Image Intensifier Characterisation

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Abstract

An image intensifier forms an integral part of a full-field image range finder under development at the University of Waikato. Operating as a high speed shutter with repetition rates up to 100 MHz, a method is described to characterise the response, both temporally and spatially, of the intensifier in order to correct for variations in the field of view and to optimise the operating conditions. A short pulse of visible light is emitted by a laser diode, uniformly illuminating the image intensifier, while a CCD camera captures the output from the intensifier. The phase of the laser pulse is continuously varied using a heterodyne configuration, automatically producing a set of samples covering the modulation cycle. The results show some anomalies in the response of our system and some simple solutions are proposed to correct for these.

Keywords: Image intensifier, irising, optical gating, range imaging, imaging lidar

1 Introduction

A full field image ranging system is being developed by the authors [1, 2] capable of quickly producing high resolution images by simultaneously measuring the distance to each pixel in the field of view. The system utilises an active light source, typically a number of laser diodes, modulated at frequencies up to 100 MHz. Rather than using a collimated beam and mechanically scanning the field of view, which can take considerable time, this system produces a beam with a much wider angle to flood illuminate the entire field of view. The light impinges on objects in the field of view and is reflected back towards a receiver, consisting of a CCD with a high speed shutter. The shutter is modulated at a slightly different frequency to that of the light source, the difference typically a few hertz or less, and the mixing effect produces a low frequency output, refer Figure 1.

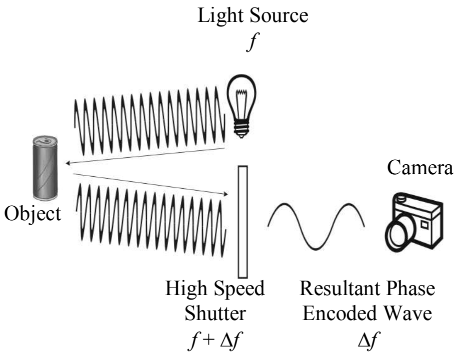

Figure 1: Heterodyning range imager.

The phase of the modulation envelope of the received light is dependent on the distance to the object, and this phase is preserved during the mixing process. A CCD is capable of capturing the low frequency signal (which is below its Nyquist rate) and digitising it. From a minimum of three frames the phase, and therefore range, of each pixel can be calculated. Further detail of the system and some results can be found in a companion paper [1].

The performance of the system is highly dependent on the "high speed shutter" component as the range precision is proportional to the modulation frequency. To achieve frequencies up to 100 MHz an image intensifier is used, with a modulating voltage applied to the photocathode.

1.1 Background

The image intensifier operates by focusing an image on to an input window coated with a suitable photocathode material, in our case S20. When struck by a photon, due to the material's low work function, an electron is released which is accelerated by an applied electric field. The electron enters a micro channel plate (MCP) where collisions with the MCP walls release secondary electrons, producing a multiplication effect of many orders of magnitude as shown in Figure 2. Upon exiting the MCP, the electrons are again accelerated by an electric field, this time colliding with a phosphor screen. The phosphor emits light, creating an output image which can be viewed by the CCD.

To produce the 'shutter' function, the voltage applied to the input photocathode is varied – a negative voltage accelerates electrons into the MCP and hence produces an output, whereas a positive voltage deflects the electrons away from the MCP and turns the intensifier off. Further detail of the intensifier drive electronics can be found in [3].

