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Improved high-voltage, high-frequency square-wave generator

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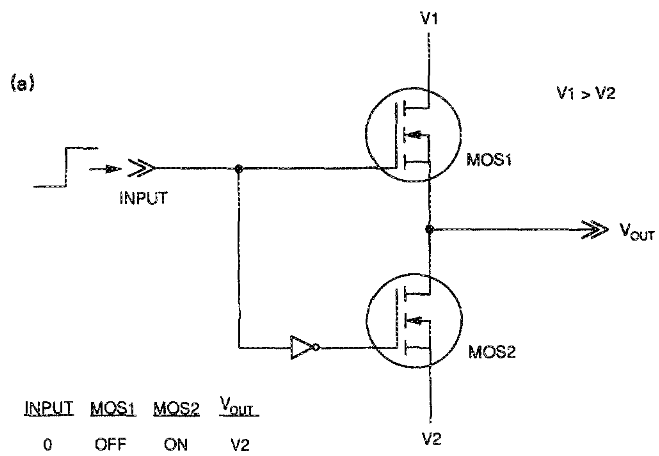
We describe an improved design and operation of a prototype high-voltage full-floating, high-frequency square-wave generator over that first described in this journal [Rev. Sci. Instrum. **60**, 779 (1989)]. The final design is seen to be more versatile, overcomes possible momentary simultaneous ON states in the totem-pole MOSFET configuration, and is less susceptible to deleterious effects caused by component aging, and replacements with nonidentical parts.

Frequently it is necessary to quickly vary the polarity and potential of electrodes in certain classes of experimental arrangements involving the generation, transport, and acquisition of charged particles in vacuum. Time-of-flight configurations coupled to resonant photoionization studies, for example, rely on pulsing grids and lens elements between arbitrary (variable) voltages of up to kilovolt potentials in submicrosecond time scales. Certainly the switching time must be kept short as compared with the drift velocity of the ions and tolerable distances involved. This need had led to the development of a high-voltage, high-frequency square-wave generator capable of switching between arbitrary voltages, as high as in the kilovolt regime, with submicrosecond response times. That design, presented in Ref. 1, was based on solid-state MOSFET circuitry as the active element, and has been applied to the operation of a novel type of negative ion source for mass spectrometry.[2] In doing so, however, several limitations in the circuit design became apparent.

For one thing, due to limited availability of discrete components at the time, the circuit was constructed of carefully matched parts with near-identical response times. As components were replaced during routine maintenance and industry standards improved in this rapidly growing field, various inconsistencies developed due to mismatched timings, causing a power consumption that varied as twice the operating frequency. When operated at high frequencies, then, the components tended to burn out.

Also, certain operating frequencies were seen to be harmonic with several unrelated sensitive electronic hardware in the vicinity—a situation apparently due to rf broadcast, and one which had to be remedied or the limited operation would curtail the utility of the square-wave generator as described. In an effort to overcome these limitations, further development resulted in a more versatile square-wave generator, which is forthwith presented.

The class of high-voltage switch under consideration is characterized by voltage-driven MOSFETs operated as "relays" arranged in a "push-pull" totem-pole configuration as seen in Fig. 1(a). As the accompanying truth table demonstrates, the output, V_{out}, will switch between V1 and V2 as the respective MOSFETs, MOS1 and MOS2, alternate between the open (OFF) and closed (ON) state. For individually selected components without complicated driving circuitry, this circuit configuration is fine: it is simple and it works. As the circuit becomes more complex, incorporating a driving circuitry and shunting (or tie-down) capacitors (to inhibit rf noise), the timing can overlap, as is shown in Fig. 1(b). When this happens, a momentary state exists where both MOSFETs are on, causing a direct short between V1 and V2, and which will be observed as a frequency-de-



