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AVALANCHE TRANSISTOR PULSER FOR FAST-GATED OPERATION OF MICROCHANNEL PLATE IMAGE-INTENSIFIERS

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Summary

Transistors operated in the avalanche mode are employed to generate a 1000 volt 10 to 30 nsec wide pulse with $<$ 4 nsec rise and fall times. This pulse is resistively attenuated to ≈ 270 volts and drives the image intensifier tube which is a load of ≈ 200 pf. To reduce stray inductance and capacitance, transistor chips were assembled on a thick-film hybrid substrate. Circuit parameters, operating conditions, and coupling to the microchannel plate image-intensifier (MCPI^2) tube are described.

To provide dc operating voltages and control of transient voltages on the MCPI^2 tube a resistance-capacitance network has been developed which (a) places the MCPI^2 output phosphor at ground, (b) provides programmable gains in "f-stop" steps, and (c) minimizes voltage transients on the MCPI^2 tube.

Introduction

Fast shuttering of 18 mm "Generation II" microchannel plate image-intensifiers (MCPI^2) tubes has been employed[1] successfully for several years at Los Alamos. The larger photocathode-to-channel plate capacitance of the 40 mm MCPI^2 tubes concerned herein inherently lengthens the shutter time. The technique to be described allows gated operation of 40 mm diameter tubes with an "on-time" of 15 nsec or less, a delay of less than 8 nsec between trigger and tube turn-on, and a triggering jitter of less than 200 psec. Mixing techniques allow a single tube to be pulsed at 50 nsec intervals for up to ten consecutive pulses. Shorter "on-times" are possible with 18 mm diameter tubes which have lower photocathode to channel plate capacitance.

The MCPI^2 tube is a double proximity focusing, microchannel plate tube whose gain can be in the thousands while retaining a resolution in excess of 20 line pairs/mm. It is comprised of three sections. The first of these is the photo cathode to channel plate gap, the first proximity focussed section (see Fig. 1). Next is the microchannel plate, a channeled electron multiplier (MCP). The last section is the proximity focussed MCP-to-output phosphor gap. Operation of the tube requires a low voltage across the photo-cathode to MCP gap (180 volts for the ITT Type F-4113 employed in the work described herein), a voltage across the MCP of a few hundred to 1000 volts, and an accelerating voltage of 5000 volts across the MCP to phosphor gap. The gain of the assembly is linearly related to the voltage across the output gap and exponentially related to the voltage across the MCP. In the operation described herein the tube is shuttered off by biasing the input gap with -90 volts and turned on with an input pulse of +270 volts. The output phosphor is required to be at ground potential.

Basic Pulsing Requirements

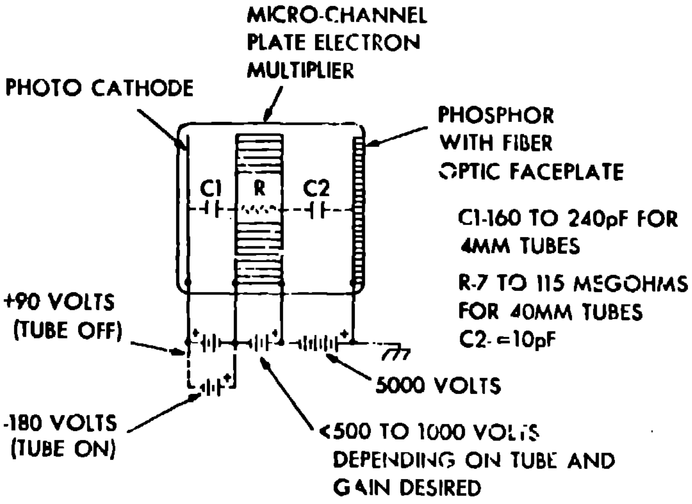
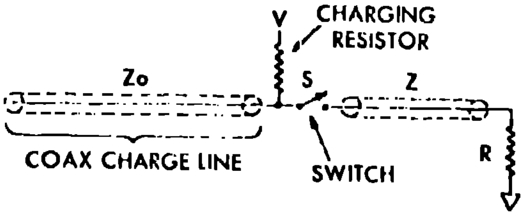


Fig. 1. Image intensifier tube.

For the particular application (conventional high explosive detonation physics studies) the MCPI^2 is used as both a camera shutter and a light amplifier. Fig. 1 shows the tube voltages necessary for proper operation. Practically, the tube shuts off with the photo-cathode only a few volts positive with respect to the input, the use of 90 volts back bias makes the tube a very effective shutter - high voltage can be left on the tube for many minutes without fogging film against the phosphor. This indicates that the noise in recent MCP's is very low.

