Active matrix organic light emitting diode (AMOLED) performance and life test results

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ABSTRACT

The US Army and eMagin Corporation established a Cooperative Research and Development Agreement (CRADA) to characterize the ongoing improvements in the lifetime of OLED displays. This CRADA also called for the evaluation of OLED performance as the need arises, especially when new products are developed or when a previously untested parameter needs to be understood. In 2006, eMagin Corporation developed long-life OLED-XL devices for use in their AMOLED microdisplays for head-worn applications. Through Research and Development programs from 2007 to 2011 with the US Government, eMagin made additional improvements in OLED life and developed the first SXGA (1280 X 1024 triad pixels) and WUXGA (1920 X 1200) OLED microdisplays. US Army RDECOM CERDEC NVESD conducted life and performance tests on these displays, publishing results at the 2011, 2010, 2009, 2008, and 2007 SPIE Defense, Security and Sensing Symposia[1,2,3,4,5]. Life and performance tests have continued through 2012, and this data will be presented along with a recap of previous data. This should result in a better understanding of the applicability of AMOLEDs in military and commercial head mounted systems by determining where good fits are made and where further development might be desirable.

Keywords: AMOLED, OLED, long-life OLED, lifetime, usable display lifetime, SXGA OLED, WUXGA OLED, display, microdisplay

1. INTRODUCTION

US Army RDECOM CERDEC NVESD and eMagin Corporation have established a CRADA with the goal of evaluating and characterizing new and existing AMOLED microdisplay technology. Under this CRADA, eMagin provides displays, display systems, and display system components to NVESD that eMagin developed under funded or IR&D programs. NVESD evaluates all delivered systems and components for life and performance as applicable. The two organizations then update and modify the Usable Lifetime Model and co-publish the results of the tests on a yearly basis.

The intent of this CRADA is to develop AMOLED microdisplays capable of being fielded in a wide range of US Army applications and to gauge when the display technology is ready for a given application, considering its requirements. The Usable Lifetime Model was established to determine if the performance would be maintained over time at a sufficient level given a certain set of requirements (color, temperature, luminance, video rate, allowed degradation)[6]. The typical test method of driving the display with a full-on (all white) pattern is not an accurate representation of how a display is used, but the characteristics of this test are essential in calculating the predicted usable lifetime.

eMagin developed the OLED-XL™ stack in 2006, reporting that the usable life of the panels may be increased significantly over that of the standard white, color, and green materials. In 2008, 2009, 2010, and 2011, via research contracts managed by RDECOM CERDEC NVESD, eMagin developed further lifetime improvements in their displays, utilizing different materials and modifying different processes for long-life monochrome and color displays. This being an R&D program, not all prototype displays demonstrated improvements in lifetime, but significant lifetime and efficiency improvements were found in most of the experiments.

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The 2011 published results[1] detailed the life test results of two new display products developed under the NVESD managed OLED-III R&D program, the High Brightness Green (HBG) and High Brightness Yellow (HBY). It also contained a thorough discussion on the improvements to the Usable Life Model, including the allowance for more variables and a change in how the overall life is calculated. This paper will discuss the 2011 life tests of the High Brightness Green and White (HBW) displays developed under OLED-III, the performance tests of the High Brightness Green and Full Color SXGA-2 (also developed under OLED-III), and the High Brightness Green WUXGA (includes development from TATRC and NVESD managed efforts).

2. LIFE TESTS ON EXPERIMENTAL DEVICES

2.1 Introduction/General Comments

As in the last reporting, the life testing this year concentrated mainly on the deliverables from the aforementioned research programs managed by US Army RDECOM CERDEC NVESD rather than on commercial microdisplays which utilize now well-established production processes. As an R&D program, not all experimental devices were expected to outperform the production OLED-XL™ displays. The intent was to explore the best options available, and determine through testing which devices would have longer life and higher efficiency and should thus be transitioned into production displays.

The 2011, 2008, and 2007 papers[1,4,5] thoroughly detailed the test setup for measuring the lifetime of the displays. This included the display optimization, calibration, measurement of luminance, and temperature and calibration correction. The displays are driven with a full-on pattern (full screen at drive level 255), to allow for a standard reading of luminance loss over time which, in turn, allows predictions of display lifetime used for video in real applications. The life test stations are shown in Figure 1.

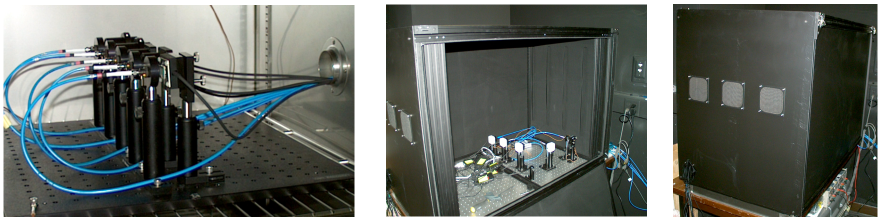


Figure 1. Life Test Station used in evaluating displays at NVESD. The far left picture shows the inside of the thermal chamber. The middle and right pictures show the ambient life station open and closed respectively.

Each test, generally of five displays, was given a number, with the first two tests (Tests 1 & 2) being covered in the 2007 paper. As more tests were run, the results were published in 2008 (through Test 4), 2009 (through Test 7), 2010 (through Test 9), and 2011 (through Test 14). The final results from Test 15 are included here. The details of all tests are shown later in Table 3.

2.2 Test Results

Figures 2-3 show the life test data of High Brightness Green and White (HBG, HBW) displays tested in 2011/2012. Sample to sample variations were minimized by monitoring display temperature and applying a linear temperature correction to each measurement, and by smoothing the data by utilizing the MathCAD™ supersmooth fuction, which is a piecewise symmetric nearest neighbor linear least squares fit procedure[7].

The High Brightness devices were developed in the R&D program with NVESD to allow for higher luminance, longer lifetime, or a mix of both. Some of the component materials of the High Brightness OLED stacks were obtained from Universal Display Corporation. The HBG devices have excellent lifetimes for the luminance at which they are driven and have thus been placed in display products. The HBW devices, however, did not have life curves as good as the OLED-XL™ displays. Under current and future R&D programs, some managed by NVESD, alternative methods of achieving White and Color with long lifetimes at high luminances are being pursued. This includes researching hybrid OLEDs, tandem structures, and direct patterning of emitters.

