parallel with a ceramic capacitor is used for supply bypassing to the driver.

As mentioned in the previous section, the optoisolator switches are used in totem-pole configuration to drive the MOSFET driver between the MOSFET source line S, and $S + 12$ V. The two MOSFETs employed in the circuit are also configured in totem-pole fashion to drive the output load between V_1 and V_2, the high voltages used in the final wavetrain. The totem pole network allows n-channel MOSFETs to switch between arbitrarily chosen variable voltages

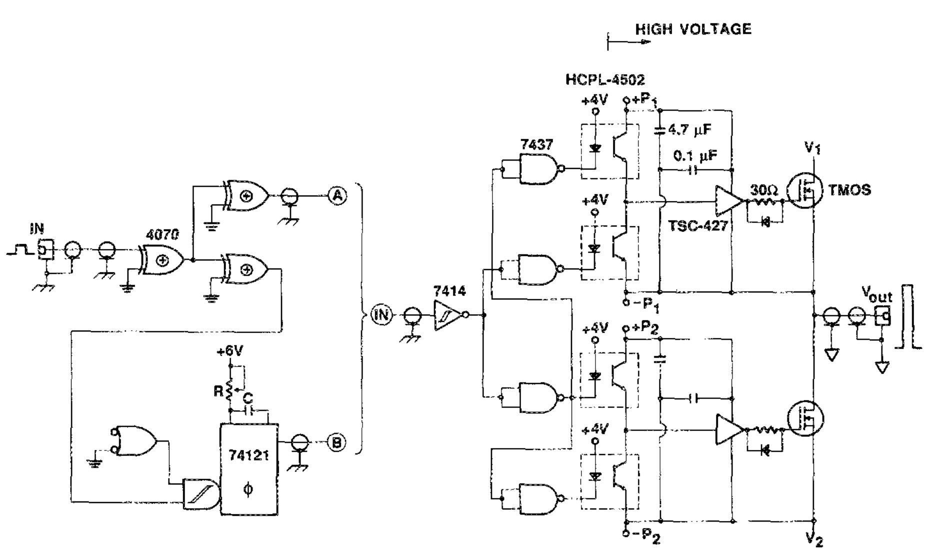

FIG. 3. Complete circuit diagram for the square-wave pulse generator with adjustable phase. The voltages V_1 and V_2 are such that $V_1 > V_2$.

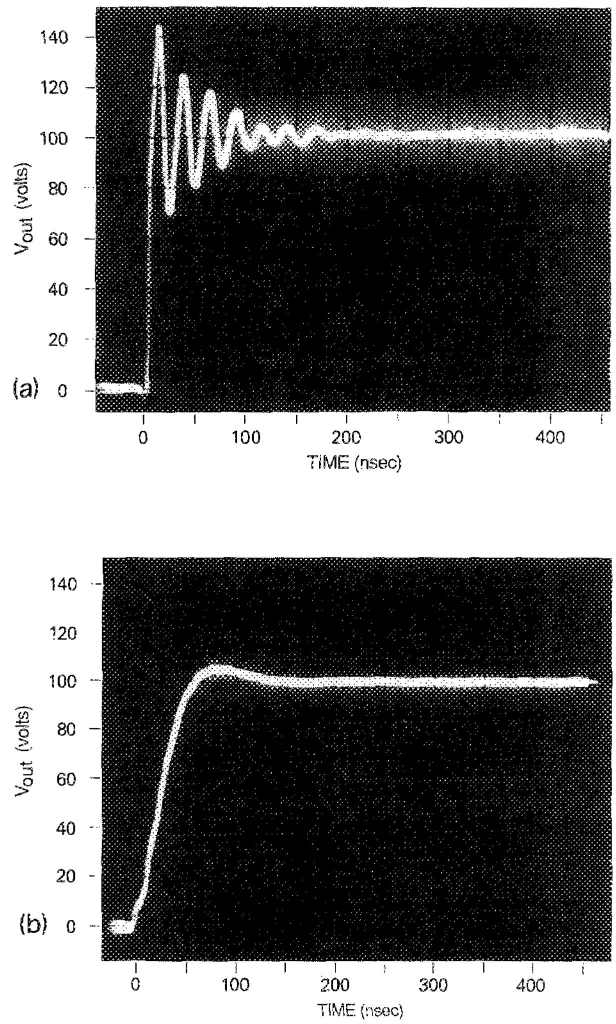

FIG. 4. (a) Rising edge of a 100-V pulse from the circuit of Fig. 3. Ringing is seen for the first 150 ns. Oscilloscope scale: 20 V/div, 50 ns/div. (b) Rising edge of a 100-V pulse with RC filter on signal line. Ringing is attenuated, rise time is 50 ns. Oscilloscope scale: 20 V/div, 50 ns/div.