Tube on-times varying from 10 ns to 30 ns were required with a trigger to tube-on jitter of less than 10 ns. In addition, it was desired to be able to sequentially pulse a tube at 50 ns or greater intervals for up to 10 pulses. Because of the high cost of the tubes (> $10,000 each), as well as simplicity; a line type pulser (Fig. 2) which has limited stored energy seemed desirable to insure against



IF |Zo| - |Z| = R

THE AMPLITUDE OF THE THE OUTPUT PULSE AT THE LOAD IS ½ V.
(ASSUMING THE LINE IS FULLY CHARGED BEFORE S IS CLOSED)

THE WIDTH OF THE OUTPUT PULSE IS EQUAL TO TWICE
THE PROPAGATION DELAY TIME OF THE CHARGE LINE.
(ABOUT 5ns/METER FOR POLYETHYLENE DIELECTRIC CABLE)

Fig. 2. Basic charge line pulser.

tube damage in case of pulser malfunction. The multiple pulsing requirement at pulse separations as low as 50 ns dictated multiple pulsers and a mixer. The 10 ns trigger to output jitter requirement, and rise and fall times commensurate with 10 ns wide pulses, suggested avalanche transistor switching. The tube capacitance (C_t in Fig. 1) of 160 to 240 pF indicates that to achieve rise and fall times of less than 5 ns a pulser source impedance of < 10 ohms is required. It was decided to obtain this using resistive attenuation of high voltage pulses in a mixer box located next to the image intensifier tube.

Avalanche Pulser

Very little hard data is available on use of modern transistors in the avalanche mode. There are no economical transistors characterized for avalanche service available from United States manufacturers and avalanche switching designs are usually based on experimentation and "folklore". Most transistors will not usefully avalanche. LASL had used Motorola MPSU04 transistors extensively for higher voltage avalanche switching but just prior to this work a manufacturing process change by Motorola rendered the MPSU04's virtually unusable for avalanche mode work. A literature search located several references[2-5] dealing with avalanche mode circuit design, two references[6-7] dealing with parallel connection of avalanche transistors for increased current capability, one reference[8] dealing with series connection for higher voltage operation, and three references[9-11] discussing avalanche sweep and gate generators based on up to twenty 2N3700's connected in series. Numerous papers dealing primarily with low voltage applications of avalanche mode switching have been published by V. P. D'yakonov[12] between 1966 and the present.

References 9-11 and personal communication with L. Coleman led us to try using 2N3700 transistors manufactured by National Semiconductor Corporation. (We have not evaluated 2N3700's manufactured by other vendors, but often it is found that avalanche characteristics vary greatly with vendor. Over 90% of the transistors received from National have exhibited satisfactory avalanche characteristics). Earlier experience with MPSU04's in series indicated that best operation was obtained when a resistor divider string was used to back bias the base-emitter junctions and maintain uniform voltage across each transistor irrespective of collector-emitter leakage current. It was also found that the most reliable triggering was obtained when a small capacitor (≈ 10 pF) was placed across the series combination of three or four of the transistors in the string and the trigger signal applied to one of these transistors. These techniques were tried with the 2N3700's with poor results. The simpler biasing scheme and single transistor trigger shown in Fig. 3 were more stable and reliable (this is essentially the scheme used by Thomas, et al[9-11]). An initial current bias of approximately 100 μ gives a stable reliable triggering. The circuit shown with twelve transistors in series and a 2 megohm resistor to a 3000 volt supply normally achieves this.(The charge line charges to ≈2800 volts). Occasionally it is necessary to short out one or two transistors to get more reliable triggering. There have been no problems with self triggering. After some period of operation it has been observed that the bias current may drop (i.e. transistor leakage current decreases), but there does not seem to be any effect on triggering stability. The trigger transformer is a transmission-line type made by wrapping 4 turns of 50 ohm #30 AWG wire-wrappable coax (W. L. Gore & Assoc., CXN-1214) around a toroidal core (Ferroxcube 3E2A266CT125). The coax shield is used as the primary and the inner conductor as the secondary. The trigger location in the string is chosen to minimize voltage stress on the trigger transformer windings although they will withstand the full 3 kV power supply voltage. Reliable triggering is obtained with 4.5 volt pulses although normally 15 volt pulses are used. Delay and jitter are reduced with the higher voltage.

