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DEVELOPMENT OF SUPPORT TECHNOLOGY FOR COLOR AMEL AND AMLCD HEAD-MOUNTED DISPLAYS

by
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Enabling technologies were developed for manufacturing 2000 lines-per-inch, flat panel displays. These critically needed technologies are: (1). Primary Color Tri-Band Lamps for AMLCD back lighting to provide good color and brightness with a 3x power reduction. Lamps were shipped and evaluated. (2). Narrow liquid crystal (LC) gap assembly techniques required for a 12 µm pixel pitch. Assembly process is in production. (3). The 24 µm pixel display design was shrunk to allow manufacture of 12 µm pixel displays in preparation for the 2560x2048 displays. Shrunk 1280x1024, 12 µm pixel AMLCD displays were demonstrated. (4). A color filter process was developed and integrated into the display fabrication process.

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TABLE OF CONTENTS

4.0. Appendices:

LIST OF FIGURES AND TABLES

Figure

Table

PREFACE

This project was funded by the Defense Advanced Research Projects Agency (DARPA) under BAA93-19 to enhance the concurrent AMEL/AMLCD DARPA HMD display development program. The objective of the AMEL/AMLCD display program is the development of high resolution active matrix displays made in both electroluminescent and liquid crystal formats. 1280 x 1024 pixel (1000 lines/in) AMLCD and AMEL displays had been delivered. 2560 x 2048 pixel (2000 lines/in) AMLCD displays were developed using the technologies developed in this project. This project augmented the display program in specific areas of manufacturability and color display quality.

A number of organizations that collaborated to attain the project goals. The technical work was carried out at Kopin (Prime Contractor, SOI materials, transfer processing, display assembly and testing, color filter process development, spacerless assembly process development), Sarnoff (active matrix circuit design, process design), Standish Industries (AMLCD packaging), AlliedSignal (AMLCD circuit fabrication), ILC (primary color lamp development), Honeywell (primary color lamp project management, lamp evaluation and integration)

A number of individuals played key roles in the program. The program manager, initially Dr. Mark Spitzer (Kopin Corporation now with The MicroOptical Corporation), was succeeded by Mr. Ollie Woodard (Kopin Corporation). Dr. Alfred C. Ipri was the principal technologist and project leader of the Sarnoff subcontract to scale down the 1280x1024 pixel display design and to develop the 12 micron pixel display fabrication process in collaboration with Allied Signal. Mr. Richard O. Shaffner was principal technologist in developing the Primary Color lamp at ILC. Mr. Henry Franklin led the effort at Honeywell to direct the Primary Color Lamp development to augment the Armstrong Lab funded Miniature Color Display. Dr. David Post evaluated the Primary Color Lamps at Armstrong Labs. Dr. George Chang developed the spacerless assembly process at Kopin. Ms. Brenda Dingle (Kopin) developed the generic integrated color filter process for the AMLCD transfer process. Mr. Henry Girolamo (U.S. Army Soldier Systems Command) provided essential guidance and management through the course of the program. Other key participants included:

Mr. Roger Stewart - Sarnoff Project Mgmt.
Mr. Gary Dohlny - Sarnoff Staff
Mr. Frank Coumo - Sarnoff AMLCD Design
Mr. Danny Kagey -AlliedSignal Project Mgr.
Mr. Gerry Becker - Allied Signal Staff
Mr. Tom Keyser - AlliedSignal Staff
Mr. Matthew Zavracky - Kopin Staff
Ms. Mary Tilton - Standish Project Mgr.
Mr. William Heinze -Honeywell TC Staff

The Project Team has a special debt of gratitude to Mr. E. C. Urban of ARPA/ESTO for recognizing the importance of these enabling technologies for miniature displays, and for funding and managing this work.