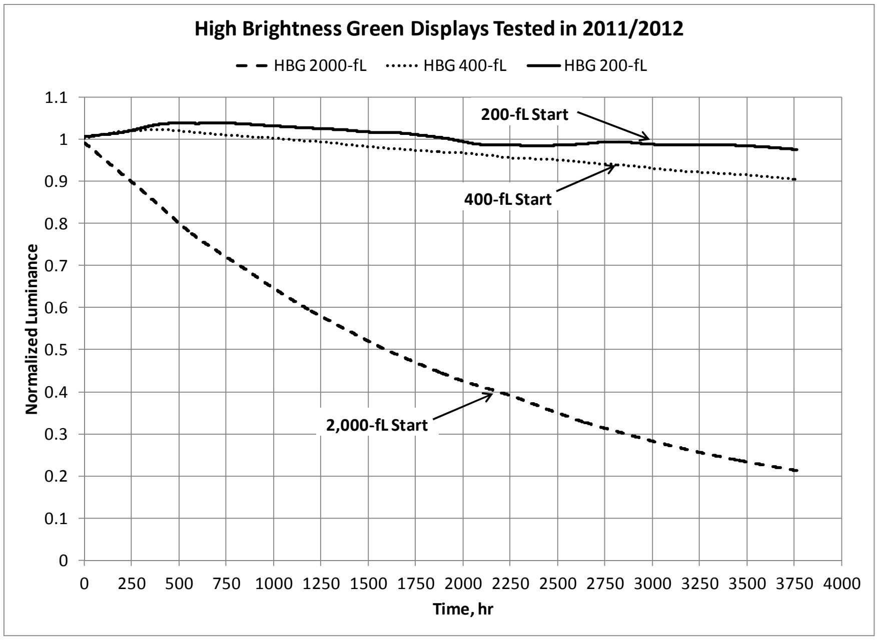


Figure 2. Life test results of HBG Displays at 2,000-fL, 400-fL, and 200-fL with all pixels 100% on

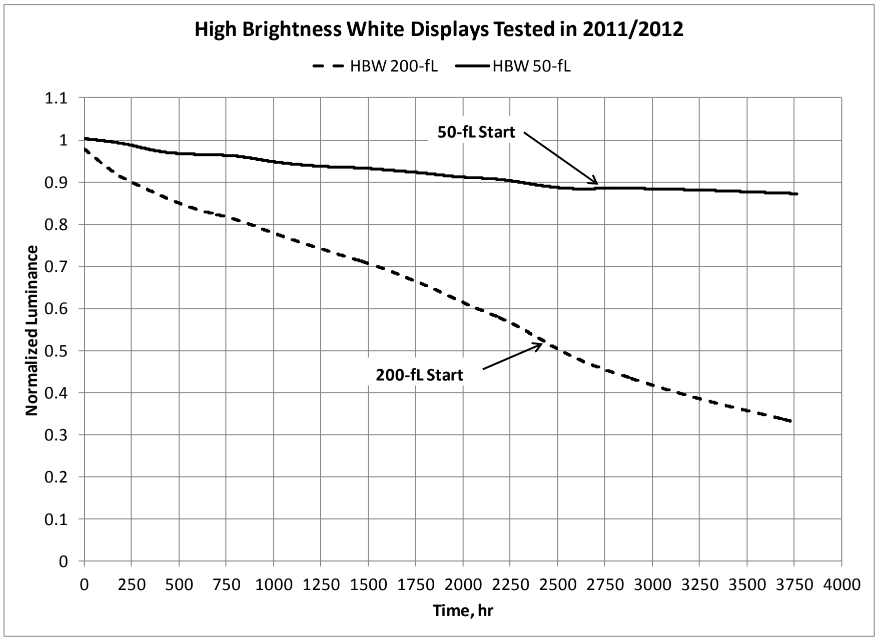


Figure 3. Life test results of HBW Displays at 200-fL and 50-fL with all pixels 100% on

Some performance metrics were tested before and after the life tests. The spectra of the High Brightness Green displays starting at 2,000-fL and 400-fL are shown in Figure 4. Considering that the 2,000-fL display is well beyond the half-life and that the 400-fL display is 10% luminance degraded, the displays have excellent color stability over time. The contrast and gamma were recorded for all 5 displays life tested. 18 evenly spaced gray shades were evaluated with over 5% difference measured between each one. There was no RS-232 control over the 2,000-fL display's design reference kit (DRK) so the registers could not be adjusted to get a good contrast. However, a SVGA HBG display (X0P2C) from the same wafer had a measured contrast of 2,873:1 at 2,145-fL when tested in the lab with a fully functional DRK.

There was no significant degradation in contrast or gamma for any of these displays. Any reduction can be accounted for by the loss in maximum luminance from the life test and sensor noise in reading the minimum luminance levels.

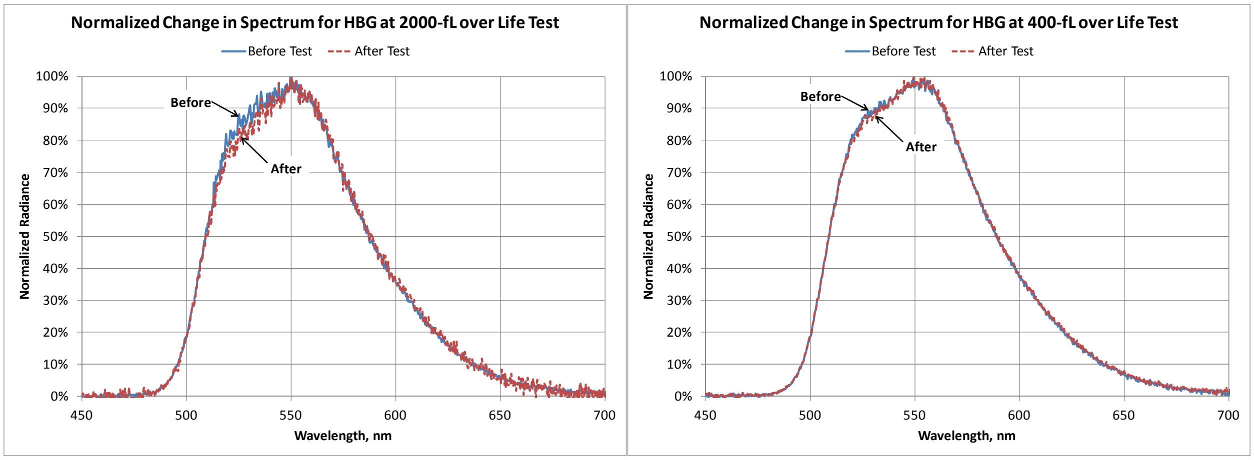


Figure 4. Change in spectra over 3,750-hr life test for High Brightness Green displays. Very little change in color took place, with the display at 2,000-fL going from CIE 1931 (0.371, 0.601) to (0.374, 0.595) and the display at 400-fL going from CIE 1931 (0.374, 0.597) to (0.376, 0.596).

Table 1. Change in contrast over 3,750-hr life test for all 5 displays. All 18 (evenly spaced) evaluated gray shades were visible at the end of the life test.

Changes in Contrast During 3,750-hr Life Test

Display	Starting CR	Ending CR	18/18 Gray Shades
HBG at 2,000-fL*	62	62	Yes
HBG at 400-fL	328	322	Yes
HBG at 200-fL	378	316	Yes
HBW at 200-fL	417	233	Yes
HBW at 50-fL	361	372	Yes

* Could not access display registers due to error in DRK, resulting in reduced contrast (not a display issue)

The summarized results of the life tests conducted last year are in Table 2. Each chart lists the serial number, a thorough description of the test conditions, and the estimated life for the display with all pixels 100% on. Lifetimes of 90% (10% degradation), 75% (25% deg.), and 50% (50% deg.) are based on the point when the curve intersects (or would intersect) that level. Actual measured lifetime results are used when available, otherwise straight-line extrapolations are used to estimate the life at a given level, and those values are highlighted.

Table 2. Summary of lifetimes for displays tested in 2011/2012. The half-life of the HBG display at 200-fL is >3X the half-life of the OLED-XL™ White and Green displays.

