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Diagnostics for light measuring devices in flying-spot display measurements

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ABSTRACT

Flying-spot displays scan an image across the display screen using a high-energy beam. Each pixel can be a narrow, submicrosecond pulse. When such displays are measured with conventional light-measuring devices (LMDs), such as luminance or illuminance meters, there is concern that the LMD may not accurately measure the display light output because of the unique characteristics of the source. The LMD may be unable to properly integrate the narrow pulses, or the high-energy signal may saturate the detector. As in all areas of metrology, it is essential to verify that the instruments used are providing the desired information. A diagnostic has been developed that allows for an evaluation of LMDs for use in measuring flying-spot and similar displays. This method tests for both integration and saturation errors using a bipartite comparator and a neutral density filter. Errors resulting from the saturation of the LMD by the flying-spot display are demonstrated. The construction and procedure of the diagnostic is described. Limitations of the technique as well as sources of error are presented.

Keywords: Display measurement, flying-spot displays, laser displays, light-measuring devices, measurement diagnostic, pulsed-pixel displays.

1. INTRODUCTION

Flying-spot displays, such as some laser projection displays (for example, see [1,2]), use a high-energy beam as a light source that scans the image across the display screen. Some experts report difficulties with measuring the high-energy beam scanning across the display screen because of limitations of the light-measuring devices (LMDs), [3]. They question whether the LMD can correctly measure the light output of such a display. Specifically, how do the characteristics of the

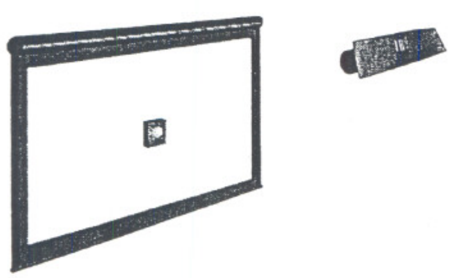

Figure 1. Measuring display light output.

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display affect how one measures its light output (such as the configuration shown in Fig. 1)? If the number of photons striking the detector window is high enough, the detector will saturate, although this limit can depend on the integration time. If the pulse width of the pixels are quite small, does the detector exhibit n adequate temporal sensitivity to these narrow pulses?

For example, we have a green 532 mm CW laser that produces a $P = 2.5$ W beam and displays an $N = 500 \times 380 = 19000$ pixel image onto a 2 m^2 screen. As the flying-spot scans by, a point on the screen would see a "pixel" at $p = P/N = 13$ μW (see figure 2). The conversion to luminous flux is approximately $\Phi_p = k \times p = 7.95$ mlm, where $k = 604$ lm/W. Assume that the area of the pixel projected onto the screen to be $A_p = 1.17$ mm^2. Because $\Phi_p = E \times A_p$, the average illuminance is easily calculated to be $E_a = \Phi_p / A_p = 755$ lx. The light output over the entire image would be $\Phi_{total} = A_p \times N \times E_a$ or about 1500 lumens. The pixel pulse width $\delta t = \Delta t/N = 88$ ns. If the LMD has an integration time on the order of a few milliseconds, will it inaccurately measure the light output? If we are measuring the single pixel A_p the peak illuminance E_p for a pulse of width 88 ns in order to produce an average illuminance of 755 lx is $E_p = E(\Delta t/\delta t) = 1.4 \times 10^8$ lx. Can the LMD deal with such a pulse? Obviously, a diagnostic would prove useful in answering these questions.