INPUT	MOS1	MOS2	V_{OUT}
0	OFF	ON	V2
1	ON	OFF	V1

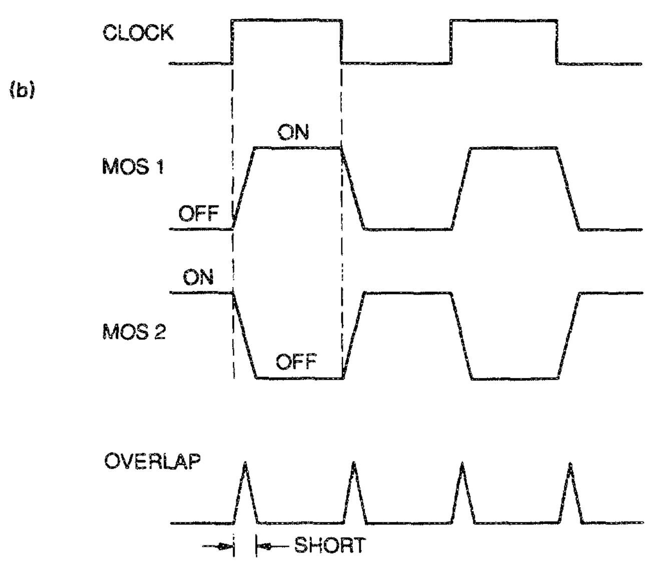


FIG. 1. (a) A MOSFET square-wave generator with the MOSFETs configured in a totem-pole fashion. The gate of MOS2 is always receiving the inverted signal applied to that of MOS1. (Gate reference to source potential is deliberately missing for purposes of clarity.) (b) Possible timing defects characteristic of the totem-pole switch. The rise and fall times of the MOSFETs are exaggerated for clarity. Note that a direct short between V1 and V2 exists when the ON cycles overlap.

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pendent power drain. Eventually, as the frequency is increased, excess power dissipation will cause components to fail.

To overcome this frequency limitation and power consumption, it is necessary to tailor the firings of the MOSFET gates in such a way that on-time overlap is eliminated. This can be accomplished using a delay circuit that operates on the rising edge of the ON-state only. Figure 2(a) shows such a configuration, where the ON transition of the MOSFETS are variable, but are triggered OFF by the input clock. The first MOSFET is delayed by a time interval equal to the inherent fall time of the second MOSFET, and likewise the second is delayed an amount equal to the inherent fall time of the first. (What we refer to as the inherent fall time of the MOSFET is the turn-off delay time of the device, which is generally dependent on discharging the gate capacitance as

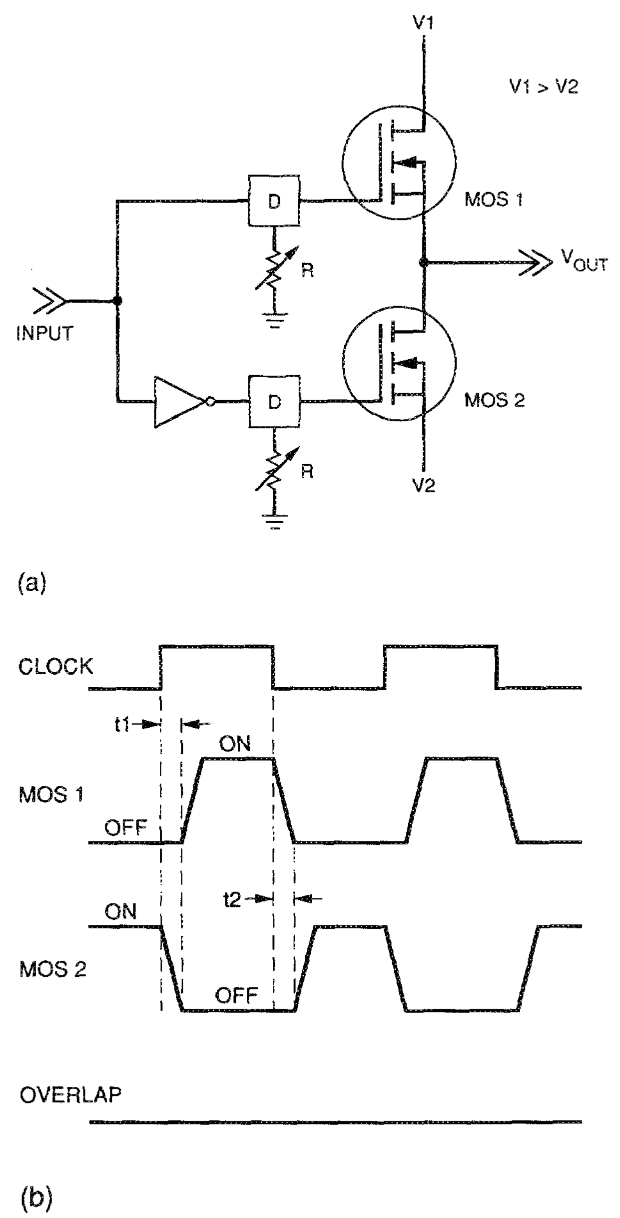

FIG. 2. (a) A remedy for the timing-overlap problem. The delay circuitry (D) allows for adjustments in the ON times of the MOSFETs, with reference to the clock. In such a way, overlap can be eliminated, as shown in (b).

the gate voltage drops below the threshold curve referenced to the source potential.) This results in elimination of ON-time overlap, as is demonstrated in Fig. 2(b). The response time of the components in the delay circuitry are frequency independent, so adjustment pots are located directly on the circuit board. They are set once, and need only be adjusted should the MOSFETs or their drivers require changing. In practice, the sum $t_1 + t_2$ of additional delay times is small relative to the total on time: the duty cycle is reduced by approximately 5% at an operating frequency of 100 kHz.

