Optical System Design Challenges for High Volume Reflective LCOS MicroDisplay Inspection

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Abstract

Inspection of reflective Liquid Crystal on Silicon (LCoS) MicroDisplays under high speed and high volume manufacturing conditions produces some unique challenges for the design of the optical measurement system. Most traditional off-the-shelf components such as lenses, polarizers, beam splitters, collimators, etc. can be utilized, but their performance must be carefully characterized, and compromises understood. The requirements of fast measurement speed and wide field of view preclude the use of logical laboratory microscopy, but the high contrast ratios and very small regions of interest almost require it. This paper examines a typical set of requirements and the types of problems encountered, as well as some novel solutions that have proven good practical implementations in the field.

1. Introduction

Liquid Crystal on Silicon (LCoS) μDisplays are a rapidly growing segment of the μDisplay market and a very promising technology to both the projection and the near-to-eye device industry. Similar to other LC technologies, LCOS displays are fairly sophisticated devices with a wide range of performance parameters. Each display must be carefully inspected for a wide set of operational metrics that are usually graded based on the intended application. Since the format and operating modes of LCOS displays are very different from traditional large format transmissive LCDs the traditional optical inspection and measurement designs are not sufficient. The key factors that lead to the need for custom inspection optics are the overall size and pixel densities, their reflective nature with very narrow viewing angle, the absence of a complete image forming polarizing stack, and a very high peak contrast ratio.

This paper will describe in detail the requirements for a "great" optical measurement system, then explain the constraints on such a design, and describe practical implementations that are currently in use for high volume production. Since this is a work in progress, some problems are not proposed to be solved, and those are explained and left open as "challenges" to the industry.

2. Requirements

Manufacturers of LCOS μDisplays are trying, as much as possible, to adopt the same measurements as described in the VESA "Flat Panel Display Measurements Standard", reference 1. A typical list of required production tests includes:

- Brightness (Absolute reflectivity)
- Contrast
- Spatial uniformity: white, black, gray
- Newton fringes
- Area defects
- Pixel defects
- Clustered pixel/line defects
- Crosstalk

These tests must be performed in a suitable amount of time, typically a maximum of 2 minutes and a stated goal of less than 30 seconds per part. Included in that time budget are any image setup, heating, and functional testing requirements. An optical system designed for this purpose must support display pixel matrices up to 1280 by 1024 today, with 1920 by 1200 matrices coming by the end of 2001. LCOS displays must be tested with incident normal polarized light at the desired color and intensity, requiring an optical system with very uniform performance over the entire visible light range.

Other requirements typically imposed on the optical system are:

- Field of view at least 30 mm by 30 mm to support a variety of physical display formats.
- Integrated viewing cone defined by an F-number of 2.5 or smaller and a working distance of 25mm or longer
- Enough over-sampling in the detector to adequately evaluate the performance of every single display pixel, typically 9:1 or 16:1 minimum two-dimensional over-sampling.
- Optical contrast/extinction ratio of at least 1000:1.
- Calibrated spatial uniformity in both black and white better than 95% over the entire useable area.

- Large dynamic range and spectrally uniform detector.

3. Ideal Design

An ideal design begins with a fairly straightforward approach. Combine an appropriate detector with a carefully constructed microscope optical system, a beam splitter, some polarizers, incident illumination, color filters and a collimator. A basic construction example is shown in figure 1.

The optical system can be designed to closely simulate an intended application, for example projection or near-to-eye (NTE). By managing the focal length and numeric aperture of the detector objective lens, the effective aperture and depth of focus of the system can be constrained to be application specific if needed. The result will be a measurement which most nearly predicts the performance capability of the device in it's final integration.

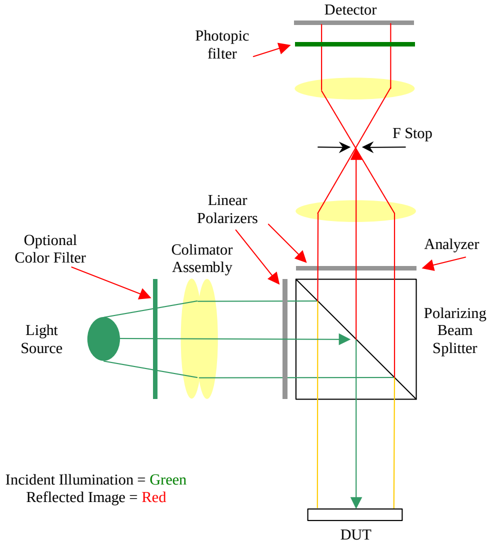

Figure 1 – Illustration of Example Design

We can now explore the basic components of this design.