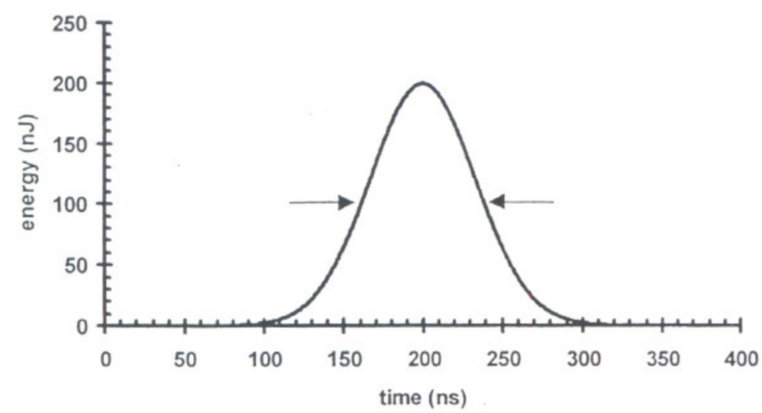

Figure 2. Flying spot "pixel."

2. BIPARTITE COMPARATOR DIAGNOSTIC

2.1 Bipartite comparator

A two-part diagnostic is developed to evaluate the performance of LMDs. We project a flying-spot display image onto one-half of a bipartite Lambertian reflectance white sample and a conventional display image onto the other half (see Figs. 3 and 4). One display is adjusted (visually) to the same perceived brightness and color as the other. Then both samples are measured with a luminance meter, the reflection samples are moved, and the beams are measured with an illuminance meter. If both samples appear to be the same brightness but their luminances or illuminances measure differently, this indicates that the LMD cannot correctly measure the flying-spot display. Placing a neutral density filter (NDF) of known transmittance in front of the display should reduce the measured luminance or illuminance by a predicted amount. If not, then the LMD is being saturated by the high-energy pulse of the flying spot. If it does reduce it by the predicted amount, and the luminances of each sample measure differently, then the LMD error may be due to its inability to properly integrate the narrow pulses.

The five-sided box, manufactured with black plastic material, rests upon a 25 cm × 15 cm black-anodized breadboard with tapped holes. Three 50 mm diameter holes are cut in the plastic at the positions shown in Figs. 1 and 2; two are entrance ports into which the projectors are imaged, and one is for viewing. White reflective material or mirrors are mounted onto rods and secured into the tapped holes such that a bipartite image can be discerned at the viewing port (see Fig. 4).

The flying-spot display is projected into the comparator box and onto the facing white sample. The test pattern produced by the reference display should be a uniform flat field, and able to match the color of the test projector image. The reference display should be projected through the opposite port onto the other white sample, displaying the same flat field pattern. A signal generator or a computer can drive this latter display, and its color and brightness adjusted to match the flying spot image. This matching may differ because of viewer preferences. If a reference projector is not available, then a mirror can replace a white sample and a conventional emissive display can be used for reference.

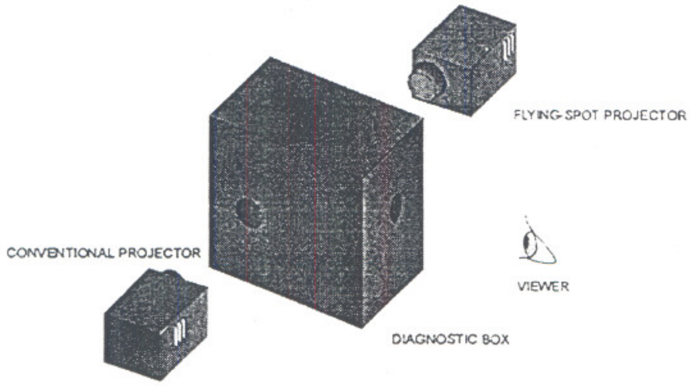

Figure 3. Comparator box.

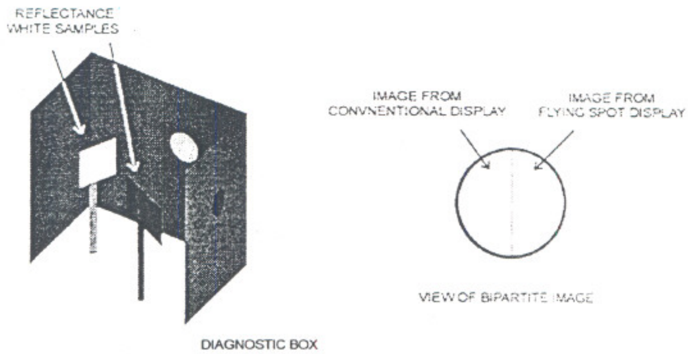

Figure 4. Bipartite image.