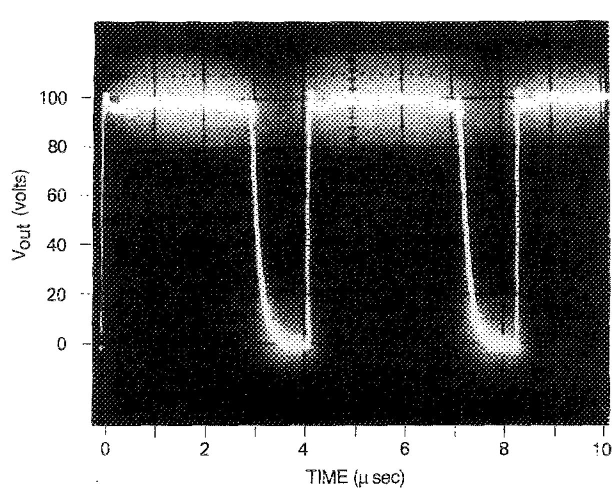

FIG. 5. 100 V square-wave pulse train at 250 kHz, using RC filter discussed with Fig. 4(b). Falling edge (500 ns) is due to rf filter resistor in series with power supply lead V_2, which is also acting as a delay. Oscilloscope scale: 20 V/div, 1 μs/div.

with the condition that $V_1 > V_2$. It is to be noted that V_1 and V_2 can be of different polarity.

III. OPERATION

Figure 4 shows the rising edge of a 100-V pulse, where ringing is apparent, as was expected with these high capacitance FET devices. A simple RC low-pass filter was installed on the output to eliminate this, as is shown in the waveform of Fig. 4(b). The rise time was also affected, and changed from approximately 10 ns in Fig. 4(a) to 50 ns in Fig. 4(b). The rise time is seen to be independent of voltage swing; or more simply, dV/dt is not a constant, whereas the absolute rise time is.

To supply the high voltages, modern switching (dc–dc converter) regulated power supplies were used. In the bench model, it was found that there was sufficient rf feedback on the supply lines to disturb the voltage stabilization circuit on the supplies when operating at high voltage. Therefore a 100-Ω resistor was placed in series at one of the voltage sources (V_2) to supply a high impedance to the rf feedback, thus attenuating its effect. This allowed us to operate the circuit over a wide frequency range without any deleterious effects. However this added resistance delayed switching to V_2, as Fig. 5 illustrates. Here a 100-V wavetrain at 250 kHz is shown. Note the rounded falling edge as the potential is driven to V_2. Adjusting the power supply's rf resistor to lower values will sharpen up the falling edge to 50 ns. But then either more rf suppression is needed on the supply line for operation at higher voltages, or use will have to be made of older regulated supplies of the preswitching variety.

IV. DISCUSSION

We have successfully operated the circuit thus described over a wide range of potential differences, with no deleterious changes in the waveform. One switching circuit card has been designed and successfully operated over a 1200-V swing with the same characteristic 50-ns rise time. To facilitate voltages beyond the present limit of 1000-V blocking capability of the single MOSFET, the design amendment shown in Fig. 6 has been employed. The resistors R are used to evenly distribute the voltage across the stacked MOSFETs, and the transzorbs Z^* (ultrafast silicon zener diodes)[5] offer picosecond response to any voltage spikes on the line. The capacitors offer the improvement of diminishing transients seen on the high-voltage line. (Probably a better way would be to distribute the capacitor C in parallel with every 1-MΩ resistor. This would provide good dynamic behavior of the voltage divider thus formed by the resistors.) With these additions, a fast waveform of thousands of volts potential difference is achieved.

Future improvements over the high-voltage square-wave generator would overcome the ringing during switching, precluding the need for a low-pass filter on the signal line, and eliminating the rf feedback on the high-voltage leads. Further, it is proposed that similar high-voltage MOS-controlled switching circuits become the subject of single high-voltage integrated circuit (HVIC) packages for convenient application, thus eliminating long component leads