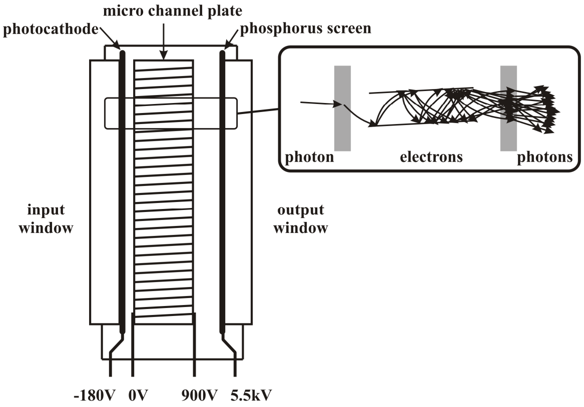

Figure 2: Image intensifier

The modulated voltage is applied to a metal ring around the outer edge of the photocathode and the voltage is conducted through the photocathode material – however the material does have a small resistance. At high modulation frequencies an 'irising' effect can occur where the centre of the image intensifier gating is delayed relative to the outer edge [4] due to the resistance of the photocathode and the capacitance between the photocathode and the MCP, forming a low pass filter. In the range imager case this causes a flat object to appear curved, with the centre of the image appearing further away [5].

Electrically measuring the (varying) photocathode voltage is not sufficient to produce information about the image intensifier response as it cannot easily account for this spatial variation. The electrical input to optical output response of the image intensifier is very non-linear, and therefore requires knowledge of this function if a measurement of the electrical signal is to be attempted. It is also worth noting that the capacitive loading by a typical high impedance oscilloscope probe (10-15 pF) would alter the waveform significantly (the photocathode capacitance is approximately 60 pF) and low impedance probes are not suitable for use with the high voltages (50 V peak to peak at frequencies up to 100 MHz).

1.2 Configuration

A simple method of optically measuring the response of the image intensifier has been developed which only requires minimal modification to the original ranging system described above. Instead of operating the laser source with sinusoidal (or 50% duty cycle square) modulation, it is replaced with a pico-second pulsed laser. This pulsed source only illuminates the image intensifier for a very small percentage of each cycle as shown in Figure 3. The output of the image intensifier is integrated over a number of pulses by the CCD to improve the signal to noise ratio. The produced image is effectively a sample of the image intensifier "shutter" action for that particular point of the cycle.

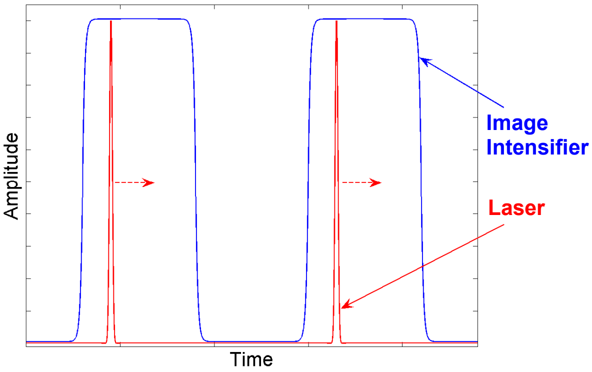

Figure 3: Picosecond illumination of image intensifier

The heterodyne configuration produces a continuously varying phase between the laser pulse and the image intensifier electrical signals, which as indicated by the dash arrow in Figure 3 causes the laser pulse to constantly move through the intensifier shutter waveform taking samples over the entire period. The signal generator also provides a synchronised frame trigger signal to the CCD so that each captured frame occurs at a known phase offset, and a predetermined number of samples can taken over the waveform period. A similar configuration can be found in [4, 6], although discrete phase steps are manually set between each CCD capture making the process more cumbersome.

2 Laser pulser

Laser pulser systems are readily available from a number of manufacturers, such as the PDL 800-B manufactured by PicoQuant GmbH (Berlin Germany), however the requirements of this configuration make it relatively simple to construct a basic pulser circuit capable of low frequency (less than 100 MHz) repetition rates. Only the pulse width is significant for this experiment as the MCP provides a large gain and therefore high laser peak power is not necessary.

Gain switching a laser diode produces a short optical pulse, down to tens of picoseconds, from a longer electrical pulse [7]. Carriers (electrons) are injected into the active region of the laser, bringing the number of carriers above the lasing threshold. Once above the threshold a large number of photons are produced by stimulated emission within the laser, which in turn reduces the number of available carriers back below the lasing threshold. If the current injected into the laser is turned off at this point, a short optical pulse is generated.