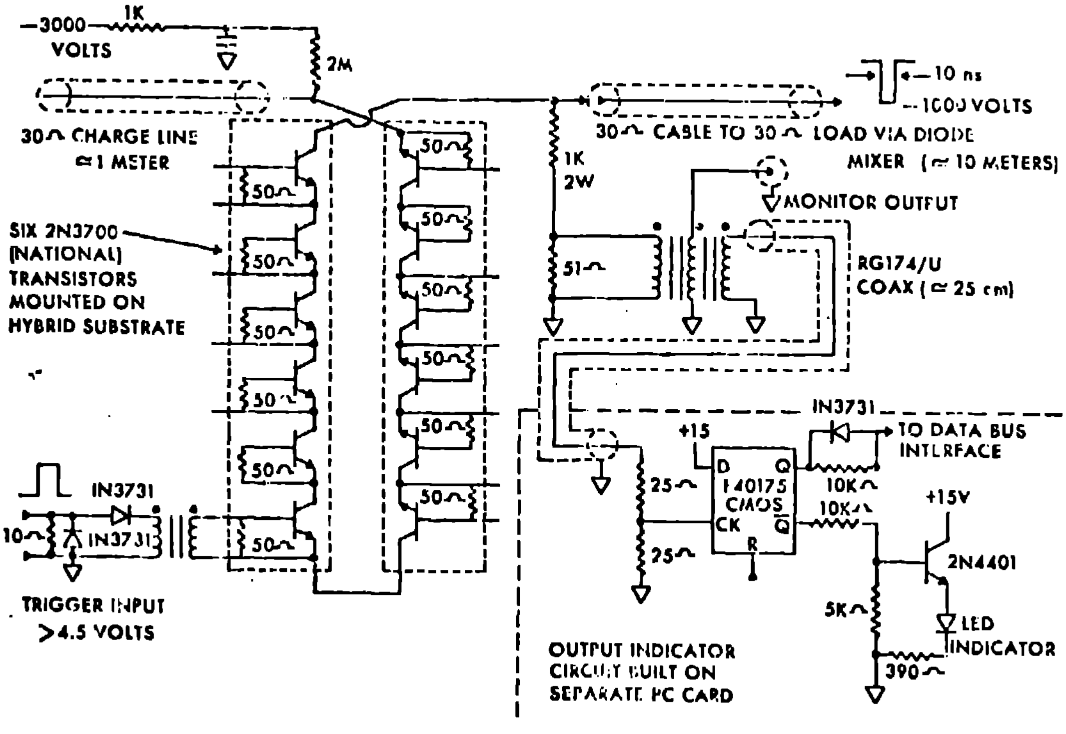


Fig. 3. Charged line pulser with avalanche transistor switch.

To reduce circuit inductance, simplify printed circuit card layout, and hopefully improve rise time the transistors were bought in chip form, epoxied in "lids", and mounted in groups of six on a thick film hybrid substrate. Figure 4 shows three of the hybrid assemblies with the center one unpotted, while the end units are potted with a silastic protective coating. The pin spacing on the units is the same as a standard 16 pin dual-in-line (DIP) IC package although pins are mounted on only one side. (The additional pins are brought out to allow flexibility in triggering and in using the hybrid string in other applications where fewer than six transistors are needed). On the printed circuit card a pin layout identical to that for a 16 pin DIP IC allows plugging in two of the hybrid assemblies to form a 12 transistor avalanche string. This is shown in Fig. 5. (Ten pulsers are mounted in a single chassis so adjacent pulser cards show in the photo). The upper left-hand corner of the DIP is the pulse output and the upper right hand corner is the charge line connection. Approximately 1 meter of charge line is coiled inside the chassis, as shown, to provide a 10 ns minimum pulse width. The end of the charge line away from the avalanche string, attaches to a rear connector to allow additional charge line length to be attached externally. To minimize the source impedance a 31 ohm, 0.195" diameter coax (Amphenol #21-412) is used for the charge line and for output cables to the mixer box. (Since the impedance of the avalanche switch in the "on" state is approximately 22 ohms, a better match would be to use 50 ohm cable for the charge line. However, because of the need for low source impedance to drive the capacitance load, this mismatch is accepted).

With the parameters given one obtains an output pulse of approximately 1085 volts across a 31 ohm load, corresponding to a current of 35 amperes through the transistors and a voltage drop of 64 volts across each transistor during conduction vs 235 volts in the "off" state. Rise and fall times are approximately 3 ns.

On the pulser chassis an output indicator showing when a given pulser has been triggered is needed - both a front panel LED indicator and a remotely readable data bus indication. Initially we tried to achieve this using TTL Shotlky flip-flops. Extreme problems were had with cross-talk between indicators and finally Fairchild F40175 CMOS flip-flops were tried and found to work well. The Fairchild F40175 "D" flip-flop clocks very reliably with 10 ns wide pulses, but 40175's from other vendors that were tried were not fast enough. The circuitry used is shown in the lower right-hand corner of Fig. 3. The coupling transformer used for the indicator circuit and monitor output is a Technitrol 11GGA.