Lifetimes (All Pixels Full-On) of High Brightness Displays Tested 2011/2012

Serial #	Test	Hours Tested	Device	Luminance, fL	Temperature	90% Life	75% Life	50% Life
X0P2L	15	3,750	High Brightness Green	2,000	Ambient	250	625	1,600
X0P45	15	3,750	High Brightness Green	400	Ambient	3,750	8,300	16,000
X0P3X	15	3,750	High Brightness Green	200	Ambient	7,500	16,000	30,000
X04N0	15	3,750	High Brightness White	200	Ambient	250	1,200	2,500
X0RPA	15	3,750	High Brightness White	50	Ambient	2,250	9,500	23,000

Table 3. Summary of lifetimes for displays tested from 2006 through 2010

Lifetimes (All Pixels Full-On) of eMagin AMOLEDs Tested Pre-2011

Serial #	Test	Hours Tested	Device	Luminance, fL	Temperature	90% Life	75% Life	50% Life
CD5N5	1	2,050	Full Color Std HRA	50	Ambient	740	1,600	3,000
CCR77	1	2,050	Mono White OLED-XL™	50	Ambient	9,000	21,500	42,000
CCLMX	1	2,050	Full Color Std	50	Ambient	440	1,230	2,500
CCLN6	1	2,050	Full Color Std	20	Ambient	1,000	3,700	8,200
CDL18	2	2,250	Full Color OLED-XL™	50	Ambient	1,500	3,700	7,500
CDL0K	2	2,250	Full Color OLED-XL™	50	Ambient	1,350	3,300	6,800
CDL0N	2	2,250	Full Color OLED-XL™	20	Ambient	4,000	9,800	19,600
CDD37	2	2,250	Mono White Std	200	Ambient	425	1,550	3,500
CKK0	2a	950	Mono White OLED-XL™	200	Ambient	1,700	4,700	9,500
X3A2Y	3	2,950	Mono White OLED-XL™	200	50°C	925	2,200	4,200
CHA21	3	2,950	Mono White Std	200	50°C	575	1,450	2,950
X3A3K	3	2,950	Full Color OLED-XL™	50	50°C	525	1,550	3,300
X3A3W	3	2,950	Full Color OLED-XL™	20	50°C	1,800	4,800	9,700
CJJ0W	4	1,300	Mono White Std	200	Ambient	1,000	3,200	6,700
CFSNM	4	1,300	Mono Yellow Std	200	Ambient	700	2,700	5,700
CK1XW	4	1,300	Mono Green Std	200	Ambient	125	475	1,700
X3PSS	4	1,300	Mono Green OLED-XL™	200	Ambient	1,150	3,600	7,800
X3RHK	4	1,300	Full Color OLED-XL™	75	Ambient	300	1,600	4,700
CK28A	5	1,675	Full Color Prototype A	50	Ambient	1,350	2,500	4,500
CK27N	5	1,675	Full Color Prototype A	50	Ambient	1,350	2,600	4,600
CL5YX	5	1,675	Full Color Prototype B	50	Ambient	265	800	2,100
CL5YP	5	1,675	Full Color Prototype B	50	Ambient	215	700	1,700
X3YC0	5	1,675	Full Color Mod Anode X	50	Ambient	1,000	4,200	9,500
CLLZZ	6	2,850	Green Phosphorescent A	200	Ambient	7,200	18,000	36,000
CLLZ7	6	2,200	Green Phosphorescent C	200	Ambient	1,080	2,150	4,000
3AAJB	6	2,200	Green Phosphorescent B	200	Ambient	1,580	3,300	6,200
CLLZR	6	2,850	Green Phosphorescnet A	50	Ambient	17,000	42,500	85,000
CLLZM	6	2,850	Green Phosphorescent C	50	Ambient	Insufficient data to estimate life		
3AAJA-1	6a	675	Full Color Mod Anode A	50	Ambient	1,200	3,000	6,000
3AAJA-2	6a	675	Full Color Mod Anode A	200	Ambient	130	360	810
3AAJ9-1	7	3,600	Full Color Mod Anode 9	50	Ambient	2,100	5,400	11,000
3AAJ9-2	7	3,600	Full Color Mod Anode 9	50	Ambient	2,600	6,300	12,500
3AAJA-3	7	3,600	Full Color Mod Anode A	50	Ambient	1,500	4,100	8,500
3AAJ9-3	7	2,500	Full Color Mod Anode 9	20	Ambient	6,000	23,000	55,000
3AAJA-4	7	3,600	Full Color Mod Anode A	20	Ambient	7,000	23,000	50,000
X58C5	8	4,600	White ExpA	200	Ambient	1,850	4,800	9,500
X58CC	8	4,600	White ExpA	50	Ambient	20,000	52,000	104,000
3AAJB	8	4,600	Amber ExpC	200	Ambient	2,000	4,000	7,500
CPJJ8	8	4,600	White ExpB	200	Ambient	4,400	11,000	22,000
CPJJA	8	4,600	White ExpB	50	Ambient	Insufficient data to estimate life		
R3BN0	9	2,800	Color OLED XL™ SXGA	50	Ambient	5,200	11,500	23,000
R39JL	9	2,800	Color OLED XL™ SXGA	50	Ambient	4,700	10,700	21,500
R3BNJ	9	2,800	Color OLED XL™ SXGA	50	Ambient	5,200	11,500	23,000
X6H4X	12	1950	High Brigh White V1	50	Ambient	4,000	10,000	21,000
X6H5N	12	1950	High Bright White V1	200	Ambient	350	1,300	3,800
X6H6T	12	1950	High Bright White V2	50	Ambient	3,000	9,000	19,000
X6H7D	12	1950	High Bright White V2	200	Ambient	500	1,500	3,900
X5K81	12	1950	High Bright Green V1	200	Ambient	900	13,000	32,000
X5TAT	13	3800	White OLED-XL™ SXGA	200	50°C	3,200	5,500	10,500
X5TCV	13	3800	White OLED-XL™ SXGA	400	50°C	500	1,800	3,500
X6F75	13	3800	White OLED-XL™	50	50°C	5,200	15,000	32,000
X64Z3	14	4000	High Bright Green V2	50	Ambient	Insufficient data to estimate life		
X64ZD	14	4000	High Bright Green V2	200	Ambient	22,000	52,000	102,000
X6543	14	4000	High Bright Yellow V1	50	Ambient	Insufficient data to estimate life		
X6557	14	4000	High Bright Yellow V1	200	Ambient	5,400	17,000	36,000
X6543	14	4000	High Bright Yellow V1	400	Ambient	1,000	5,200	14,500

Table 3 shows the results presented in all previous SPIE DSS papers, and a thorough discussion of those tests can be found in those documents[2,3,4,5]. Each test was given a number with Test 1 being the first, and Test 14 being the last one discussed in previous papers. Tests 10 & 11 were stopped less than 400 hours into each test with no meaningful data accumulated. The HBG display at 200-fL has over 3X the half-life of OLED-XL™ White and Green displays.

In 2005, eMagin and NVESD developed an application model that allows users to derive realistic estimates of usable display lifetime for a wide range of conditions[6]. The model has since been modified several times with the intent to more accurately represent the life of the eMagin AMOLEDs in military systems, with significant improvements being made in 2011[1]. These previous publications thoroughly detailed the usable lifetime model, and the reader may reference these documents if more detail is required.

