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Nanosecond optical shutters

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Abstract

A comparison of gated optical shuttering responses for commercially available micro-channel plate image intensifier tubes (MCPTs) with the performance of a new design for improved optical shuttering is presented. Measurements of opacity, photocathode quantum efficiency, and shutter pulse propagation characteristics are discussed.

Introduction

The optical shuttering properties of nanosecond, electrically gated MCPTs and SITVs (Silicon-Intensified-Target Vidicons) have been measured and reported in our previous works.¹⁻⁴ In this paper, we report recent measurements in two new areas, opacity and quantum efficiency, as well as a comparison of optical shutter responses for two domestic and two foreign manufactured MCPTs (all with minor, if any modifications to their "standard" night vision goggle design). We also report improved performance for redesigned MCPTs which feature reduced perimeter capacitance, lower photocathode sheet resistance, and low inductance MCP and photocathode tabs for more efficient gate pulse injection.

Standard Design MCPTs

The shortest gating period of a typical "double undercoated" (photocathode underlay or substrate) ITT F4111 18-mm-diameter MCPT was compared with similar sized MCPTs from Varo (Model 5772-II), Delli Delti (Model 5306), and RTC-Phillips (XX1410/SP 21120-210 11). Most of our measurements have been on ITT units which historically were used exclusively in our imaging experiments, therefore responses of new devices are normalized to the F4111 response.

Using the criteria that a fully open shutter is the condition where optical transmission occurs over the total photocathode area, the following was observed: (1) the RTC-Phillips MCPT gated fastest; (2) the ITT and Varo MCPTs gated in similar times, slower than (1) above but faster than (3) below; (3) the Delli Delti MCPT gated slowest. These data are indicated as "narrowest" under gate width entries in Table 1. The times required for each MCPT to achieve approximately equal resolution or CTF (contrast-transfer-function) at 4.5 lp/mm are also found in Table 1. It should be noted that different manufacturers applied different and to us, unknown amounts of photocathode undercoatings. Our interest was to identify useful optical shutters for potential applications with shutter periods greater than 5ns. For shuttering in 1 ns modifications are required and are described below.

<u>MCPT</u>	<u>GATE WIDTH (ns)</u>		CTF(% of DC response)
	<u>NARROWEST</u>	<u>4.5lp/mm</u>	
ITT	2.0	2.5-5.4	40-60
RTC-PHILLIPS	1.0	2.7-4.8	55-60
DELLI DELTI	2.9	3.7-5.0	35-40
VARO	2.1	2.7-5.0	40-50

Table 1. Optical gate speed and gated resolution.

The observed differences in resolution as functions of optical gate width are attributed to differences in photocathode sheet resistance. The resistance, together with the photocathode-to-microchannel plate capacitance forms a distributed RC network that must be fully charged by the gate voltage for effective opening of the shutter. Indeed, at least 20V of effective forward bias must be applied between the photocathode and MCP input for resolution ≥ 4.5 lp/mm (CTF $> 5\%$). MCPTs with smaller values of sheet resistance gate faster yielding the higher resolution for short gates. At longer gate widths for DC operation, the resolution for most standard design MCPTs is about equal.

A comparison of responsivity (optical sensitivity) at 610 nm measured for each MCPT is found in Table II. The light source used was a dye laser driven by an Argon ion laser synchronized with the MCPT electrical gate pulse (experimental setup found in Ref. 1). The data are normalized by taking into account the various ND filters required to give the same phosphor brightness, as measured with a TV camera fiber-optically coupled to the MCPT) to the ITT responsivity which is set equal to unity.

The much-lower responsivities for the RTC-Phillips and Varo units is probably due to their heavier photocathode undercoating which attenuates incident photon fluxes before they reach the S-20 photocathode. The "double undercoated" ITT units are typically 50% transmissive.

To further investigate the wide differences in responsivity, we measured the opacity (light transmission through the image intensifier with no voltage applied) and quantum efficiency for each MCPT. The opacity data in Table III indicate highest attenuation (lowest optical transmission) for the RTC-Phillips unit, similar attenuations for the Varo and Belli Delti units, and lowest attenuation for the reference ITT unit. The opacity is an important parameter in the overall shutter ratio when the readout system has enough sensitivity to detect direct light transmission through the image intensifier.