4. Light Sources

Stable, well characterized, incident light is projected through an appropriate collimating lens. For monochrome displays appropriate light sources are generally broadband tungsten halogen style lamps with feedback circuitry for temporally stable output and color filters closely matching the spectrum that will be used in the target application. Tungsten halogen lamps are fairly spectrally uniform and highly reliable white light sources except for their high infra-red output. This infra-red energy should be filtered as close to the source as possible to mitigate potential problems with the display under test and/or the detector used. Matching color filters is fairly easy and very narrow passbands can be achieved with still plenty of light available for measurement. However, tungsten light sources are very slow and unsuitable for pulsed applications.

For color field sequential style displays testing can be conducted either by illuminating all three fields with the same light, or by switching to a source that can be pulsed quickly such as LEDs or Xenon flashlamps. LEDs generally produce low light levels and very specific spectra that are hard to tailor to custom needs. Xenon flashlamps produce plenty of light output, but have a somewhat non-uniform white spectrum, and produce lots of dangerous UV emissions, which must be carefully filtered for operator safety. Matching color filters and creating uniform narrow spectrums of colored light can be challenging from Xenon sources.

The physical delivery of the light is easily achieved using an integrating sphere for a large uniform field, or a fiber optic simulating a point source. Matching an appropriate collimator/condensor lens is required to uniformly illuminate the display surface. A simple lens structure such as a singlet planar-convex of appropriate EFL is typically used. However, these lenses do not collimate well over the whole visible spectrum resulting in polarization and optical alignment problems. They may also produce differences in incident uniformity as a function of wavelength making calibration difficult. Many off-the-shelf doublet designs are available that overcome these concerns.

If a point source such as a fiber optic is employed, additional diffusion may be needed to avoid rendering a faint image of the lightsource on the display. A highly diffused uniform field ahead of the collimator is the best approach to avoid this problem but it further challenges the design of the collimator. More sophisticated designs use a complete optical system incorporating a numeric aperture and exit pupil for conditioning the incoming light.

5. Making Contrast

LCoS reflective displays usually require light that is incident to the display at a normal angle to the top of the LC structure. Unlike direct view type reflective displays, LCOS devices have a very narrow viewing cone and no surface polarizer, requiring the incident light angle to be very precise and the incident light linearly polarized for good contrast performance. The most convenient way to achieve this is by putting a polarizer in the collimated light stream and then using a beam splitter to divert the incident light 90 degrees onto the display. The reflected image can then be viewed directly through the beam splitter. Another linear polarizer is employed on the image exit side of the beam splitter to analyze the reflected light. Generally, the incident polarizer and the analyzer will be set to 90 degrees out of phase, or crossed, such that the twisted reflected image from a normally white display will produce the most efficient transmission through the system, i.e. white, and an un-twisted image will produce the least efficient transmission, i.e. black. The ratio of the highest amount of light transmitted in the twisted state to the lowest amount transmitted in the untwisted state becomes the system contrast ratio. Of course, this assumes a normally white implementation. A normally black implementation is also achievable. System contrast is affected by many details in the design and a high system contrast is essential to achieving a good measurement system. Typical monochrome LCOS devices can have an optimum optical contrast better than 500:1. The measurement system contrast must be much higher than that over the entire field of view, preferably 2:1 better than the device being tested, hence 1000:1.

Proper incident light polarization is a very important component to the achievable system contrast and the choice of polarizer must be made in tandem with the rest of the system design. A typical PVA style sheet linear polarizer can do a good job with low insertion loss. However, they tend to have poor efficiency in blue and are highly sensitive to the angle of the incoming light. Improperly collimated light will not be correctly polarized, especially around the edges, degrading system contrast substantially.

The same issues apply to the analyzer, whose effective working angle is controlled by the numeric aperture of the objective lens. Using a small f-stop number (larger aperture) will reveal more analysis distortions reducing effective contrast as well.