3. DISPLAY PERFORMANCE TESTING

3.1 Introduction

Three different microdisplays were evaluated for this publication: a High Brightness Green SXGA-2 (1280X1024), a Full Color SXGA-2, and a High Brightness Green WUXGA (1920X1200). The SXGA-2, developed under the OLED-III R&D effort, features an on-board LVDS interface and 9.6-µm pixels as advances over the eMagin's commercially available SXGA. The development of this display is discussed in detail by Dr. Ihor Wacyk et al. in "Ultra-high resolution and high-brightness AMOLED" (Paper 8383B-25), which is being published concurrently with this paper. The SXGA-2 display and GUI is still at the "engineering prototype" level and is not yet expected to perform as a commercial product.

The WUXGA was developed under an R&D program for US Army TATRC and later improved by an additional commercialization program overseen by the US Army. The HBG materials, developed under OLED-III, were integrated into the WUXGA as a prototype for high brightness aviation applications.

All photometric measurements were made with a calibrated PhotoResearch PR-880 photometer with an MS-55 lens. The PR-880 was also used to record the color coordinates of the Full Color SXGA-2 and the unit's PMT was used to evaluate the response time of both SXGA-2 displays. Radiometric and spectral measurements were made with a calibrated PhotoResearch PR-715 spectrometer.

A Team Systems ASTRO VG-849 pattern generator was used to drive the SXGA-2 during the response time tests and the Full Color Viewing Angle test. At all other times, the displays were driven by the digital output of a desktop PC in the display's native format (1280X1024 or 1920X1200). The Gray Scale and Checkerboard patterns used by the computer are shown in Figure 5.

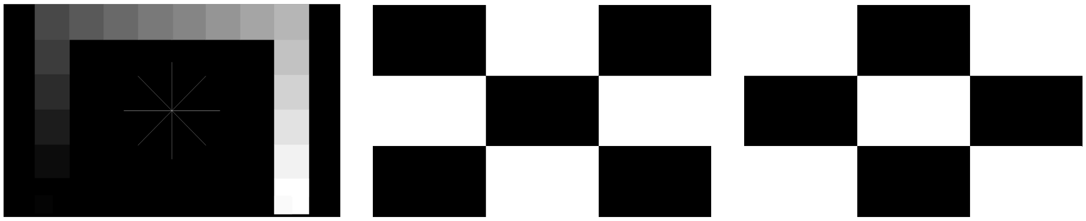


Figure 5. Patterns on PC for testing microdisplays. The Grayscale Pattern includes 18 evenly spaced shades of gray (in steps of 15). In the bottom squares (black and white), smaller squares of 7/255 and 248/255 (respectively) are added. Two checkerboard patterns, one with black in the middle and one with white in the middle, were used to measure contrast.

3.2 SXGA-2 High Brightness Green

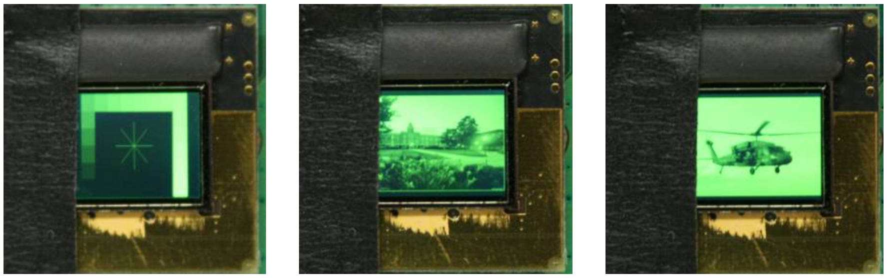


Figure 6. The High Brightness Green SXGA-2 display showing the Grayscale pattern and two pictures. Black masking tape was placed over the bright calibration bar on the left side of the screen for all tests.

The HBG SXGA-2, shown in Figure 6, was optimized at 0.1-fL, 1-fL, 50-fL, 400-fL, 1,000-fL, and 5,000-fL. Two brightness settings, IDRF and DIMCTL, the internal ramp maximum value, VDACMAX, and the rate of pulse width modulation (PWM), ROWRSTL, were adjusted to get the required luminance with minimum artifacts (such as flicker). The gamma was set by adjusting the system gamma value until the beginning of the transfer curve resembled a curve with a gamma of 1.7 (chosen arbitrarily). All tests for each light level were run at the optimized settings. The transfer curve or gamma test results can be seen in Figure 7.

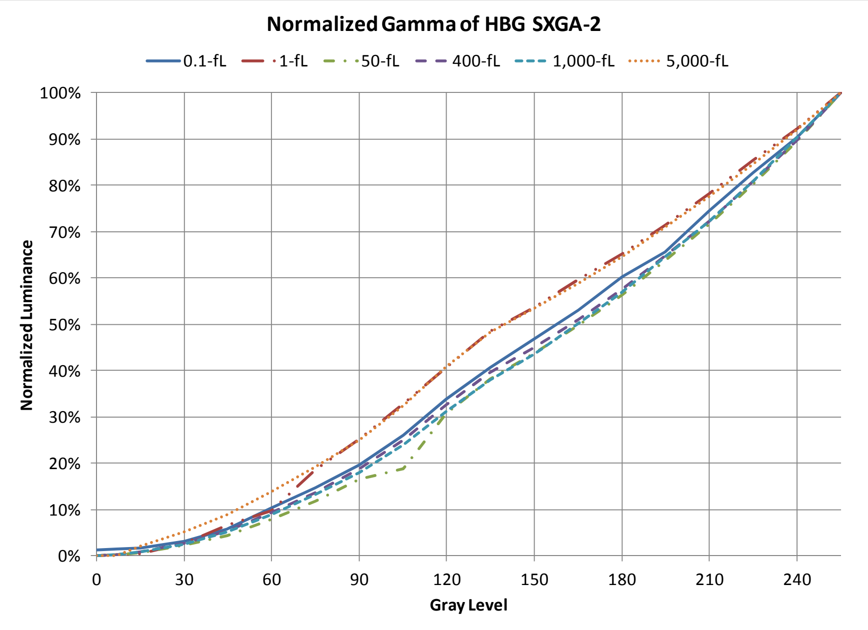


Figure 7. The transfer curve for the HBG SXGA-2 at 6 different light levels. The gamma coefficients in the GUI can be adjusted for finer control than setting the system gamma, which was used for rapid setup.

The full on/full off contrast was calculated from the 0/255 and 255/255 measurements of the gamma tests. Contrast is calculated as below in Equation 1. The checkerboard contrast is calculated from measurements of the 0/255 and 255/255 center square of the Checkerboard patterns. All squares aside from the center square are covered with black flocking material during this test. The contrast results are shown in Table 4.

$$C.R. = \frac{Max}{Min} \qquad \text{Michelson Contrast} = \frac{Max - Min}{Max + Min}$$

Equation 1. Calculations of contrast

Table 4. Contrast for HBG SXGA+ display at 6 brightness levels. The display has high contrast at levels 1-fL and above.