Figure 6 shows a bottom view of the chassis with five pulser cards and five charge lines visible. The top view is essentially identical with five additional pulser cards. Top and bottom circuits are separated by two 1/16" thick copper sheets which have a lip bent up at the rear of the chassis. The rear panel connector mounting holes line up with holes in the lips of the copper sheets to provide good connector ground reference. This lip proved absolutely essential to prevent cross talk between pulsers. A ground plane was used on both sides of the pulser printed circuit cards. The indicator circuit printed circuit cards are mounted just behind the front panel and can be seen at the bottom of Fig. 6. The data bus interface card is visible in the upper right hand corner of Fig. 6. This card uses standard TTL-LS logic without any memory elements and interrogations of the unit are not done during pulsing. Once the

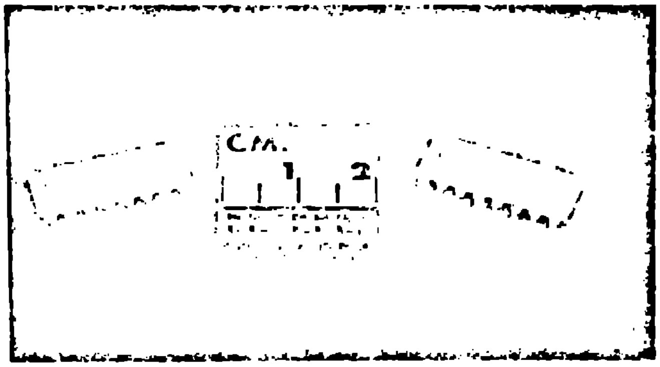


Fig. 4. Hybrid avalanche assembly.

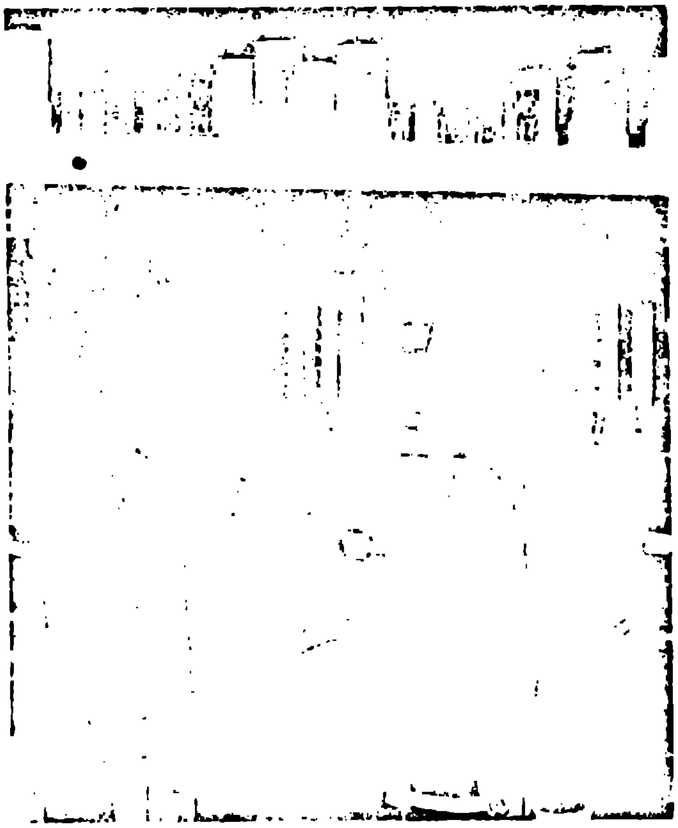


Fig. 5. Pulser printed circuit card.

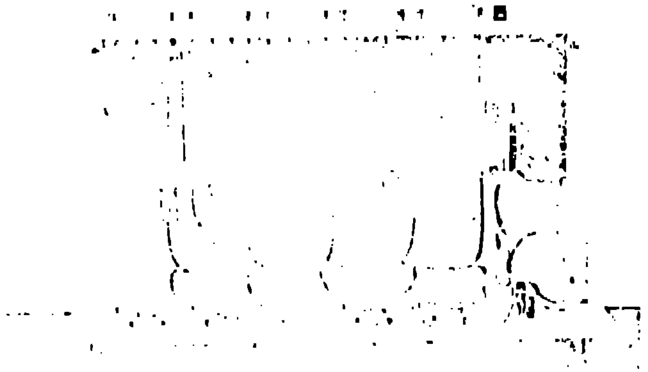


Fig. 6. Bottom view of pulser chassis.

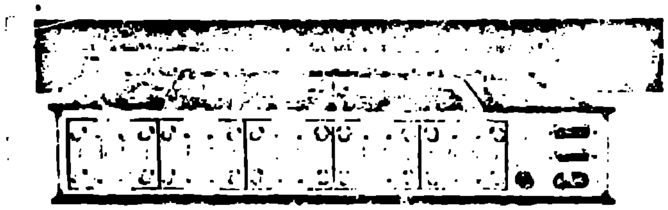


Fig. 7. Rear view of pulser chassis.

copper plates with lips were added, there have been no problems with the generated 1000 volt, 35 ampere pulses affecting the low voltage logic. Figure 7 shows the rear panel. Each pulser circuit has four associated connectors - trigger input (BNC), connector for additional charge line (SHV), pulse out (SHV), and a monitor output (BNC), used to drive an oscilloscope or time interval meter.