Once the brightness and color match is achieved, each half of the bipartite image is measured with the LMD in question. A luminance meter is aimed through the viewing port to measure the white samples directly. An illuminance meter is lowered down through a slot in the top of the comparator box and positioned in place of the white sample to measure the luminous flux per unit area. The deviation between the measurements of both halves indicates the degree of confidence in the performance of the LMD in measuring the light output of the particular flying-spot display. For illuminance meters, the distances to the projectors can be critical particularly if the projectors are close (within a meter or so) to the diagnostic box.

If the measurements from the two different displays differ significantly, it is instructive to perform the NDF test. To perform this test, the luminance of a stable light source is measured. Then a NDF is placed between the source and the LMD, and the luminance is measured again. The ratio of the measurements without and with the NDF provides a short-term, relative calibration of the filter's transmission. This test is performed with the light source set a various light-output levels to verify that the instrument's response is linear. Next, the flying spot display is measured, both with and without the NDF in place (see Fig. 5). The transmission should be approximately the same as measured with the tungsten source. (Note: it is probably best to use NDFs such as the metal evaporated type to avoid wavelength dependence as much as possible.) A significant deviation indicates that the display is saturating the LMD.

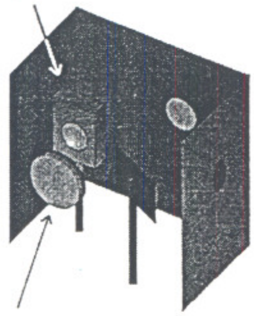

Figure 5. Saturation test using a neutral density filter.

We make no attempt to determine how much deviation is acceptable, as this can be a function of the uncertainty of the instrument and of the particular application. If you are concerned with 10%, and the display measurements differ by 5%, you might determine that any measured difference is negligible for your application. That must be your careful decision. However, even if your results match to within 1%, we still recommend performing the NDF test.

2.2 Description of other equipment[§]

For this experiment, we use two projection displays. The flying-spot display is a developmental model that "writes" directly onto the screen. This system, mounted onto an optical bench, uses a microlaser [4] modulated by an acousto-optic modulator, and scanned by a rotating polygon mirror in the horizontal direction and by a galvanometric scanner in the vertical direction. The 532 nm, 2.5 W beam produces a spot that traveled across the entire screen at 60 Hz. The projector is operated at National Television Standards Committee (NTSC) resolution.

Because the flying-spot display has only the green laser in operation, we use a LCD-modulated display with a laser source as the control [1]. This projector uses a 1280 by 1024 reflective-LCD panel to modulate two microlasers (at wavelengths of 532 nm and 457 nm) and a red diode laser (with a wavelength of 652 nm). The laser operates in continuous mode with the beam spread to fill the entire LCD panel, and the LCDs modulated the light to provide a pixel pulse greater than 10 ms. The unit operates at a refresh rate of 60 Hz. We use the unit with only the green laser switched on to match the chromaticity of the flying-spot display.

We measure the displays with two simple, hand-held LMDs: a luminance meter and an illuminance meter. The luminance meter uses a photodiode and lens system with a 1° measurement aperture. The illuminance meter uses a cosine receptor head.

3. RESULTS

The luminance meter passes the integration test, with an average measured luminance deviation of 1.3% between the two displays when the perceived brightness between the two id matched (see Table 1). The measurement uncertainties[**] are approximately 10% for the luminance measurements and 15% for the illuminance measurements. These results are based on an average of tests, with five members of the research group serving as subjects and at least three measurements per test. To be thorough, we also use the NDF test (Table 2) with a NDF of a nominal optical density of 0.2. The NDF transmission is measured to be 70% using a tungsten integrating sphere source, indicating that a saturation condition was not present.