Contrast from Optimized HBG SXGA-2 Displays

	0.1-fL	1-fL	50-fL	400-fL	1000-fL	5000-fL
Full On/Off CR	76	584	2,674	19,744	476,235	37,766
Full On/Off Michelson	0.9739	0.9966	0.9993	0.9999	1.0000	0.9999
Checkerboard CR	79	400	647	997	1,053	1,043
Checkerboard Michelson	0.9751	0.9950	0.9969	0.9980	0.9981	0.9981

Uniformity was calculated by comparing the measurements of the center of 9 evenly spaced windows at 255/255 and at 0/255. The luminance of all 9 windows is averaged, and the percentage difference relative to the average is calculated for the brightest and dimmest window. The absolute value of these two percentages is added to calculate the overall non-uniformity. The results for bright and dark are shown in Table 5 for the display at 400-fL and 5,000-fL. The bright calibration bar on the left side of the screen affected the dark uniformity significantly. The bright uniformity at both light levels is excellent.

Table 5. Uniformity test for the HBG SXGA-2.

HBG SXGA-2 Uniformity

Luminance	Setting	Max, fL	Min, fL	Nonuniformity
400-fL	Bright	411	392	4.60%
	Dark	3.941E-02	1.499E-02	98.20%
5,000-fL	Bright	5,986	5,622	6.30%
	Dark	0.1648	0.07854	71.47%

The viewing angle was tested at 400-fL by measuring the luminance of the center of the display at 255/255 and 0/255 from -30° to +30° in steps of 10° for the display in typical landscape view, rotated halfway to portrait view, rotated to portrait view, and rotated halfway beyond portrait view. The display maintained high contrast and good luminance uniformity over the viewing angle. Figure 8 shows the luminance uniformity vs. angle.

The spectra at 50-fL and 400-fL were measured. The results are shown in Figure 8.

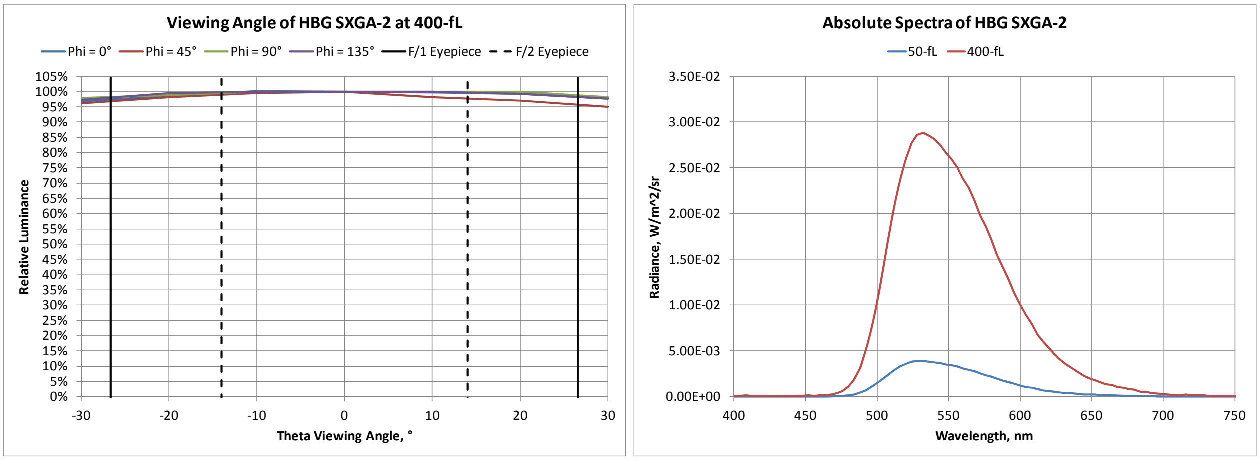


Figure 8. The viewing angle (left) and spectra (right) of the HBG SXGA-2. The cone angle of an F/1 and an F/2 eyepiece are shown on the viewing angle plot for reference.

The output of the photometer's PMT was sent to an oscilloscope to capture the waveform of the response time test. Two horizontal lines flashed on and off at a cycle of 8 frames. The waveforms of the rise and fall can be seen in Figure 9. The rise and fall times are on the same order as the 15.6-μs line time. The rise time was calculated by measuring the 10% to 90% time of the first line being turned on. Since the decay to steady state is slower than the line time, the fall time was approximated by measuring the time from 95% to 5% for both lines and dividing by two. With a rise time of 6-μs and a fall time of less than 21.5-μs, this display is readily capable of video rates.

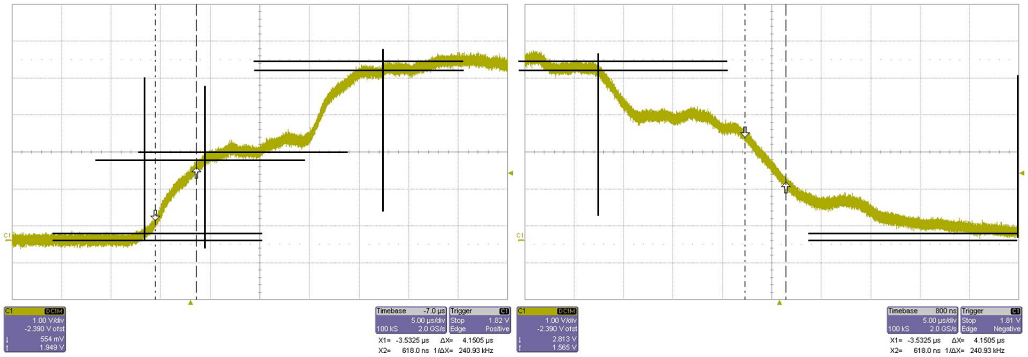


Figure 9. Response time waveforms for HBG SXGA-2 display with two lines turning on and off. The horizontal (time) axis divisions are 5-µs.

The display was qualitatively evaluated at each of the brightness levels with the Shades of Gray pattern, full screen uniform gray scale patterns, pictures, a PC desktop, and the HD video "wildlife.wmv" included with Windows™. An ND 1.0 was used in front of the display at 1,000-fL, and an ND 1.5 was used in front of the display at 5,000-fL. The countable gray shades from the Shades of Gray pattern are detailed in Table 6. The PWM required for 50-fL and below caused flicker. The calibration bar, though covered, did cause a reduction in contrast on the left side of the screen. Stuck-on pixels, which could be physically turned off permanently, could be seen with the full screen black pattern. Aside from these issues, the contrast was excellent, especially at 1-fL and above. The video and image quality was excellent throughout. No color or gray scale banding could be seen, and there was no image retention in the desktop application.

Table 6. Countable shades of gray during qualitative test for the HBG SXGA-2.