Another major consideration is the beam splitter. A common broadband 50-50 type can be employed. However, most commercially available types have a number of issues. First, they are affected by the polarization angle of the light and do not split S and P oriented light uniformly. This makes calibrating the system for a spatially uniform and linear dynamic range difficult. Second, by splitting the returning light between the input and exit path, a series of back scatter reflections at various polarization angles can develop polluting the input and return light paths. Third, just the process of splitting the light non-selectively can reduce ideal system sensitivity substantially. Systems with contrast ratios of many thousands to one can be built with these types of splitters but they generally incorporate very small viewing areas and extremely high quality polarizers. More often system contrasts of less than 250:1 are realized without heroic efforts in other areas of the design.

For these reasons listed above and others, designers are choosing to use polarizing beam splitters. The coatings on the interface of these devices will select light at one polarization angle for diversion while passing through light at the other orthogonal angle. For example, S polarized light will always be turned, while P oriented light will always be passed through. On the input side, this characteristic enhances the purity of the incident light onto the device and on the return side the coating enhances the selection process desired by the analyzer. The backscatter issue mentioned previously becomes insignificant and the light efficiency goes up dramatically over non-PBS systems. System contrast ratios better than 3000:1 for narrow/small viewing regions and 1000:1 over large viewing areas are easily achievable with this approach.

Several deficiencies exist in the current off-the-shelf commercial versions of PBS cubes. First, they tend to be least efficient in the blue regions, between 80% and 95%. This is unfortunately the same problem found in PVA polarizers. Using narrow spectrum blue filters can create a system with much lower blue contrast. Manufacturers can adjust the recipe of these coatings on-demand to emphasize certain wavelengths in an attempt to tune the system. Second, just like many polarizers, their performance seems to also be very dependant on the angle of the incoming light amplifying errors in collimation and degrading spatial uniformity as well as creating a spatially non-uniform contrast. Common problems observed are bright “star” or “cloverleaf” patterns visible in the dark state images due to poor spatial uniformity of extinction. Third, PBS coatings tend to exhibit some chromatic aberration properties (dichroism?), causing sometimes significant spatially dependant color distortions with poorly aligned optics or poorly controlled coatings. Despite all these issues, the PBS approach is still the most common method for achieving high system contrast, especially when building an off-the-shelf design.

Using a commercial 2” PBS cube, a 2” diameter 40mm EFL collimator, a high efficiency polarizer, and a high efficiency analyzer, a red-green system contrast of 1000:1 is easily achievable over a 1 inch diameter central area. In the blue region, an equivalent contrast of 500:1 or better can be achieved.

6. Detectors

Once the optical system is designed, a suitable detector is used to complete the measurement system. For measurements where reflectance and contrast of small areas are desired, a simple fiber optic and Photo-

Multiplier Tube (PMT) can be employed. In this case an aperture is placed in the optical system at the correct focal point to define the precise area of measurement. PMT devices are well understood and can produce very large dynamic ranges well suited to this purpose. If spatial information is required, the only option with a PMT design is to move the display relative to the optical system and repeat the measurement again.

For more sophisticated (and faster) measurements a high quality CCD array can be employed. The number of detector pixels chosen should be based on the magnification of the optical system, the size of the display, and the amount of over or under sampling desired. In this case, the term “sampling” refers to the ratio of detector pixels to target display pixels. For example, to measure a 1K by 1K display without motion and reliably detect all types of single pixel defects with a single image, a detector array of 4K by 4K would be desired (16:1 two-dimension over-sampling). For a fast low resolution system capable of reliably detecting area defects a 1K or even 512 pixel array detector could be employed.

Another consideration is the bit depth, or dynamic range of the detector. To measure both light and dark characteristics simultaneously on a display with contrast of 500:1, you need mathematically 9 bits, but practically about 11 bits to compensate for noise, linearity, spatial non-uniformity, dark image, etc. Hence generally a 10-12 bit detector will be used. Needless to say, these detectors are relatively expensive. However, in this case the target activity is a manufacturing environment with the overwhelming goals usually being high repeatability and low tact time.

Simply combining high detector resolution with high dynamic range will not ensure a fast measurement system because of the time required to transfer multiple frames of raw data into a computer system. With our 4K by 4K 12 bit camera example, you will need to transfer 32Mbytes of data for each raw image acquired.