[§] Any reference to a particular manufacturer is identified in this paper to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does imply that the equipment identified is necessarily the best available for the purpose.

[**] Throughout this paper, all uncertainty values are given as an expanded uncertainty with coverage factor k=2.

Table 1. Test for LMD's Ability to Measure Flying-Spot Displays

	luminance meter			illuminance meter		
	flying spot cd/m^2	LCD cd/m^2	deviation	flying spot *lux*	LCD *lux*	deviation
average	107	105	1%	640	656	9%
std. dev.	5%	2%	5%	7%	1%	7%
range	17.9	8.2		116	24	
max. dev.			8%			23%

Table 2. Test for Possible Saturation Limitations of LMDs

	luminance meter		illuminance meter	
	flying spot cd/m^2	LCD cd/m^2	flying spot *lux*	LCD *lux*
no NDF—average	159	155	87	113
with NDF—average	111	109	56	79
measured transmission of NDF	70%	70%	65%	70%

The same can be said for the illuminance meter, but some alignment challenges create difficulties in reducing the associated measurement error. Measuring illuminance of a light source is dependent on the distance of the detector to the source, proportional to the inverse of the distance squared. Therefore at close ranges, small displacements of the illuminance meter can introduce large errors. The angular sensitivity proves a significant factor in this experiment. The laser display, as described above, is an early prototype still mounted onto an optical table. Because of the room configuration, the comparator box can be placed no more than 2 m away. Thus the measurements are very sensitive to orientation resulting from the uncertainty of the meter displacement and angle. This becomes more noticeable if the light is collimated. The meter can also be affected by any non-uniformity in the image. Related to the configuration limitation is the resulting fact that we measured a circular field of 855 pixels (± 50 pixels). This results in a flash of light that has an equivalent width of roughly 32 μs and a peak illuminance of 3.3×10^5 lx, providing an average illuminance of 640 lx.

4. ANALYSIS

4.1 Alignment errors

Alignment errors can be seen by the data in Table 3, which shows the results of a reproducibility determination. Using both projectors, we display the same flat-field image. Using different operators, we move the LMD into position, measure, and move out of position. This gives us an indication of the reproducibility of the measurement (as opposed to the repeatability). The larger standard deviation for measuring the flying-spot display indicates the difficulty in maintaining a reproducible positioning of the illuminance meter. We observe similar variation by slightly turning the meter a few degrees off normal in several directions.

Table 3. Reproducibility of Measurements

	luminance meter		illuminance meter	
	flying spot cd/m^2	LCD cd/m^2	flying spot *lux*	LCD *lux*
reproducibility (std. dev.)	2.4%	2.2%	4.7%	1.6%

4.2 Cross-corruption

One possible source of error is cross-corruption from the two displays. The light entering one port can reflect off the sample and other surfaces, contaminating the measurement of the other sample. A simple test can be made to determine if such an effect is present. Placing two different wide-band color filters (one blue, the other red) over each of the ports, we then project light through each port using common white-light projectors. Then we measure the spectral distribution of the light reflecting off each white sample with a spectroradiometer (see Fig.6) in three conditions: one source on, the other source on, and finally, both sources on. Each spectral distribution shows negligible effects (less than 1%) because of the presence of the other source.