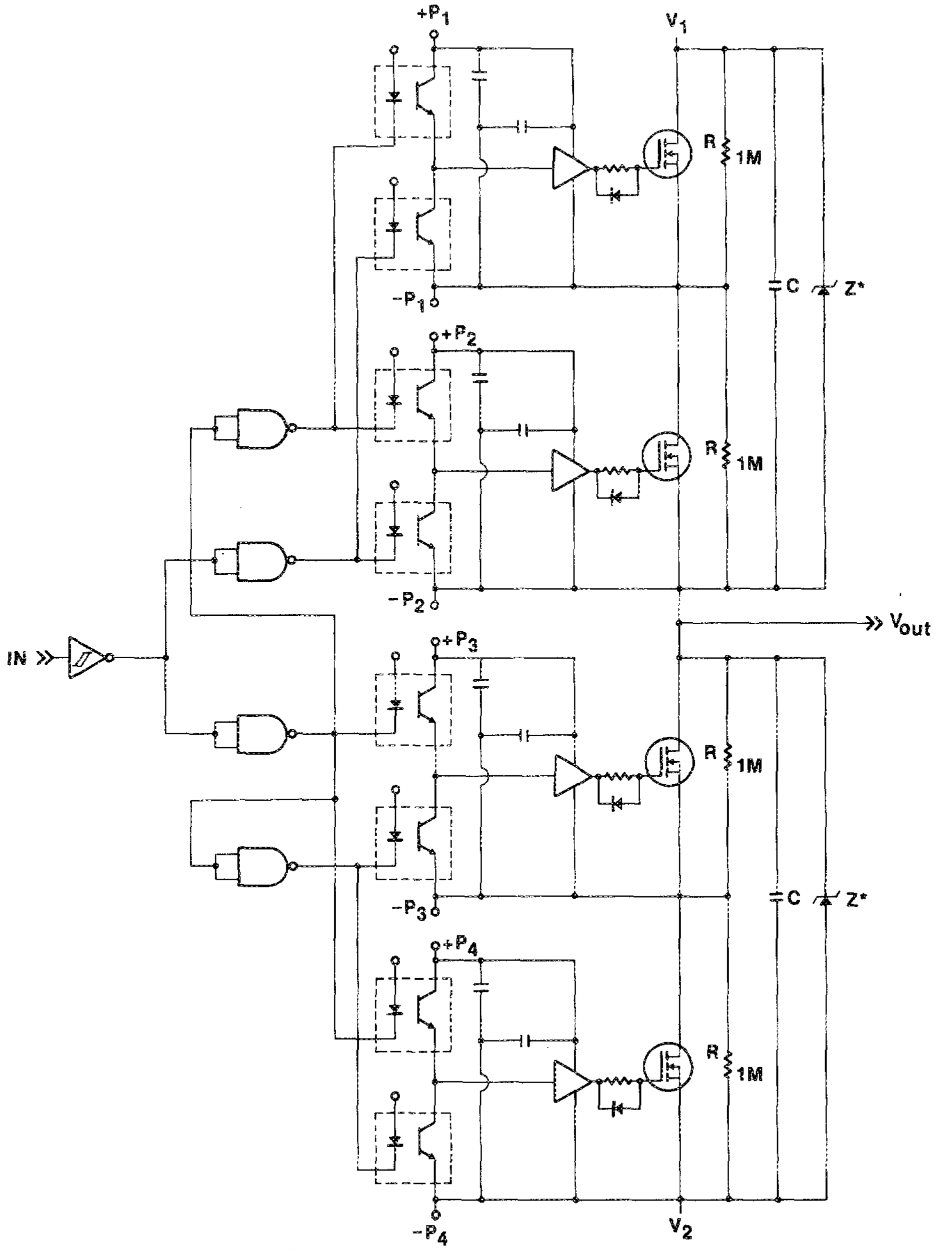

FIG. 6. Technique of stacking power MOSFETs to achieve voltage blocking capability beyond the ratings of a single device. Shown also are filter capacitors C, voltage divider resistors R, and transzorbs (ultrafast silicon zener diodes) Z^*. The voltages V_1 and V_2 are such that $V_1 > V_2$.

and reducing overall dimensions for faster, cleaner operation. Then rise and fall times of less than 50 ns between a reasonably unlimited voltage range would be possible for experimental exploitation.

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[1]N. Theophanous, S. Tsitomeneas, G. Alexakis, A. Arapoyianni, and G. Papaioannou, J. Phys. E **21**, 667 (1988).
[2]We use TMOS power MOSFETs from Motorola. Devices should be chosen according to voltage and current requirements; consult Motorola data book DL135 for details. (Motorola, Phoenix, AZ.)
[3]BNC Pulse Generator 8010, Berkeley Nucleonics Corp., Berkeley, CA.
[4]Here we use Teledyne's TSC-427 power MOSFET driver. There are faster drivers, including the capability of driving 2500 pF in 25 ns with 6 A peak drive current. (Teledyne Semiconductor, Mountain View, CA.)
[5]"Transzorbs" is a registered trademark of General Semiconductor Industries, Inc., Tempe, AZ.