Intermediate compromises include using moderate resolution detectors combined with some X-Y and theta motion to characterize the devices in multiple tiles. Image processing and recognition techniques can be employed to “stitch” these tiles back into a super high resolution master image of the device. Some designers incorporate electro-mechanical means to adjust the focus and magnification of the optical system during testing to maximize the utility of a single detector. Others incorporate multiple detectors and move the devices between them to reduce complexity and maximize system utility. Still others use multiple lower density detectors through a complex optical system to minimize device movement. Parallel processing of the detector data is more easily implemented now because they have different physical interfaces. Usually the optical system proves to be the most challenging aspect of this design.

7. Calibration & References

A significant part of the system performance is determined by the methods employed for calibration. Many of the optical shortcomings described above can be overcome with compensation in the computational image processing software employed. Generally, any effect that is an error source in one domain (or sometimes two) at a time can be easily measured and corrected. For example, non-uniformity of optical transmission/reflectance in the spatial and frequency domains can be corrected for with calibration. If the non-uniformity is simultaneous in three domains: spatial, wavelength, and polarization, the problem gets unwieldy. Similarly, errors in optical magnification (spatial linearity) are manageable even if they are also dependant on wavelength. But, if they further depend on the polarization angle, the problem becomes exceedingly complex. Therefore, as in other classical engineering problems, the designer is forced to accept compromises between what can be solved with calibration, and what must be solved in the fundamental optical hardware.

Typical references required for proper calibration include: White state uniform reflector, dark state uniform reflector, spatial accuracy reference, and polarization alignment (angle) guide. Determining the correct reference for white and dark state reflectance requires making some assumptions about the physical properties of the display being tested. Since most LCOS devices have a very narrow viewing cone, a precision flat first-surface surface mirror can be presumed to be a similar appropriate reference. A mirror chosen for this purpose should be one that has very well defined spectral and spatial properties including a high degree of flatness, neutral color, and no optical coatings that will affect the polarization properties of the incident light. Precision laboratory grade protected aluminum mirrors are usually used. New or unknown samples must be evaluated for their treatment of linearly polarized light. The evaluation must include measuring the amount of linearly polarized light reflected at all polarization angles, including the incident angle. A specification of less than .5% polarization distortion is both necessary and achievable.

In addition to the mirror, to accomplish selection between white and dark, a device such as a broadband quarter wave retardation plate (QWP) is required. A QWP is used to simulate the rotation of the polarized light by the LCOS display. However, a QWP does not truly model a LCOS device and as such should be treated as a reference, not a full simulation. The QWP does not have significant optical depth and does not act on light at different incident angles the same way as the display. Therefore, physical errors in the angle of incident light or other mechanical alignment problems with the optical system can not be compensated by this reference. Nonetheless, a properly characterized mirror and QWP pair is an easy and straightforward way to establish white and dark state references. Sometimes an actual LCOS device in the unpowered (normally white) state is used as the white reference and calibrated against a known standard such as a mirror with un-crossed polarizers. In a normally white system, a mirror with no QWP and properly adjusted polarizers should return no more than about .1% of the incident light to the detector, making it a 1000:1 or better contrast reference. In reality, most good systems can measure 3000:1 or higher based on the mirror dark state reference. When the QWP is added to the optical path above the mirror and properly adjusted, the combined set should produce around 60%-70% white reflectance with very good uniformity. For manufacturing quality systems, a simple transmission and reflectance calibration value for the pair is sufficient. For laboratory grade optics, a 2D spatial profile may be indicated. If the system allows the rotation of the input polarizer, and/or the analyzer, regardless of whether a PBS is employed, it is advisable to perform white and dark state calibrations in every intended setting of these polarizers. Significant differences in transmission can be frequently seen at different polarization angles.

Good spatial and polarization references are readily available and are used mainly for system setup. The reference polarizer is used to establish the correct rotation of the input polarizer and analyzer, unless a PBS is employed. If a PBS is used, it becomes the reference polarizer and all others should be aligned to it. The spatial reference should be accurate to better than 5 micons with repeating white and black linear features for adjusting the system magnification and characterizing the spatial magnification errors between the display under test and the detector array. In some cases, the display itself can be used as the spatial reference because the methods used to image the pixel array on the substrate are probably better than those used to make the spatial reference targets.