Shades of Gray for HBG SXGA-2

Luminance Level	Shades of Gray Visible in 18-Shade Pattern	0/7 Visible?	248/255 Visible?
0.1-fL	17	No	No
1-fL	18	Yes	Yes
50-fL	18	Yes	Yes
400-fL	18	Yes	Yes
1,000-fL	18	Yes	Yes
5,000-fL	18	Yes	Yes

3.3 SXGA-2 Color

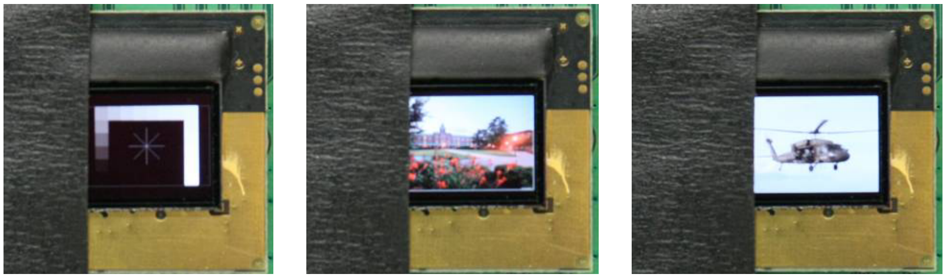


Figure 10. The Full Color SXGA-2 display showing the Grayscale pattern and two pictures. Black masking tape was placed over the bright calibration bar on the left side of the screen for all tests.

The Full Color SXGA-2, shown in Figure 10, was optimized at 0.1-fL, 1-fL, 20-fL, 50-fL, 100-fL, and 200-fL. The display optimization followed the same procedure as was used for the HBG display. The transfer curve or gamma test results can be seen in Figure 11.

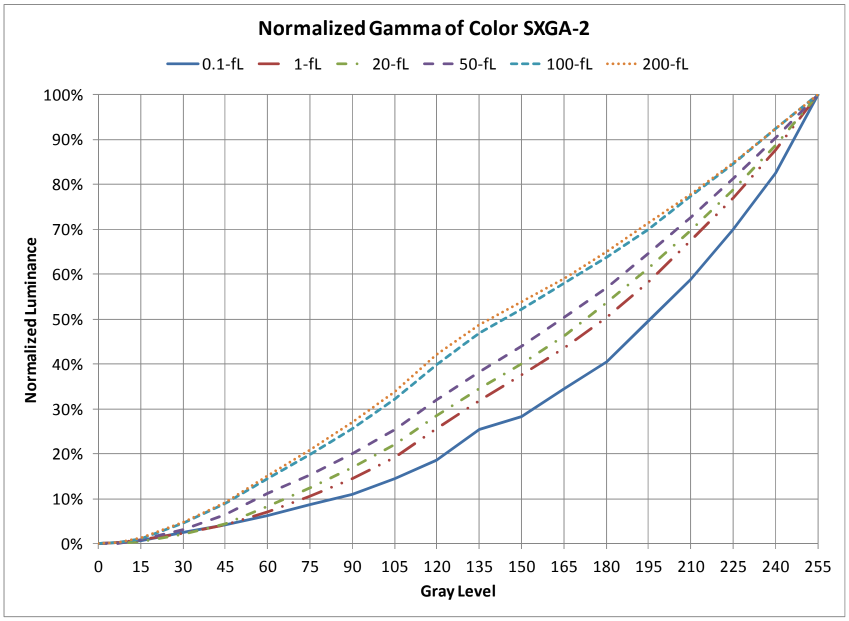


Figure 11. The transfer curve for the Full Color SXGA-2 at 6 different light levels. The gamma coefficients in the GUI can be adjusted for more fine control than setting the system gamma, which was used for rapid setup.

The contrast, evaluated in the same way as it was for the HBG SXGA-2, is shown in Table 7. Uniformity, in Table 8, was evaluated in the same manner as it was for the HBG, but the test was done at 50-fL.

Table 7. Contrast for Full Color SXGA-2 display at 6 brightness levels. The display has high contrast at all levels.

Contrast from Optimized Color SXGA-2 Displays

	0.1-fL	**1-fL**	**50-fL**	**400-fL**	**1000-fL**	**5000-fL**
Full On/Off CR	2,145	32,017	>1,100,000	1,062,968	2,797,073	1,290,116
Full On/Off Michelson	0.9991	0.9999	1.0000	1.0000	1.0000	1.0000
Checkerboard CR	1,738	13,929	19,085	17,688	15,851	18,296
Checkerboard Michelson	0.9988	0.9999	0.9999	0.9999	0.9999	0.9999

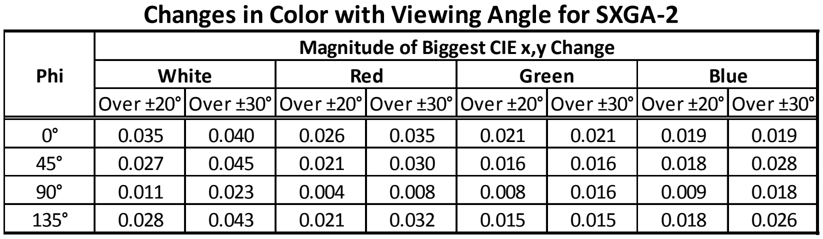
Table 8. Uniformity test for the Full Color SXGA-2.

Color SXGA-2 Uniformity

Luminance	**Setting**	**Max, fL**	**Min, fL**	**Nonuniformity**
50-fL	Bright	54.47	52.52	3.64%
	Dark	4.907E-05	2.477E-05	72.18%

The viewing angle was tested at 50-fL by measuring the luminance and color coordinates of the center of the display at full screen white, red, green, blue, and black for the same angles measured for the HBG SXGA-2. Because of the color filters, the uniformity over angle is not as good as it is for the HBG, but the color and luminance stability is still good. The results are in Table 9 and Figure 12.

Table 9. Color uniformity with viewing angle for Full Color SXGA-2. The magnitude is the root sum square of the difference in CIE x,y coordinates from the starting values.



Changes in Color with Viewing Angle for SXGA-2

Phi	Magnitude of Biggest CIE x,y Change							
	White		Red		Green		Blue	
	Over ±20°	Over ±30°	Over ±20°	Over ±30°	Over ±20°	Over ±30°	Over ±20°	Over ±30°
0°	0.035	0.040	0.026	0.035	0.021	0.021	0.019	0.019
45°	0.027	0.045	0.021	0.030	0.016	0.016	0.018	0.028
90°	0.011	0.023	0.004	0.008	0.008	0.016	0.009	0.018
135°	0.028	0.043	0.021	0.032	0.015	0.015	0.018	0.026

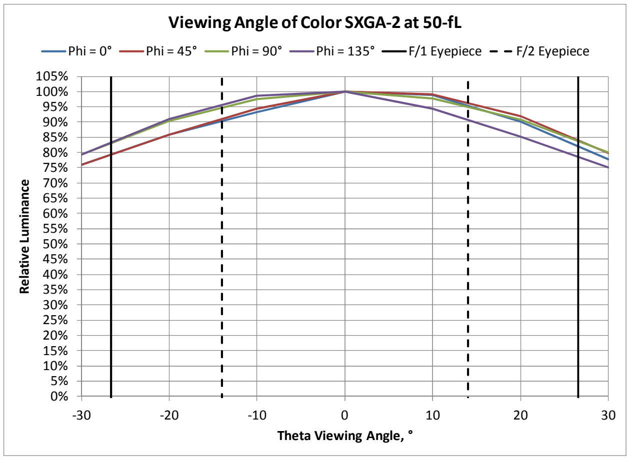


Figure 12. The viewing angle for the color display driven white. The cone angles of an F/1 and an F/2 eyepiece are shown for reference.