The relative quantum efficiency plots, Figs. 1a-1c for three of the MCPTs indicate similar responses at 610 nm. The absolute sensitivities, however, are not available from these plots, therefore no correlation between responsivity and quantum efficiency is possible. The RTC-Phillips unit was too insensitive to measure with the quantum efficiency instrumentation (Gamma scientific radiometer with standard light source/silicon diode sensor). This is consistent with the much lower responsivity measured for this MCPT.

Assuming that the quantum efficiencies for the ITT and RTC-Phillips S-20's are about equal, there appears to be good correlation between the opacity and responsivity measurements for the two units. The ITT unit has $\sim 40\times$ higher sensitivity and $\sim 56\times$ lower attenuation than the RTC-Phillips unit. There is poor correlation between relative responsivities and opacities for the reference ITT unit when compared with the Varo and Belli Delti units, but this may be because of differences in absolute quantum efficiencies and perhaps differences in phosphor coatings which affect both opacity and gain. In addition, the relationship between responsivity and opacity for a modified ITT MCPT (described later) substantiates the trend shown for the reference ITT versus the RTC-Phillips units. The reference ITT unit has $4\times$ greater sensitivity (equalizing filters of ND 3.2 versus ND 1.6 for the reference and modified units respectively) and $3.3\times$ lower input attenuation (0.61×10^6 vs. 2.0×10^6 respectively) than the modified ITT unit.

In summary, the performance of most commercially available MCPTs of the standard night vision goggle design very similar. Differences in gating speed, resolution, responsivity, and shutter ratio can usually be identified with different processing by the various manufacturers. The standard design (some degree of photocathode undercoating is assumed for all units) should give the following gated performance: (1) optical gate of ~ 5 ns duration, (2) limiting resolution (5 to 10% CTF) ≥ 8 lp/mm, (3) shutter ratio of $\sim 10^6$, (4) responsivity (for S/N = 2/1) of $\sim 1 \times 10^{-4}$ eqn/cm², (5) perimeter turn-on with tripping characteristic during shuttering.

Improved MCPT

Because gating times of MCPTs are proportional to the product of the photocathode sheet resistance and the gate (photocathode-to-microchannel plate gap) capacitance,^{4,5} improvement was made by using nickel undercoating instead of the "double undercoated" chromium normally used. The nickel provided $\sim 94.7/\text{sq}$ at 50% transmission compared with $\sim 22.7/\text{sq}$ at 62% transmission for the chromium. The second modification was to double the photocathode-to-microchannel plate gap at the perimeter to reduce total input gate capacitance from typical value of ~ 33 pf to ~ 22 pf. The center gap remains fixed at 7 to 10 mils (~ 10 pf) as required for proximity focusing between photocathode and microchannel plate. Shutter speeds should therefore improve by the ratio of the sheet resistances or a factor

⁴See SPIE paper #669-12 (LA-OR-85-2743) for further opacity data.

<u>MCPT</u>	<u>CATE WIDTH RANGE (nm)</u>	<u>EQUALIZING FILTER (ND)</u>	<u>NORMALIZED (ITT = 1)</u>
ITT	2.0-5.4	2.2	1.0
RTC-PHILLIPS	1.0-2.0	0.6	0.025
DELLI DELTI	2.9-4.3	1.9	0.5
VARO	2.1-3.7	0.9	0.05

Table 7.1. Conditions for approximately equal optical sensitivity at 610 nm for optical gates in the indicated ranges.

<u>MCPT</u>	<u>AVERAGE OPTICAL POWER ($\mu\text{W}/\text{cm}^2$)</u>		<u>ATTENUATION</u>
	INPUT	OUTPUT	
ITT	1.27×10^3	2.1×10^{-3}	6.1×10^5
RTC-PHILLIPS	1.35×10^3	4.0×10^{-5}	3.4×10^7
DELLI DELTI	1.28×10^3	2.5×10^{-4}	5.1×10^6
VARO	1.30×10^3	2.1×10^{-4}	6.2×10^6

Table 7.2. Opacity measurements, performed using a CW incandescent source.

≈ 3.1 to < 1 ns. The reduced perimeter capacitance requires less charge from the gate pulse resulting in a more efficient interface to external gate pulse generators.

Radiographs of a standard design MCPT and the modified MCPT are shown in Figs. 2a and 2b respectively.