The circuit shown in Figure 4 converts the sine wave input into a short optical pulse. A comparator

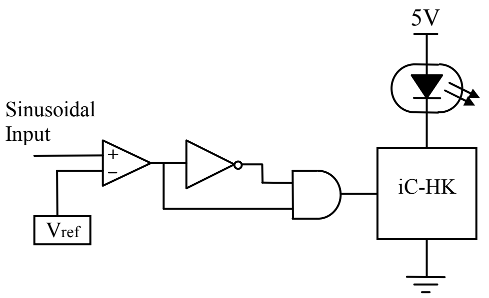

Figure 4: Laser pulser circuit

generates a CMOS level square wave which passes to two inputs of an AND gate, although one input is inverted. Every time the input comparator toggles from low to high, the propagation delay of the inverter ensures both inputs to the AND gate are high for approximately 3 ns, and hence a pulse is produced at the output of the AND gate. An iC-HK laser switch (iC-Haus, Bodenheim, Germany) is used to provide the output drive to the laser diode, and allows the peak current level to be adjusted to optimise the generated output pulse.

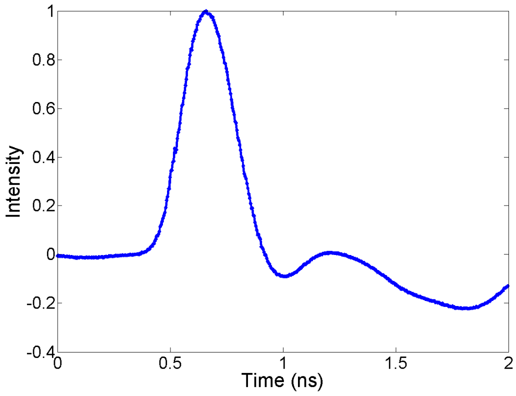

Figure 5: Generated laser pulse, FWHM 266 ps

A recorded pulse is shown in Figure 5 using a Hitachi HL6501MG laser diode. The FWHM pulse width of 266 ps shown is limited by the ~2 GHz bandwidth of the photodiode used (Thorlabs SV2-FC), and therefore the laser pulse may be shorter than that shown. For the purpose of this experiment the pulse width here is considered satisfactory as it is significantly shorter than the period of the image intensifier gating.

3 Experimental Configuration and Results

The pulsed laser beam is expanded, and to minimise geometric variation, the image intensifier is placed approximately 1.5 m from the light source so that the light pulse simultaneously illuminates the entire face of the image intensifier. Ground glass is placed in front of the intensifier to remove interference patterns generated by the laser and to ensure the illumination intensity is uniform. Under normal range finder operation a focusing lens is used in front of the image intensifier, but this is removed for this experiment.

A direct digital synthesiser [8] provides the modulation signal to the image intensifier driver and the laser pulser at a selected frequency with a 0.1 Hz difference, hence it takes 10 seconds for the phase between the laser pulse and the image intensifier gating to cycle through 360°. The output of the intensifier is imaged onto a CCD digital video camera (Dalsa 1M60), which is configured to operate at 100 fps. Therefore 1000 points are captured over the image intensifier period.

3.1 Temporal Response

To measure the 'shutter' action of the image intensifier, a small number of pixels in the centre of the recorded image are averaged (to increase the SNR) and are plotted against the frame number as shown in Figures 6 and 7.