Mixer & Attenuator Circuit

The mixer-attenuator circuit is shown in Fig. 8. In normal operation the pulser chassis is located about 8 meters from the image intensifier camera but the cable length is not critical. The mixer-attenuator must be very close to the image intensifier tube for proper performance - there is inherent cable impedance mismatch when driving the capacitive load of the tube and the cable inductance must be minimized to achieve fast rise and fall times. At present 30 cm of RG174/U 50 ohm, 1/8" diameter cable is used but this does limit the performance. We plan to try flat ribbon cable.

The attenuator is made up of the 20 ohm input resistors driving the four parallel 43 ohm resistors (10.75 ohm combined) through the series-parallel 1N-3731 diodes. The voltage drop across the diode string during the 35 ampere pulse is approximately 20 volts. Selected 1N3731's were used which had a reverse breakdown voltage in excess of 100 volts.

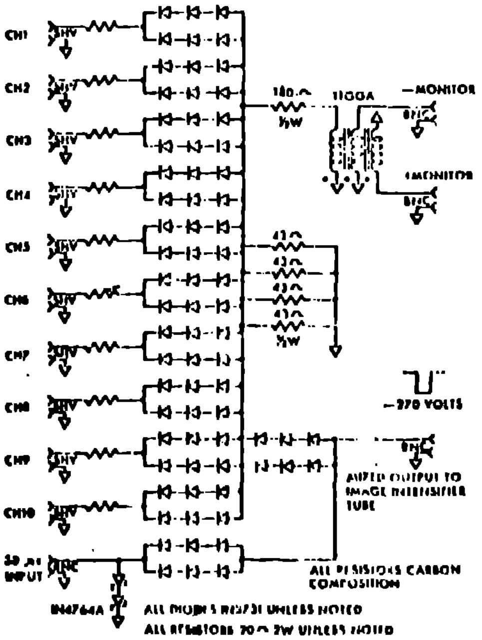


Fig. 8. Mixer-attenuator circuit.

The output diodes allow coupling a 270 volt, 30 μs long pulse from a 50 ohm lumped line pulser for ambient light photography. These output diodes do adversely affect pulse shape and also drop about 10 volts during the pulse. The layout of the mixer-attenuator is shown in Figs. 9-10.

Pulser, Mixer-Attenuator Performance

Figure 11 shows the output of the mixer-attenuator with a 50 ohm resistive load. The scale factors are approximately 60 volts/division vertical and 5 ns/division horizontal. Figure 12 shows the output at the mixer-attenuator with the image intensifier connected through a 30 cm cable which is terminated with a 50 ohm resistor at the tube (R_6 in Fig. 13). The pedestal on the output is due to charge-line to load impedance mismatch. The effective load impedance is the switch impedance, - ≈22Ω plus the external load impedance - 31 ohm.

Since the photocathode-MCP input is back biased by 90 volts the pedestal is tolerable. Rise time on the pulse is clearly less than 4 ns at this point. The pulse at the tube electrodes is smoother with little ringing but with slower rise and fall times due to the inductance of the 30 cm coupling cable.

With this system, LASL Group M-3 has made image intensifier camera photographs with effective exposure time of 15 ns. The measured resolution is 17 to 19 line pairs/mm. Most of the 40 mm tubes received to date, however, will not perform well at this speed. There appears to be a photocathode resistance problem on many tubes which prevents one from turning-on the central portion of the tube with such a short pulse.

Electrical measurements were made with a Tektronix 7904 oscilloscope, a 7A19 50 ohm input preamplifier, and a P6057 probe. The P6057 probe provides 100x attenuation and 5000 ohms input impedance with the 7A19 preamplifier but is rated for only 50 volts. Rise time for the combination is 0.8 ns. With 10 ns to 30 ns pulses it tolerates 300 volts but will not tolerate the 1000 volt pulses. For those, a Phillips PM9358, 100x probe used with a Tektronix 7A16A preamplifier gives a rise time of better than 2.0 ns.

Measurements indicate the jitter between trigger signal and pulse out is less than 200 ps. The delay to the output of the pulser is about 8 ns with a total delay to the mixer output of about 50 ns when using 8 meter cables. Repetition rates of 1 kHz on each pulser can be run with the 10 ns charge lines but normal operation is to single pulse the units. The most disappointing aspect of the performance has been failure problems with the transistors when trying to generate longer pulses. There appears to be a cumulative damage problem with the transistor when they are operated at this current level (35 amperes) which results in sudden shorting of transistors after a fixed number of pulses of a given length have been generated. With 10 ns pulse length, the life is several million pulses but when pulse length is increased to 30 ns the life drops to approximately 15,000 pulses. This is tolerable in our application but discouraging compared to the performance we had seen with Motorola MPSU01's, which had virtually unlimited life under similar conditions. The 2N3700's in contrast have much higher useable yield from each batch, and much lower trigger jitter and delay.