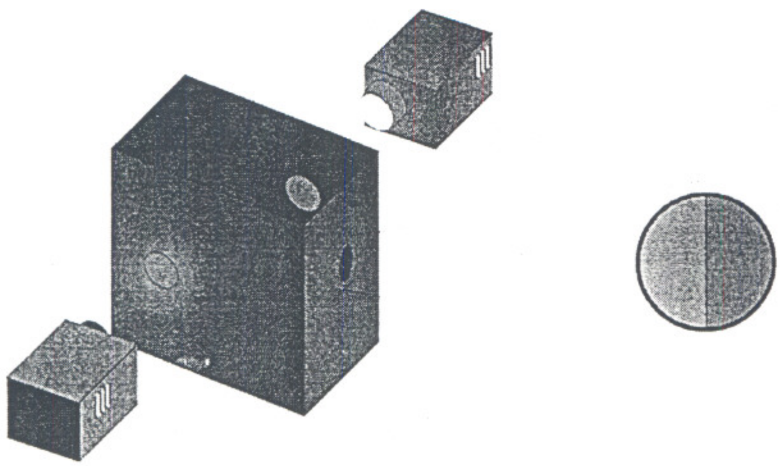

Figure 6. Cross-corruption evaluation.

4.3 Alternative verification

To further test the diagnostic using narrower pulses, we simulate a pulsing pixel display by using a small xenon flashlamp, with a 1.6 μs pulse width (full-width half-maximum, FWHM) at a 60 Hz repetition rate. Although providing a wider pulse than a single pixel of the flying-spot display, it is narrower than the accumulated pulses from measuring the multiple pixels of the laser display. The lamp is projected (with a condenser) onto a white sample in the comparator box, while a cathode-ray tube (CRT) monitor is placed before the other port. A mirror is used in place of a white sample to image the CRT in the bipartite image. We adjust the image through a software-controlled signal via a laptop VGA port.

After matching the two displays, we measure the luminance directly. Because one half of the bipartite image is a mirror, we use an indirect method for determining the illuminance (the luminance may be matched, but because the CRT is not a projection system, the illuminances are not comparable). The reflectance of the white sample is calculated using a tungsten source in place of the xenon lamp by measuring the sample luminance through the viewing port and measuring the illuminance striking the sample. We can then ascertain the amount of light from the xenon lamp illuminating the sample by using the following equation:

$$E = L\frac{\pi}{\rho}, \qquad (1)$$

where E is the calculated average illuminance in lux, L is the measured average luminance of the sample illuminated by the lamp, and ρ is the luminance factor of the white sample (with the source at 45° and the detector at 45°) as determined by the above procedure (in this case, $\rho = 1.02 \pm 0.01$, for the 45 / 45 configuration).

Using the luminance meter, we obtain similar results to the earlier tests, as shown in Table 4. The measured luminances of each half of the bipartite image (after matching) only deviates by an average of 1.3%. This established that the luminance meter is not affected by the width or energy of the xenon pulses. Thus, we can use the measured luminance for calculating the illuminance.

In contrast to the earlier tests with the flying-spot laser, the illuminance of the sample using the xenon lamp measures significantly less that the calculated illuminance based on the measured luminance (see Table 4). The measured illuminance is almost 50% of its calculated value, indicating that the illuminance meter is probably saturating. The uncertainty of these measurements is improved as a result of better control over positioning of the sources and brightness of the images. The expanded uncertainty is approximately 5% for both illuminance and luminance measurements. The reproducibility of the measurements improved to a standard deviation of 0.6% for the luminance measurements and 0.8% for the illuminance measurements.

Table 4. Comparator Diagnostic Using a Flashlamp

	luminance meter			illuminance		
	flashlamp *cd/m^2*	**CRT** *cd/m^2*	**deviation**	**measured flashlamp** *lx*	**calculated based on luminance measurement** *lx*	**deviation**
average	53.41	52.72	1.3%	88.3	167.8	47.4%
std. dev.	0.6%	0.1%	0.5%	0.8%		
range	0.53	0.10		1.5		
max. dev.			1.9%			48.0%

Table 5. Test for Possible Saturation Limitations of LMDs

	illuminance meter	
	flashlamp *lx*	tungsten source *lx*
no NDF—average	84.2	30.2
with 0.2 NDF—average	73.1	19.9
measured transmission of NDF	87%	66%
measured optical density	0.06	0.18