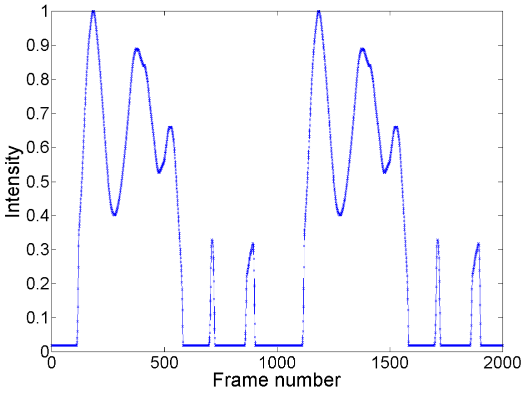

Figure 6: Image intensifier response at 10 MHz

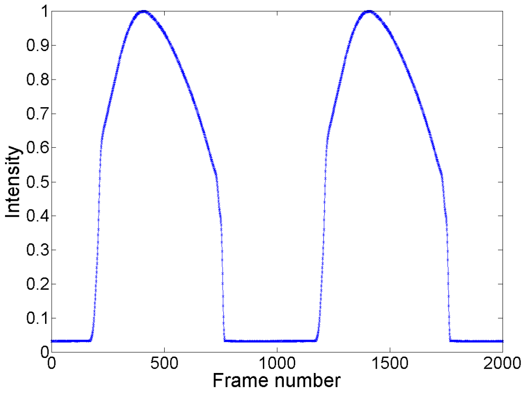

Figure 7: Image intensifier response at 65 MHz

Figure 6 shows that the response is far removed from the desired square wave modulation. Significant ringing occurs due to the capacitance of the photocathode combined with inductance from the interconnecting wires from the electronic driver. During the 'on' state the intensity varies up to 60%. During the 'off' state the electrical ringing peak is larger than the MCP input voltage, causing the photocathode to turn on for short pulses. The non-zero output when the intensifier should be in the off state is due to CCD dark current. The resonant frequency is seen to be approximately 50 MHz. The response in Figure 7 approaches the ideal waveform; however the rise and fall times are significantly different. The 10% to 90% rise time is measured to be 2 ns, while the fall time is 3.6 ns.

3.2 DC Response

To understand the optical gain occurring within the image intensifier as a function of the photocathode voltage, a separate experiment was performed. A uniform DC light source is placed in front of the image intensifier, and a DC voltage applied to the photocathode is varied while capturing the image with the CCD. The intensity recorded is graphed in Figure 8.

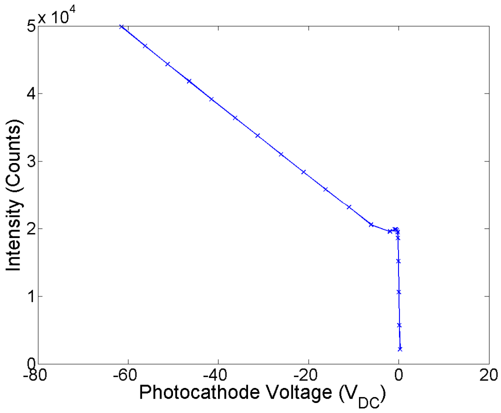

Figure 8: Image intensifier DC response

For a positive photocathode voltage the output drops to zero (slightly above zero in the graph due to CCD dark current). When the voltage becomes slightly negative, a large increase in gain occurs as the electrons emitted from the photocathode are accelerated towards the MCP. From about -2 V onwards the number of electrons reaching the MCP does not significantly change, but each electron receives more kinetic energy from the applied electric field between the photocathode and the MCP, which produces higher gain due to more secondary electrons being produced within the MCP.

The modulation voltage used to drive the image intensifier in section 3.1 was −40 V to +10 V. By looking at the amplitude of the unwanted short pulses in Figure 6, it can be seen from the response in Figure 8 that the ringing after the falling edge is likely to only be slightly negative at its peak, and therefore by altering the bias voltage by a few volts, for example modulating the photocathode voltage from −38 V to +12 V, these extra pulses will be removed.

3.3 Spatial Response

As mentioned in section 1.1, it is possible that the modulation voltage is delayed in the centre of the photocathode compared to the outer edge due to the resistance of the material forming a low pass filter with the capacitance to the MCP. Figure 9 shows this effect, where the intensity of a single captured frame from the rising edge of the waveform is plotted. Instead of a flat surface, a bowl shape can be seen, with the intensity of the centre pixels being less than those at the outer edges.