It was interesting to note in working with the pulser that while the 1000 volt, 10 ns pulses will create a visible and audible arc in air, no shock can be felt when applied to ones skin.

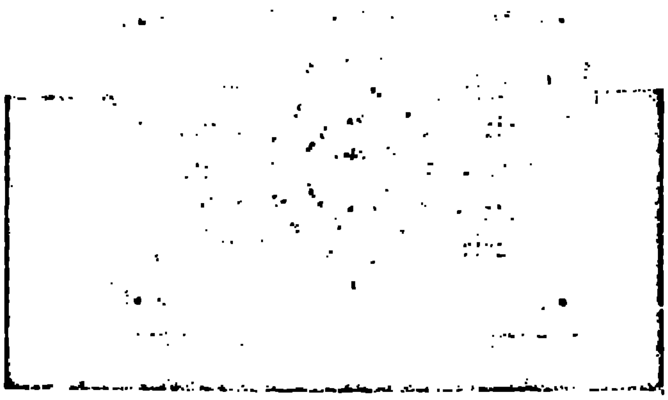


Fig. 9. Mixer-attenuator printed circuit card.

Fig. 12. Output of mixer of MCPI^2 tube load.

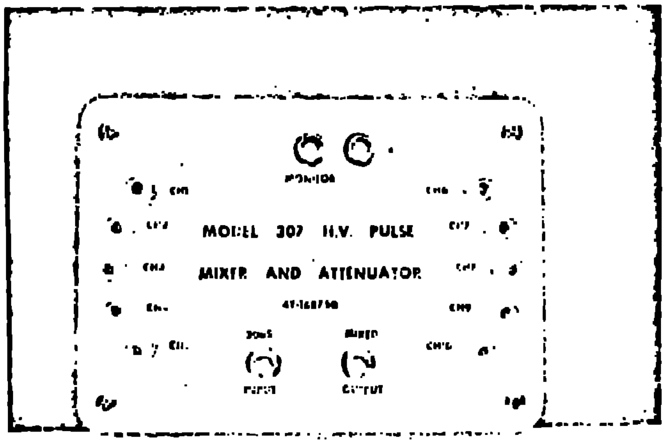


Fig. 10. Mixer-attenuator.

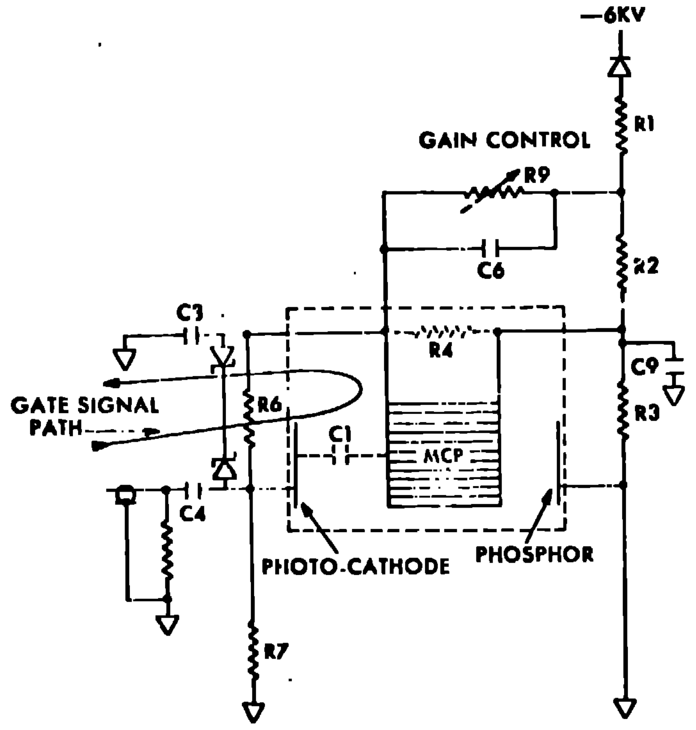


Fig. 13. Divider network circuit for MCPI^2 tube.