To confirm that this deviation from the predicted illuminance results from the saturation of the LMD by the xenon pulses, we perform an NDF test with a filter with a nominal optical density of 0.2, the results of which are in Table 5. The NDF is certified to be 0.2 using a tungsten source, but the illuminance meter incorrectly indicates the NDF density. This indicates the illuminance meter is being saturated. We further examine the saturation effect by lowering the illuminance until no saturation is seen. We accomplish this by using a series of NDFs with different optical densities, and changing the separation between the flashlamp and the sample. The xenon-lamp-illuminated white sample is measured by both the luminance meter and the illuminance meter. Based on the luminance data, we then calculate the illuminance, using Equation 1. An agreement between the calculated luminance and the measured luminance would indicate no saturation effects. The results, shown in Fig. 7, demonstrate how the illuminance meter measurements begin to flatten out after about 50 lux, indicating a saturation threshold for the 1.6 μs pulse. (The data in Fig. 7 are collected with the source normal and the illuminance meter at roughly 30 °. The reflectance factor $\rho_{0/30} = 1.05 \pm 0.1$ for this configuration.)

The difference between this test with the xenon lamp and the earlier test with the laser projector results from the differences between the pulse peaks. As mentioned earlier in the paper, the measurement field of the illuminance meter contains a cluster of about 855 pixels. For the xenon lamp, we simulate a single pixel, which provides more instantaneous energy per pixel than does the individual pixels of the laser display. This suggests that there might be a peak power density limit for the illuminance meter. If this quantity is known, then one can determine the effect of the flying-spot pulses on the meter based

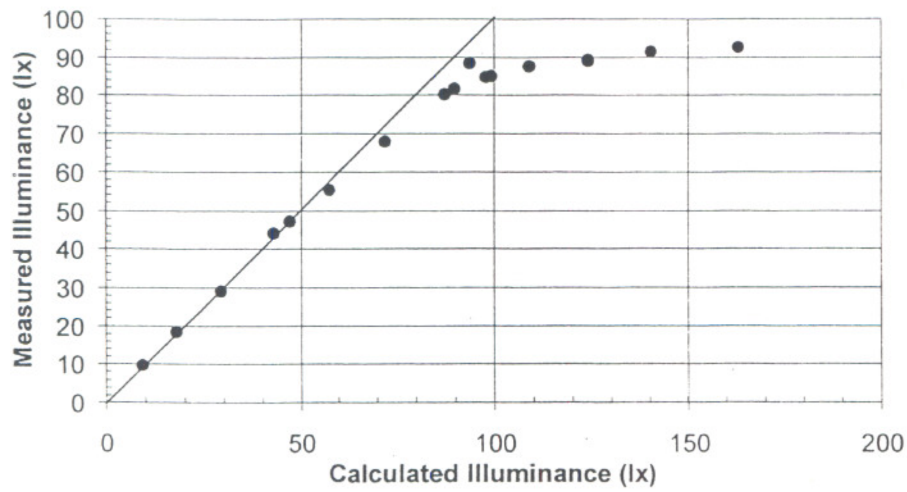

Figure 7. Deviation of illuminance meter from predicted values due to saturation.

on the flux of the projector, the size of the screen, and the number of pixels in the measurement field. These relationships can be described in Equation 2.

$$E_p = \frac{\Phi_{total}}{A} \frac{N}{N_{obs}} \tag{2}$$

where Φ_{total} is the total flux of the projector, A is the image area, N is the number of pixels in the image, and N_{obs} is the number of pixels in the measurement field. As long as $E_p \leq E_{th}$, where E_{th} is the saturation threshold of the LMD, then no saturation effects will be observed.