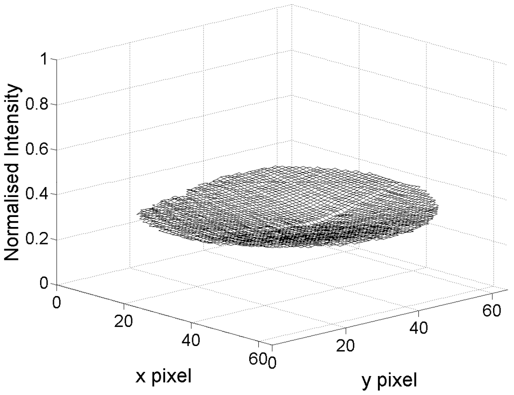

Figure 9: Irising during rising edge at 10 MHz

The irising effect is dependent on the speed of the rising edge transition, and this can be affected by the modulation frequency, therefore the experiment was performed over a range of different frequencies. Figure 10 shows that the irising is much more pronounced at 100 MHz than at 10 MHz as was shown in Figure 9.

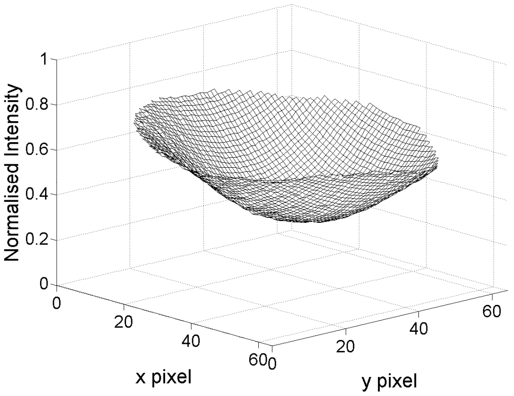

Figure 10: Irising during rising edge at 100 MHz

Figures 9 and 10 show the irising at the most severe point of the waveform (at the sharp rising edge), but it is useful to understand its effect over the entire pulse. Using the assumption that waveform is symmetrical over the round image intensifier, the intensity of a row of pixels through the centre of the image is recorded for each captured frame to represent the entire surface. By plotting this intensity data for various captured frames the irising effect can be seen as the waveform changes, as shown in Figures 11 and 12. It is worth noting that these graphs are generated by the same data capture as was used to generate Figure 7, however now the plot shows both temporal and spatial information.

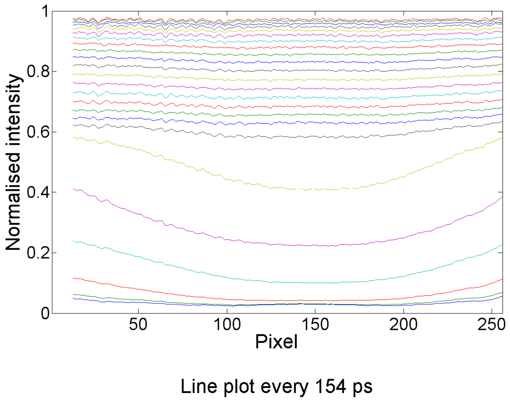

Figure 11: Irising during rising edge at 65 MHz

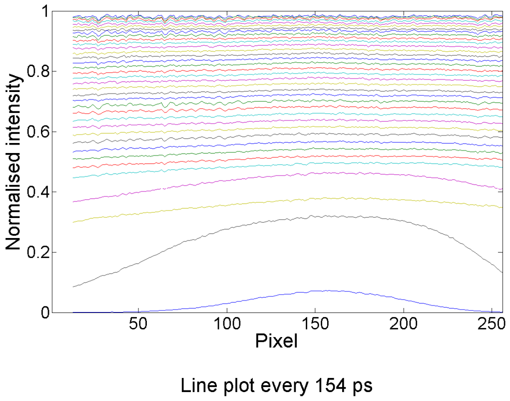

Figure 12: Irising during falling edge at 65 MHz

Figure 11 shows significant irising occurring during a 600 ps interval where a large change in intensity occurs (the lines are separated by large spacing showing a rapid change). The following 2.6 ns illustrate a much slower change in intensity, and as such the level of irising is significantly reduced (although still present). From this figure, the electrical time delay from the edge to the centre of the image is estimated to be 150 ps. The falling edge waveform at the same 65 MHz frequency, refer Figure 12, exhibits different levels of irising to that of the rising edge. The waveform is not symmetrical as can clearly be seen in Figure 7, which leads to this variance due to the different rates of change.