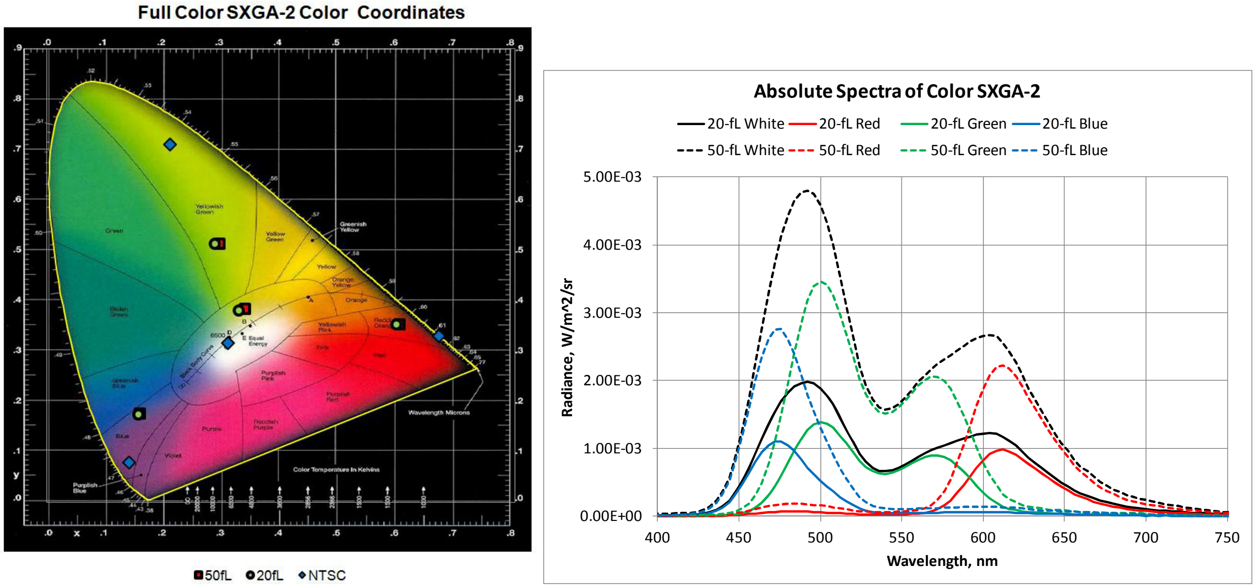


Figure 13. The plotted color coordinates (left) and spectra (right) of the HBG SXGA-2. The color coordinates are consistent with luminance and are good for red white and blue but could use some improvement in green.

The spectra of the white, red, green, and blue for 50-fL and 20-fL were measured. The results are shown in Figure 13.

The response time of the Full Color SXGA-2 was evaluated the same way as it was for the HBG, with the waveforms of the rise and fall being shown in Figure 14. The rise time was calculated by measuring the 10% to 90% time of the first line being turned on. Since the decay to steady state is slower than the line time, the fall time was approximated by measuring the time from 95% to 5% for both lines and dividing by two. With a rise time of 4-µs and a fall time of less than 9µs, this display is readily capable of video rates.

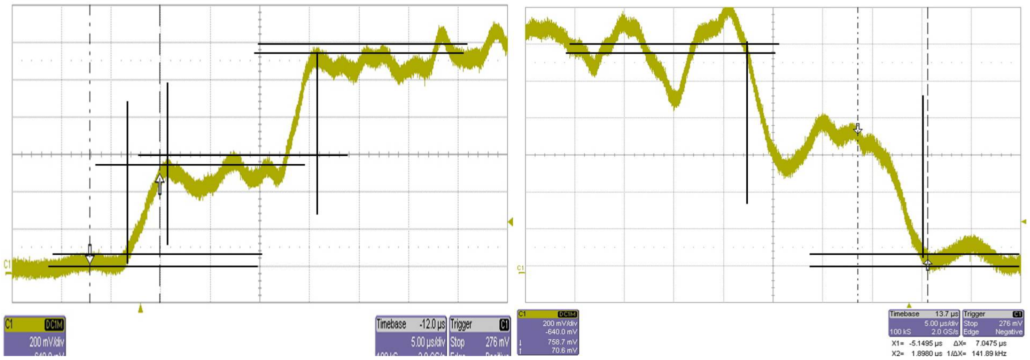


Figure 14. Response time waveforms for Full Color SXGA-2 display with two lines turning on and off. The horizontal (time) axis divisions are 5-µs.

The display was qualitatively evaluated at each of the brightness levels with the Shades of Gray pattern, full screen uniform gray scale patterns, pictures, a PC desktop, and the HD video "wildlife.wmv" included with Windows™. The countable gray shades from the Shades of Gray pattern are detailed in Table 10. PWM was not required for any light levels. A small amount of flicker was visible at 0.1-fL at one upper-mid gray level. Two stuck on pixels were noticed until the display was set to 200-fL when 10 to 20 became visible. Aside from these issues, the contrast was excellent for all light levels. The video and image quality was excellent throughout. No color or gray scale banding could be seen, and there was no image retention in the desktop application.

Table 10. Countable shades of gray during qualitative test for the Full Color SXGA-2.

Shades of Gray for Full Color SXGA-2

Luminance Level	Shades of Gray Visible in 18-Shade Pattern	0/7 Visible?	248/255 Visible?
0.1-fL	17	No	Yes
1-fL	18	Yes	Yes
20-fL	18	Yes	Yes
50-fL	18	Yes	Yes
100-fL	18	Yes	Yes
200-fL	18	Yes	Yes

3.4 WUXGA HBG

The High Brightness Green WUXGA, shown in Figure 15, was optimized at 0.1-fL, 1-fL, 50-fL, 400-fL, 1,000-fL, and 5,000-fL. The display optimization followed the same procedure as was used for the SXGA-2 displays. The transfer curve or gamma test results can be seen in Figure 16.

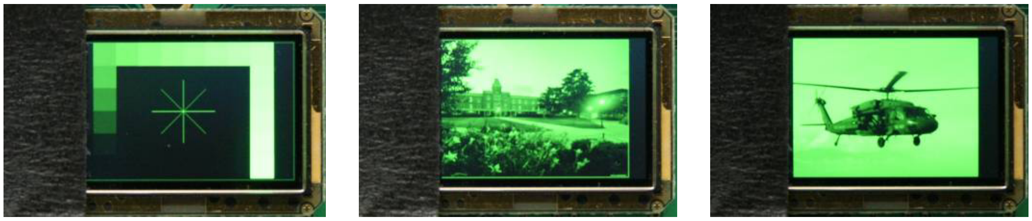


Figure 15. The High Brightness Green WUXGA display showing the Grayscale pattern and two pictures. Black masking tape was placed over the bright calibration bar on the left side of the screen for uniformity and qualitative tests. Black flocking material was placed over calibration bar for contrast measurements.