We estimate that the illuminance meter begins to saturate when the measured illuminance is larger than 50 lux. If we assume that 50 lux is at the threshold, then we can determine the saturation threshold by Equation 3:

$$E_{th} = E_{sat} \frac{\Delta t}{\delta t} \tag{3}$$

where δt is the pulse width f 1.6 μs and $1/\Delta t$ is the repetition rate of 60 Hz, giving us a saturation threshold of 522 klx. During the earlier tests, the laser display projects a flux of about 250 lumens onto an image area of approximately 403 m^2. The illuminance meter measures a field of 855 pixels in the 300 pixel/line, 500 line image. Using Equation 2, we arrive at a peak illuminance of 138 klx, well under the saturation threshold and thus the meter does not saturate. However, assume that the same display is driven at 500 lumens and projected onto a 3 m × 2 m screen, and the illuminance meter has a measurement field of around 20 pixels. Then the peak illuminance of the projector would be approximately 792 klx, over the saturation threshold, and thus the illuminance meter might be expected to provide erroneous data.

7. CONCLUSION

Simply because a LMD has been calibrated and appears to be functioning correctly doesn't mean it will correctly measure all display technologies. When measuring flying-spot displays with conventional LMDs, we must be aware of possible limitations. We have shown that measuring instrument may be influenced by the optical characteristics of the high-powered flying-spot scanning across the measurement aperture. We observed no discernable integration errors, but did discover a peak power density limit in the illuminance meter that could give inaccurate readings in certain applications. Whether the effects we observed resulted from the saturation of the detector or limitations of the meter electronics, goes beyond the scope

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of this paper. Keep in mind that some of these instruments are not necessarily designed for these conditions. The luminance meter demonstrated no observable influence from either the laser display or the flashlamp. Clearly, since the illuminance meter measures reflected light and the light is diffused from the white sample in the entire hemisphere, the luminance meter deals with much less energy that does the illuminance meter. As an alternative to the illuminance measureent, one can place a calibrated white sample in the image plane and measure the luminance (as we have shown). However, correct luminance meter performance must be verified

No integration error due to the narrow pulse widths was discovered. It would be of interest to see the effect from a single narrow pulse. The xenon flashlamp is limited in its minimum pulse width. To reduce the pulse width even further, we have considered devising a "Pockels-cell pulse plucker" [5]. Figure 8 shows a block diagram of the set-up. A pulse source flashes a xenon lamp, creating a 1.6 μs pulse. The pulse source, slightly delayed, also engages a controller that switches the electro-optic Pockels cell, allowing the light pulse to pass through. The cell would, however, be switching on for a duration of 40-50 ns, essentially plucking the narrower pulse from the wider one produced by the flashlamp. The most challenging aspect of this configuring had not yet been realized due to the difficulty and expense in developing a repeatable fast-switching high-voltage controller to operate the cell.

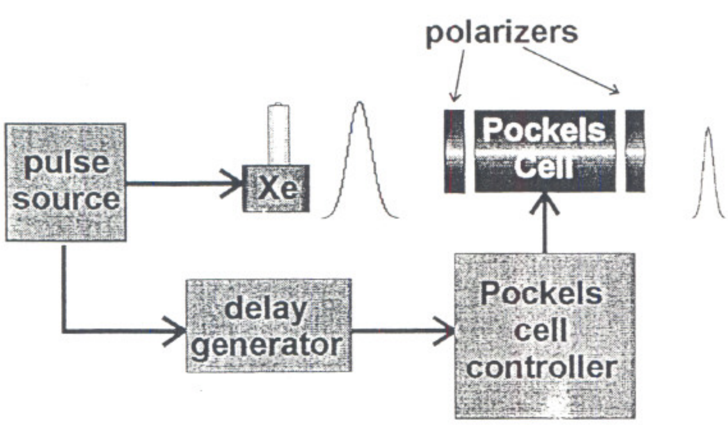

Figure 8. Pockels cell pulse plucker.

Of greater importance to manufacturers and users of flying-spot systems is to remember that, as in all areas of metrology, it is essential to verify that our measurement instrumentation is providing the correct information that we desire. Diagnostic tests prove an invaluable tool to assure accurate performance. The relatively simple technique using a comparator box and NDFs can verify or eliminate the performance concerns of a particular LMD and display, in terms of integration and saturation, for a particular flying-spot display measurement configuration.

ACKNOWLEDGMENTS

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