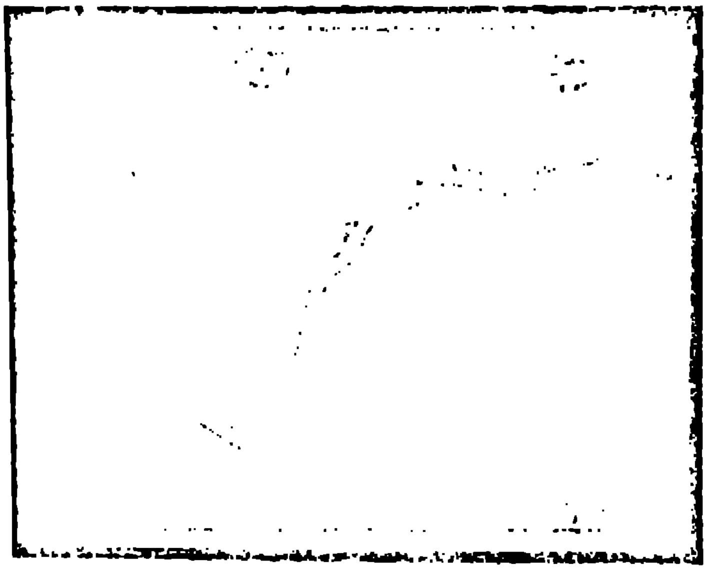


Fig. 11. Output of mixer with resistance load.

Divider Network For MCPI² Tube

The original network,[1] with its associated capacitors, was designed to meet the following criteria:

a. Place the output phosphor at ground potential.
b. Provide a low impedance path for the gating signal.
c. Provide a cut-off bias voltage across the photo-cathode to MCP gap.
d. Stored energy available for tube damage when arc-overs occur shall be a minimum.

The network employed for the 40 mm tubes shown in Fig. 13 is essentially the same except for component types and values and the addition of zener diodes across the photo-cathode to MCP gap. The changes were made to accommodate the following additional criteria:

e. Gain stability.
f. Gain control in "f stop steps".
g. Transient voltages at turn-on and turn-off to be within tube ratings.
h. Total current from a -6 kV supply to be less than 0.5 mA.

Criteria b, d, and g conflict, therefore compromises will be involved in an acceptable design.

D.C. Analysis Of The Network

The gain G of the MCPI² tube can be closely approximated by the relation

$$G = K[V_{cp} - V_{th}]e^{V_{mcp}} \qquad [1]$$

where V_{cp} is the channel plate to phosphor voltage, V_{th} a threshold voltage determined by phosphor backing and thickness, and V_{mcp} the channel plate electron multiplier voltage. By varying V_{mcp} from less than 500 volts to 800 volts the gains of typical tubes can be varied by 7 or 8 stops (120 to 256X). This is accomplished by changing R in Fig. 13 in discrete steps according to the relation

$$R_g = \frac{\left[A\ R_4 + B\right] V^{(G)}_{mcp} + C\ R_4}{\left[D\ R_4 + E\right] V^{(G)}_{mcp} + F\ R_4} \qquad [2]$$

where V_{mcp} is a unique function of gain for each MCPI² tube (derived from data supplied by the manufacturer for each tube), R_4 is the MCP resistance, and the coefficients A, B, C, D, E, and F are determined by the remaining network resistance values. Values for R_4 range from 7 to 120 megohms. To make V_{cp} relatively independent of R_9 the current through R_9 is made as large as permitted by the available power supply.

The gain is a strong function of V_{mcp}, therefore it is essential that the resistors which determine V_{mcp} be very stable and precisely the values required. Adequate gain stability was obtained by changing to 1% low voltage coefficient and low temperature coefficeint metal film and metal oxide resistors and operating these well below their maximum voltage rating wherever possible.

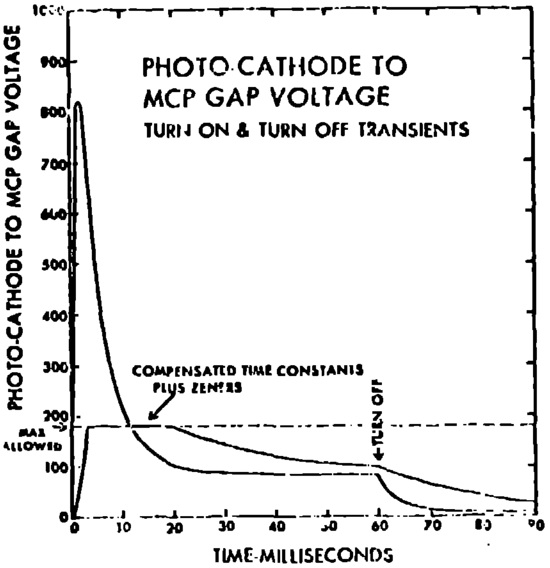


Fig. 14. Photo-cathode to MCP gap transients.