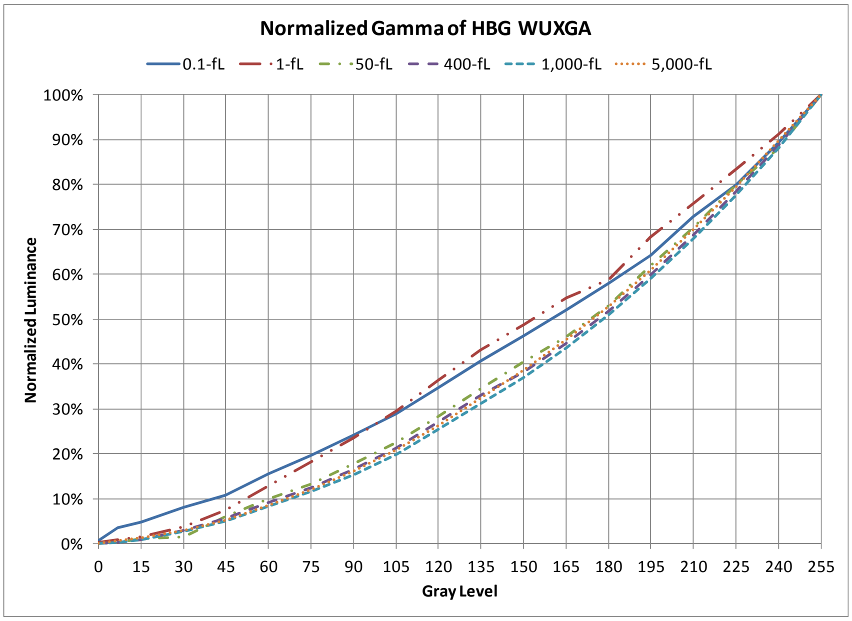


Figure 16. The transfer curve for the HBG WUXGA at 6 different light levels. The gamma coefficients in the GUI can be adjusted for more fine control than setting the system gamma, which was used for rapid setup.

The contrast, evaluated in the same way as it was for the SXGA-2 displays, is shown in Table 11. Uniformity, in Table 12, was evaluated in the same manner as it was for the SXGA-2, but the test was done at 400-fL, 1,000-fL, and 5,000-fL.

Table 11. Contrast for HBG WUXGA display at 6 brightness levels. The display has high contrast at 1-fL and above.

Contrast from Optimized HBG WUXGA Displays

	0.1-fL	1-fL	50-fL	400-fL	1000-fL	5000-fL
Full On/Off CR	132	339	10,250	68,406	150,354	938
Full On/Off Michelson	0.9850	0.9941	0.9998	1.0000	1.0000	0.9979
Checkerboard CR	25	220	691	840	831	805
Checkerboard Michelson	0.9241	0.9909	0.9971	0.9976	0.9976	0.9975

Table 12. Uniformity test for the HBG WUXGA.

WUXGA Uniformity

Luminance	Setting	Max, fL	Min, fL	Nonuniformity
400-fL	Bright	434	385	11.97%
	Dark	1.165E-02	5.803E-04	196.26%
1,000-fL	Bright	1,144	1,013	12.16%
	Dark	1.766E-02	3.364E-03	141.83%
5,000-fL	Bright	5,799	4,957	15.88%
	Dark	5.005	4.585	8.75%

The viewing angle was tested in the same way as it was for the HBG SXGA-2 at 400-fL. The display maintained high contrast and good luminance uniformity over the viewing angle. Figure 16 shows the luminance uniformity vs. angle.

The spectra at 50-fL and 400-fL were measured. The results are shown in Figure 17.

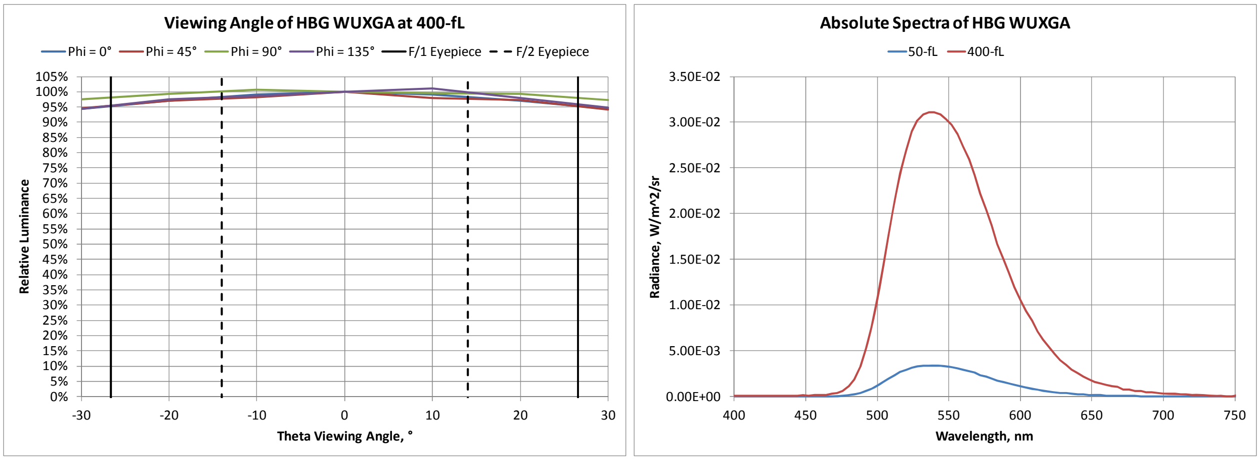


Figure 17. The viewing angle (left) and spectra (right) of the HBG WUXGA. The cone angle of an F/1 and an F/2 eyepiece are shown on the viewing angle plot for reference.

The display was qualitatively evaluated at each of the brightness levels with the Shades of Gray pattern, full screen uniform gray scale patterns, pictures, a PC desktop, and the HD video "wildlife.wmv" included with Windows™. An ND 1.0 was used in front of the display at 1,000-fL, and an ND 1.5 was used in front of the display at 5,000-fL. The countable gray shades from the Shades of Gray pattern are detailed in Table 13. The drive board is more advanced than the SXGA-2 board and could be set such that flicker was almost eliminated. Very slight flicker could be seen in limited situations (certain uniform gray shades) for 0.1-fL, 1-fL, and 50-fL. The calibration bar, though covered, did cause a reduction in contrast on the left side of the screen. Stuck-on pixels, which could be physically turned off permanently, could be seen with the full screen black pattern. Aside from these issues, the contrast was excellent, especially at 1-fL and above. The video and image quality was excellent throughout. No color or gray scale banding could be seen, and there was no image retention in the desktop application.

Table 13. Countable shades of gray during qualitative test for the HBG WUXGA.

Shades of Gray for HBG WUXGA

Luminance Level	Shades of Gray Visible in 18-Shade Pattern	0/7 Visible?	248/255 Visible?
0.1-fL	18	No	Yes
1-fL	18	No	Yes
50-fL	18	Yes	Yes
400-fL	18	Yes	Yes
1,000-fL	18	Yes	Yes
5,000-fL	18	Yes	Yes

4. CONCLUSIONS

The research and development programs conducted by eMagin with oversight from the US Army have produced excellent results: longer lifetime display devices that are becoming commercially available and two high pixel density display products (SXGA-2 and WUXGA) that generally have very good performance, including contrast, gamma, response time, and image quality. The integration of the long life/high brightness devices into the SXGA-2 and WUXGA was an important step towards developing a display capable of high brightness and HD resolution while having reasonable lifetime and having good power efficiency. Improvements can still be made in the engineering prototype SXGA-2 and the WUXGA by reducing flicker at low light levels, reducing stuck-on pixels, and adding color capability for high brightness operation, and efforts to achieve these goals have already started with US Army and DoD guidance.

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