4 Evaluation

By recording the response of the image intensifier and electrical driver, the results indicate that a number of enhancements could be made. The first improvement is to simply adjust the bias voltages so that the electrical ringing after the falling edge cannot turn the image intensifier on as it did in Figure 6. Despite appearing obvious in that figure, it should be noted that these short pulses are not visible in the captured data when the range imager is running under normal conditions.

The pulse width of the image intensifier optical gating may not necessarily match the duty cycle of the electrical input. Making the negative voltage as large as possible is advantageous as it increases the intensifier gain, refer Figure 8; while a large positive voltage is undesirable as it only increases power dissipation within the system. A sinusoidal input to the photocathode with peaks at +10 V and −40 V is then expected to produce an asymmetrical output which is on 63% of the time (when the photocathode voltage is negative). From the graphs in Figures 6 and 7 a measurement of the duty cycle can be made without knowing the exact characteristics of the electronic pulse (which can often be difficult to measure due to the high voltages and frequencies involved).

Electrical resonance produces significant ringing when frequencies below 50 MHz are used in our system, which distorts the waveform and will therefore introduce an error into the range measurements. In the current configuration, the electrical amplifier output is connected to a second PCB which provides the bias voltages to correctly operate the image intensifier. Redesigning a single PCB to include both the amplifier and bias electronics, as well as reducing the length of the wires to the photocathode, will lower the stray inductance and improve the overall response.

As the magnitude of the irising is dependent on the rate of change of the electrical drive signal, the shape of the waveform becomes important. In a system where the rising and falling edges are not symmetrical the exposure time near the centre of the image may be slightly longer (or shorter) than that near the edge. One possible method to achieve equal rise and fall times is to operate the image intensifier near its resonant frequency, which can be found by observing the oscillation on the rising transition such as that shown in Figure 6. The most significant contribution to the irising occurs when the voltage is very close to zero and the output magnitude is less than 60%. As the output image resolution is also dependent on the photocathode voltage [9], it is desirable to quickly transition through the range near zero volts to produce a higher quality image at the expense of increasing the irising.

In the ranger imager application, the resultant range errors due to irising are independent of the distances measured in the scene. They are dependent on the modulation frequency (as the electrical waveform may not be identical at all frequencies), but are constant for a given frequency and therefore can be calibrated for. The 150 ps delay between the centre and edges of the image (estimated in Section 3.3) corresponds to a range error of 22 mm, and is consistent with measured errors [5].

5 Conclusion

An image intensifier is used as a high speed optical shutter as part of an image ranging system. An irising effect, where the modulation at the centre of the image is delayed relative to the outer edge, causes the ranger to produce a reconstruction which is curved, with objects at the centre of the image appearing to be at a greater distance than those at the outer edges. Despite the temptation to simply numerically compensate for this effect, it was investigated in depth.

A gain switched laser diode was used to produce pico-second pulses that were temporally scanned across one cycle of the intensifier drive signal. This effectively sampled the image intensifier gating waveform, allowing its optical response to be mapped both spatially and temporally. This temporal scanning was achieved using a heterodyne configuration to continuously alter the phase between the laser pulser and the image intensifier driver. A CCD camera, with a frame trigger synchronised to the other drive signals, was used captured the image intensifier output.

The experiments revealed that the image intensifier response deviated from the ideal response, most notably with electrical ringing causing a number of problems for low frequency (<50 MHz) operation. This emphasised the fact that the response is dependent on both the image intensifier and the electronic driver as a complete system. Simple variations to the image ranger configuration are proposed to improve its performance, including modifying the driver PCB, adjusting the bias voltages, and selecting the operating frequency at resonance. It is noted that the irising effect cannot be eliminated from the imaging process as it will compromise the image quality, therefore we suggest compensation be added to the image ranger processing software.

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7 References

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