The final modification was to introduce wide tabs to the photocathode and the MCP input and output perimeters as opposed to the normal wire lead connections used in the standard MCPT. This improves the high frequency geometry of the MCPT. In one of the new MCPTs tabs are introduced on two sides (180° apart) of the MCPT as shown in Fig. 3; one for the gate input and the other for the output termination. On another, three tabs are introduced (120° apart) as shown in Fig. 4 to allow experimentation with dual gate inputs while terminating the third tab position. Gate boards were developed for each of the MCPTs to impedance match them for the inherent photocathode impedance of ≈ 12.5 ohms to a 50 ohm gate generator system. The impedance matching is incorporated in the stripline geometry of the gate boards. Top and bottom views of the 2-tab MCPT in the gate board are shown in Figs. 5a and 5b. Figure 6 shows the schematic for the 2-tab MCPT. The wider perimeter gap indicated as d, can be clearly seen in the radiograph of Fig. 2b.

Fig. 1. Quantum efficiency plots for several MCPTs. The plots in a through c are for the ITT, Vaco, and Bell Bell units respectively.

Fig. 2. Radiographs of standard and reduced gate gap MCPTs.
a) Standard MCPT b) Modified MCPT

Fig. 3. Two-tab ITT MCPT

Fig. 4. Three-tab-ITT MCPT

Fig. 5. Two-tab MCPT in impedance-matching stripline boards
a) Top view b) bottom view

**1 POINT DRIVE - 50% NICKEL
REDUCED PERIMETER CAPACITANCE**

Fig. 7. Gate sequence for ring-point driving of 3-tab MCP.

**2 POINT DRIVE - 50% NICKEL
REDUCED PERIMETER CAPACITANCE**

Fig. 8. Late turn-off sequence for two-point driving of 3-tab MCP.

a) Linac/50 ohms b) Linac input to stripline c) Linac/output to stripline

Fig. 9. Linac gate pulse at various locations in 2-tab MCPT/stripline driver boards.

Fig. 10. Gate sequence for 2-tab nickel MCPT using GSA/stripline board, 3ns FWHM gate pulse, and 60 ps FWHM light pulse.

Fig. 11. Turn-off sequence for 2-tab MCPT using GSA/stripline board but with 180 ps FWHM gate pulse from linac. Part d is included to show illumination uniformity used for the sequence.

Shuttering Characteristics of Modified ITT MCPTs

Initial measurements were performed on a 3-tab nickel MCPT with the ≈ 180 ps FWHM Linac gate pulse (described in Ref. 6) but without stripline impedance-matching gate boards. The light source was a 20 ps FWHM 610 nm pulse from a dye laser. Directional wave propagation of the gate pulse as opposed to "irising" was observed on this device. Fig 7 shows the propagation characteristic for single-point driving of the MCPT. Figure 8 shows effects from two-point driving for the same MCPT. The long gate times are associated with dispersion of the gate pulse when attached to the MCPT load.

The stripline gate boards were used for evaluation of the 2-tab nickel undercoated MCPT. The improvement in preservation of the Linac gate pulse is obvious from Fig. 9. Previously, gate pulses were widened by attachment of the load. The widened pulse width at the termination indicates some dispersion as the pulse reached the MCPT. An average of the input and output pulse widths probably best describes the effective electrical gate width.

The sequence for 2-tab MCPT shown in Fig. 10 was taken using the GSA⁷ (gate sequence analyzer) which generates an electrical gate pulse of ≈ 140 V 3 ns FWHM synchronized with a 60 ps FWHM light pulse from a laser diode. The gate pulse is introduced at the left side of the MCPT and terminated at the right side. Figure 10 shows turn-on first on the left with darker area near center and right edge of MCPT. Figures 10e and 10f show turn-off last at right edge, opposite the point of gate pulse injection. This type of shutter response indicates wave (of gate pulse) propagation across the photocathode rather than inward propagation from the perimeter (irising) as observed for standard MCPTs.¹⁻⁴

Turn-off was further analysed using the 180 ps FWHM Linac gate pulse. Jitter problems (20 to 50 ps) encountered with synchronizing the GSA/laser diode and the Linac smeared the effective time resolution, but the wave propagation feature is repeated and appears to traverse the entire 18-mm-diameter in 500 ps or less as shown in Fig. 11.

The jitter problem with the Linac/GSA system was eliminated by removing the GSA and using all passive delays between the gate pulse and the laser diode. Essentially, a sample of the MCPT gate pulse was used to trigger the laser diode while phasing was accomplished with passive coaxial cable delays.