8. Test Implementation

The details of how the required tests are implemented form the most substantial part of the trade-off process between ideal lab conditions, and high volume manufacturing implementations. An ideal laboratory system would use a very small 1-10 pixel circular aperture of view and move the display under scrutiny as many times as needed to gather all the required information. The advantage is that almost all of the imperfections in the optical system are repeated exactly over the entire device, making them insignificant to the test results. For example, measurements of white and black spatial uniformity at 9 locations would be made by moving the display 9 times and flashing a white and black image at each location. Any errors in uniformity or absolute accuracy in the optics would be repeated at each location so the uniformity result would be as accurate as the temporal repeatability of the system. However, this test alone could take many minutes to perform

An ideal manufacturing system would make the same measurement by rendering the entire display through the optical system and onto an appropriately sized detector. Using the previous example, the uniformity test would be conducted by acquiring only one or two images in one fixed position, and analyzing the results on the corresponding pixels of the detector. This test could take less than 1 second. In this case, all of the imperfections of the optical system are now accumulated along with the actual display in the measurement. A much larger range of uncertainty exists with the computed result. Looking just at spatial uniformity, if the optical system were 95% uniform over a given square area, and the display under test were 100% uniform, the result would still be 95%. However, if the display were 90% uniform, the measured result could be between 94.7% and 85.5%, depending on the profile of the display non-uniformity relative to the optical system error[1]. Hence, a 95% uniform optical system produces a roughly +/- 5% multiplicative uncertainty on the final measurement. If the goal would be to never ship a display that could have less than 90% uniformity, the failing criteria would have to be at 94.7%. However, if the goal were to never fail a device that could be over 90%, then the pass/fail criteria would be set at 85.5%. The uncertainty becomes the price paid for speed over accuracy and a yield management exercise for manufacturing and product management to grapple with. Achieving a compensated 95% spatially uniform optical system over the entire display measurement area including collimation angle, spectral distortions, polarization errors, contamination, and reflections/scattering effects is a reasonable expectation. Frequently the uncertainty becomes a confounding error source in correlation exercises. In a

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[1] Using the formula $Uniformity[\%] = \frac{Min}{Max}*100$

situation where two or more measurement systems on parallel production lines are required to correlate on a family of sample devices, our uniformity example above illustrates how they could produce very different results on the same devices while both systems are essentially identical. A variance in the profile of the system non-uniformity from machine to machine is the cause while independently both systems are identically calibrated. These issues are frequently mitigated by the use of single calibration references for all machines at a given site.

Similar analysis applies to almost all of the tests listed at the beginning of this paper. Generally all of the tests listed except *Pixel Defects* can be performed from a few very fast simple image acquisitions. In the case of the pixel defects test a relatively higher sampling density is required. As discussed above in the topic of detectors, high pixel density detectors would seem to yield the highest speed design until the data transfer and processing aspect is considered. Reducing the sampling density below about 9:1 camera pixels to display pixels, raises dramatically the uncertainty of properly characterizing single pixel defects. For low resolution displays, the high density camera approach seems to be most often selected. For high resolution displays such as 1920 by 1280, step and repeat methods are the only practical solutions at this time.

Test time is mostly driven by the rate at which an image can be acquired and transferred across the channel to the host computer. Consider using 9:1 over-sampling on a 1280 by 1024 device with a 1K by 1K camera. When alignment errors are included, your working area is about 300 by 300 device pixels per image. You need 20 steps, or ‘tiles’, to cover the whole device. Each position may require 3 or 4 images to capture white, gray, and black defects. Assuming 4 required images yields 80 images per device or 160 MB of raw image data to transfer and process in semi-real time. Even with fast off-the-shelf camera interfaces and short frame periods, it will take about 75 mS per image and tact times can be expected to approach 1 minute per part for this example when motion is included. In the near future, falling prices and new solutions for 2K and 4K CCD detectors and higher speed digital interfaces are going provide a nice path for improvement.

9. Final Thoughts

LCOS devices really are a somewhat unfamiliar target for the traditional optical metrology community. Even locating a calibration laboratory that can properly calibrate a mirror-QWP assembly under polarizing illumination can be challenging. Many of the design ideas (as well as a some of the optical components) are coming from the projection community as they create target applications for the devices. Hence, just as LCOS MicroDisplays themselves are a new and evolving technology, so is the methodology for test and characterization. Many of the challenges discussed above do not have definitive solutions, but they can be mitigated with good system design, properly chosen components, and a realistic expectation of testing performance.

The industry will grow quickly and would benefit greatly from standardization of the test definitions and related analysis. The detail implementations of the testing will probably remain part of the recipe that makes each manufacturer unique.

10. References

1) “Flat Panel Display Measurement Standards”, Video Electronics Standards Association