Hand in hand with this development is the elimination of any possible rf broadcast, either in the MOS1-MOS2 area acting as a dipole antenna, or by inductive means over the transmission line. This is accomplished by the liberal use of tie-down capacitors, where appropriate, on the low-voltage TTL components in the driving circuitry, and by employing a modified 'snubber" arrangement as was first described in Fig. 6 of Ref. 1. The widespread use of capacitors should be done carefully, however, as it will limit the final speed over which the switch will work. In general, UHF circuit construction techniques were employed throughout,[3] which include special attention to PC-board layout, respective component placement, and keeping component lead lengths short.

The final design for a 2-kV square-wave generator is presented in Fig. 3. The Schmidt-triggered buffer takes either a sinusoidal or square-wave pulse train, and produces a noise-free inverted square wave for the delay circuitry. The delay uses an AND gate to compare fixed-delay, nondelayed, and variable-width pulses to produce a square pulse in phase with the input clock pulse. (The fixed delay is necessary to prevent a "double-pulsing" glitch due to the lag time involved with passing a logic signal through the various components.) The resultant square pulse has a variable delay ON cycle (with respect to the clock) between 0–1 μs, but turns off with the clock pulse due to the incorporation of the nondelayed pulse in the AND gate logic.

The resultant pulse train with variable ON times are directed towards NAND-gate buffers capable of sinking 50 mA when driven LOW. This permits hooking them up directly to the optical isolators as shown. The optical isolators,[4] wired in totem-pole fashion, drive the industrially new MOSFET drivers,[5] which are supply-bypassed by a 10 μF solid tantalum capacitor in parallel with a 0.1 μF ceramic disk capacitor. The driver biases the gate of the MOSFET at + 12 V with respect to its source, when the MOSFET is desired ON. Table I lists all the components and suppliers.

The operation of the switch is straightforward. By monitoring the output of the MOSFET drivers on an oscilloscope, the ON delays are first set to zero. Then by observing the driver outputs relative to each other (one need only examine two—one from the upper half of the circuit and one from the lower half), the delays are adjusted until overlap disappears. Finally, a check is made by observing the output signal at high frequency and monitoring and minimizing any current drawn.

As presented, the circuit performs well over a wide voltage and frequency range, until a limit is imposed by the operating characteristics of the active MOSFET elements.