During experimentation with this system it was noted that the shuttering sequence could be produced by either altering the gate delay relative to the light or by varying the reverse bias which has the same effect because the gate pulse has finite rise and fall times. Therefore, the forward bias or effective start and end of the optical gate varies with bias even though the time of occurrence for the light is fixed in time. The gate width is also affected by bias as shown in Fig. 12c and f. Because the electrical gate widths for both cases (≈ 300 ps and 100 ps) are shorter than the propagation time (≈ 500 ps) across the total photocathode, measurements became a mixture of pulse propagation properties across the photocathode and the time duration of the gate pulse. The interpretation of the partial shuttering shown in Fig. 12 is that the electrical gate pulse has propagated approximately halfway across the photocathode and persists for 300 ps at the time that the light occurs (parts a,b). For parts d,e, light occurs when the gate pulse is 75% of the way across the photocathode and has approximately 100 ps width. For this case time is from left to right for the photographs. If instead the sequence represents turn on, the interpretation is that the light has occurred before the gate pulse fully propagated across the photocathode with their widths being too short to gate the total surface. For this case, time goes from right to left. Additional 2-tab MCPTs are being manufactured and this mode of operation will be further investigated.

The gate voltage propagation time from the perimeter to center of the photocathode was measured for the 3-tab nickel undercoated MCPT when driven from a single point. The time, t , was estimated from Fig. 7 (photos zero + 0.66 ns, zero + 0.9 ns, and zero + 1.0 ns) as ≈ 365 ps. Zero here means the start of the optical gate for this shutter sequence. For this MCPT, the total turn on time to fully close the shutter is 660 ps.

To compare the measured propagation time with the time predicted, t , by the model from Ref. 4&5, we use

$$t = T(R_s C_1 a^2)$$

where R_s is the photocathode substrate resistance per unit area, c is the capacitance per unit area of the photocathode to MCP gap, a is the radius of the gated surface, and is equal to the radius r of the photocathode when the gate voltage reaches the center of photocathode, t is the universal time parameter which describes the voltage amplitude $V/V_{\max}$ (as a fraction of the applied gate voltage $V_{\max}$) versus the radius traversed a/r (as a fraction of the total radius r).

For $T = \text{unity}$, the gate voltage at the center of the photocathode is equal to the applied gate voltage. For that case, using the measured sheet resistance ($\sim 94\Omega/\text{sq}$), the calculated gate capacitance ($\sim 4 \times 10^{-14}\text{F}/\text{mm}^2$), and using $a=9\text{mm}$ for an 18-mm-diameter MCPT, $t=305\text{ps}$. The measured and calculated propagation times are within 16% of each other.

A similar analysis of propagation velocity for a 3-tab chromium MCPT with $2\Omega/\text{sq}$ sheet resistance (see Fig. 13) gives a measured t of 490 ps versus a calculated value for t of 447 ps. Again there is fair to good correlation between measured and predicted propagation velocities within the assumed model. Accuracy of this measurement is no better than 15%.

In summary, these modified MCPTs show no "irising" during turn on as is typical for standard MCPTs. Instead, they exhibit directional propagation of the gate voltage. The nickel undercoated units more clearly show this effect, probably because of their faster response. It is not obvious whether the "non-iris" turn on pattern is due to the reduced perimeter capacitance, the lower sheet resistance, or the low inductance gate tabs. These minor modifications to the standard design, when used with external stripline geometry gating circuitry should produce image shutters capable of total shutter times with good resolution in the lns domain.

"Standard" Gen II type image intensifiers without modifications will give optical shutters with $> 5\text{ns}$ periods. Different manufacturing techniques give varying opacities and absolute sensitivities.

Fig. 12. Gate performance for 2-tab MCPT at two reverse bias voltages. The gate pulse, injected at the left, (see text) sequentially gates the photocathode as it propagates across the surface. Gating occurs at crosshairs marked on c and f.

Fig. 13. Two gate sequences for the 3-tab chromium undercoated MCPT. Top series shows gate pulse injected at one input while the second input was terminated and the third input was floating. Gate pulse propagation direction is from gated input to floating input. Bottom series shows effect from reverse of gated and terminated inputs. Again, propagation is from the gated input to the floating input. The tabs are located 120° apart. Time t_0 represents the start of the optical gate. The darkest contours represent the "turned on" or transmitting portion of the MCPT.

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