Transient Analysis Of The Network

The digital computer network analysis program, NET-2 was employed to analyze the turn-on and turn-off transients. These transients are shown for the original network and the modified network in Figs. 14 and 15. In Fig. 14 it may be noted that the turn-on transient across the photo-cathode to MCP gap exceeds 800 volts, far above the maximum rating for the tube of 180 volts. This transient is caused by the different time constants of the branch comprised of R_6, R_7, C_3, and C_4, and the branch comprised of R_2, R_3, and C_1 (Fig. 13). It was not possible to change C_3

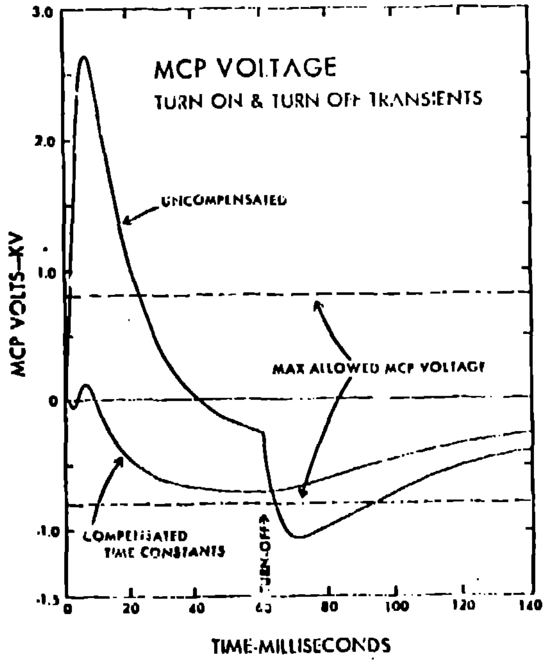


Fig. 15. MCP voltage transients voltage.

and C_4 for it is essential that $C_3 = C_4 >> C_2$ to preserve a low impedance gate signal path. Therefore, C_9 was added to slow the rise of voltage across R_3 and R_4. Reasonable values for C were still not adequate, therefore a string of zener diodes were added across this gap to hold the transient to 180 volts. The zener diode string was actually made a back-to-back string to also hold the gating voltage to a safe value. The presence of the zener diodes did not appreciably affect the gating signal rise and fall times.

Figure 15 shows the transient voltage across the MCP - as high as +2700 and -1000 volts for a tube whose maximum rating was 800 volts! After modification of the time constants the transients were held within 800 volts. Therefore, though the addition of C adds to the energy available to destroy the tube if a tube arc-over should occur its presence does reduce the probability of arc-over considerably.

Physical Configuration of Network

A donut shape for the network nicely adapts to the MCPI^2 tube. The pc board carrying the network is shown in Fig. 16 with all components mounted. All external leads are brought out along one radius to fit with existing hardware. These leads are two coaxes, one for high voltage and one for the gate signal pulse and a twinax for the external gain control resistors and switch. All resistors are 1% low voltage coefficient units. The larger ones are Victoreen metal oxide, type MOX-1, and the smaller ones are metal film units.

The reliability of the capacitors in the network are a cause of concern because a capacitor shorting could destroy the image intensifier tube. Space considerations dictate that ceramic dielectric be used. Units designed for high reliability and with special individual pre-testing have been obtained from Semtech Corporation.

The entire network assembly is potted in Epo-Cast 202 and installed concentric with the tube.

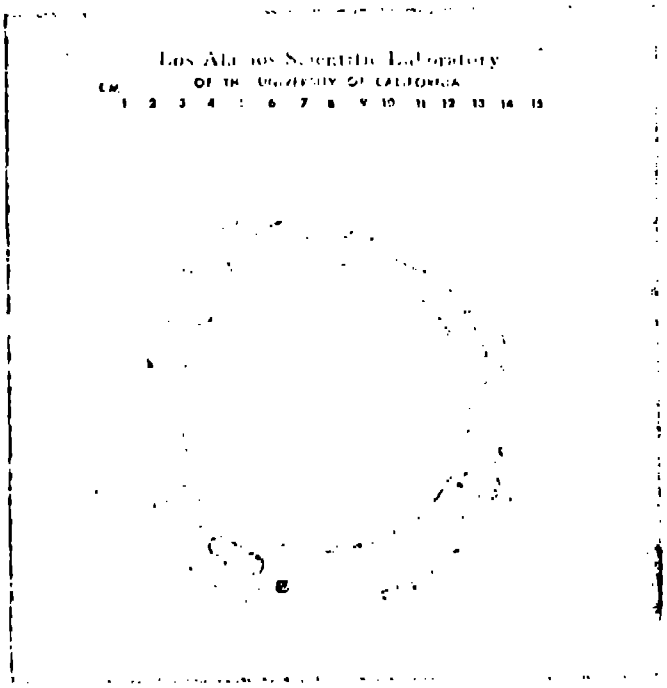


Fig. 16. Unpotted divider network for MCPI^2 tube.

Acknowledgements

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