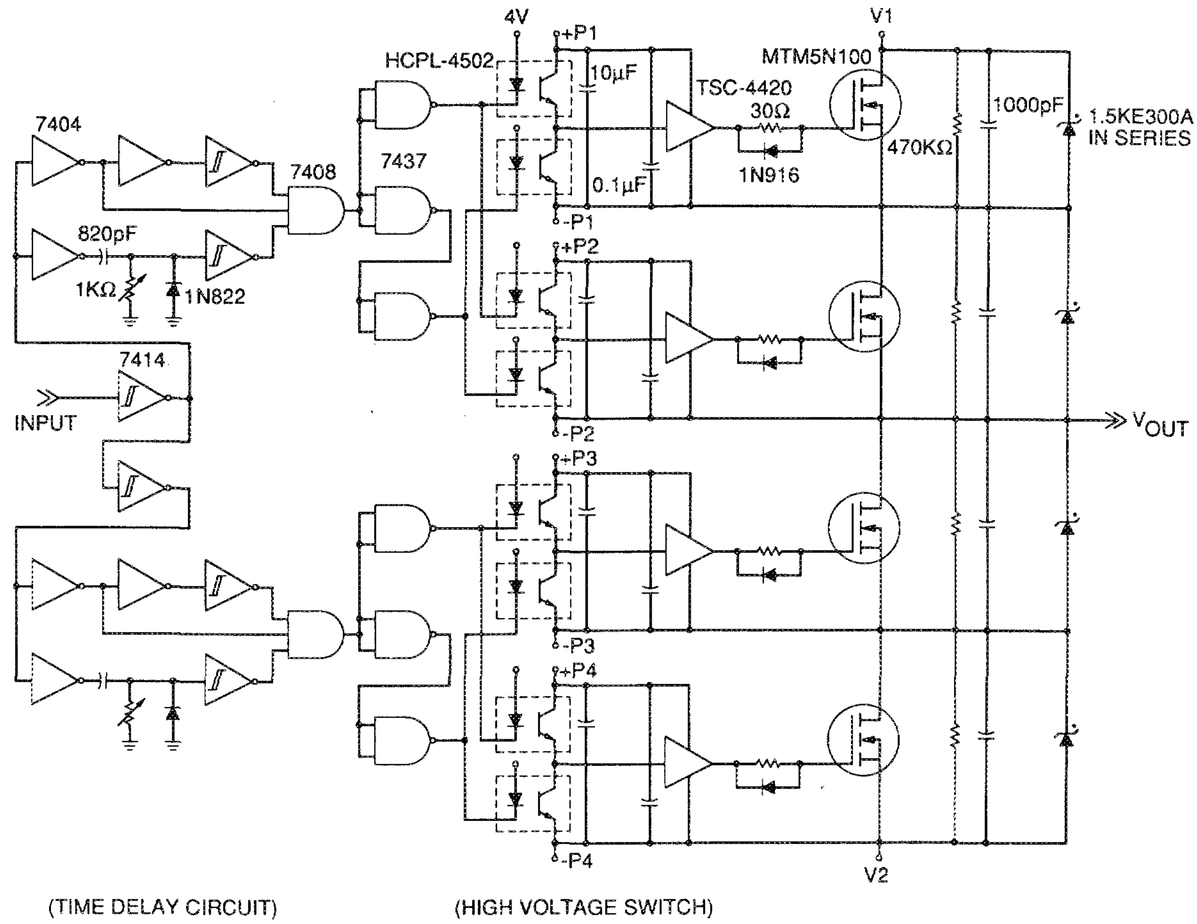

FIG. 3. A 2-kV square-wave generator with modified timing adjustment to overcome "timing overlap." Details of the circuit methodology are shown, with parts and associated manufacturers listed in Table I. This figure should be compared with Fig. 3 in Ref. 1. The optically isolated transistor switches are operated between rail potentials P1,..., P4 which are 12 V each and supplied by a quadruple ground-isolated power card (not shown).

Although we are only using the current design (at present) for switching 1000 V at frequencies of about 20–50 kHz with switching speeds of about 100 ns, the changes described over the previous circuit[1] permit the driving of high capacitive loads with minimal power consumption—a distinct advantage over transistor-based circuits. Improvements are possible and further progress is ongoing, with present interest in incorporating ferrite pulse sharpeners, as described in Ref. 6, for faster response times with minimal overshoot.

We would like to acknowledge Dr. P. W. Zetner at JPL for helpful discussions, and we would like to thank all those who contacted us regarding a HV switch design of a more general nature for providing the impetus for this paper. This work was supported by the U.S. Department of Transportation and the National Science Foundation, and was carried out at the Jet Propulsion Laboratory, California Institute of Technology through agreement with the National Aeronautics and Space Administration.

TABLE I. Parts listing. (Note: Estimated cost per HV switch, including support hardware is about $100.)

Components	Manufacturer
7404, 7408, 7414, 7437 IC chips	Texas Instruments
HCPL-4502 opto-isolators	Hewlett–Packard
TSC-4420 MOSFET Driver	Teledyne Semiconductor
MTM-5N100 (1 kV MOSFET)	Motorola
1.5 KE300A Transzorbs	General Semiconductor
Various resistors, capacitors and diodes	Ubiquitous

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[1]M. T. Bernius and A. Chutjian, Rev. Sci. Instrum. **60**, 779 (1989).

[2]M. T. Bernius and A. Chutjian, J. Appl. Phys. **66**, 2783 (1989).

[3]To get an idea of UHF circuitry techniques, consult Chaps. 7 and 13 in *The Art of Electronics*, by P. Horowitz and W. Hill (Cambridge U. P., Cambridge, 1980).

[4]We have noticed that the HCPL-4502, which has a small base-collector capacitance for high speed operation, is also very susceptible to electrostatic discharge (ESD) damage. A substitution may be made with the HCPL-2601 (40 ns response time) for faster response with added ESD protection.

[5]TSC-4420, by Teledyne Semiconductor, can drive a 0.01 μF capacitive load in 60 ns. Its rise and fall times are typically matched at about 25 ns.

[6]N. Seddon and E. Thornton, Rev. Sci. Instrum. **59**, 2497 (1988).