DEVELOPMENT OF SUPPORT TECHNOLOGY FOR COLOR AMEL AND AMLCD HEAD-MOUNTED DISPLAYS

1.0. OVERVIEW

Enabling technologies were developed by this project for manufacturing 2000 lines per inch (LPI) active matrix electroluminescent (AMEL) and active matrix liquid crystal displays(AMLCD's). Critically needed manufacturing technologies which independently augmented the 2000 LPI program were developed in the four tasks below.

(1) Primary Color Tri-Band Lamp Development For Color AMLCD's
Lamps were developed for color AMLCD backlighting applications to provide good color gamut and brightness with a 3x reduction in power consumption.

(2) AMLCD Manufacturing Assembly Technology Development
Narrow liquid crystal (LC) gap assembly techniques were developed. The LC gap between the pixel electrodes and the faceplate counter electrode must be small compared to the pixel size for good pixel light valve performance. Otherwise, electric fields from adjacent pixels and from row and column lines adversely affect display performance.

(3) Display IC Yield Enhancement
The 1280x1024 AMLCD design with 24 μm pixels was shrunk by a factor of 2 to allow manufacture of 12 μm pixel displays in preparation for the of 2560x2048 displays. "Shrink" displays provided data for the 2560x2048 display design and manufacturing.

(4) Color Filter Process Development For Small AMEL/AMLCD Pixels.
Color filter materials were evaluated and selected material processes developed for integration into the display fabrication process. Conventional color filter plates, useful with larger pixels, cannot be positioned to operate properly over 12 μm pixels. The integrated process forms the red, green and blue filters directly on the pixel apertures.

The four processes developed proved instrumental in the development of 2000 LPI displays. Operational 2560x2048 AMLCD's have demonstrated the viability of 2000 LPI displays. Product displays have been developed and are being manufactures in large volumes such as Kopin's CyberDisplay™ based on 2000 lines/in technology.

2.0. EXECUTIVE SUMMARY

The project developments augmented the AMEL/AMLCD project, as well as other ARPA display projects, by enhancing color displays and by improving the manufacturability and yield of advanced active matrix displays. The following specific innovations were developed:

2.1. PRIMARY COLOR LAMPS FOR COLOR AMLCDS

A primary color metal halide arc lamp was developed by ILC Technology. This tri-band lamp substantially improved the luminous efficiency and increases the color gamut of color light valve projection systems. HMD improvements were demonstrated by substituting the new lower power lamp into displays delivered to Amstrong Laboratories for DARPA.

In the preceding DARPA subtractive color HMD contract, Honeywell used a 300 watt xenon arc lamp as the backlight. The lamp is filtered into red, green, and blue bands by means of notch filters to improve the display color gamut. The filtering process throws away 65% of the lamp power. The new triband lamp developed, with similar system luminous efficiency, reduced the required power by a factor of three.

Lamp development, pursued by ILC and Honeywell, resulted in the development of a multi-spectral lamp optimized for narrow-band red, green, and blue wavelengths. Narrow red, green and blue spectral peaks are produced with minimal background radiation between peaks. This lamp improved the color gamut and reduced the power consumption in the subtractive color display because it allowed much more efficient color band separation. The ILC lamp was integrated in a subtractive color system by Honeywell-Phoenix Technology Center (PTC), replacing a broad band Xenon arc lamp. The new 105 Watt lamp resulted in a 300% increase in luminance efficiency, thereby replacing the 300 Watt Xe lamp with no loss of display brightness. Honeywell-PTC intends to use production versions of these lamps in subtractive color displays. In addition, significant improvements in brightness of DARPA funded additive color displays are feasible. Lamps delivered to Kopin were evaluated toward integration of these lamps into future Kopin display products. This task was extended by additional funding by Armstrong Labs. The results will benefit the HMD program through Armstrong Labs. The release of this report was held for the new lamp results; however, it will now be reported separately.

The principal tri-band lamp advantage stems from its three specific colors characterized by three narrow wavelength bands, rather than a broadband white lamp. Such a lamp has the potential for simplifying the optical systems in LCD-based systems, including HMDs, avionics displays, computer monitors, and large format displays. All of these displays require a bright lamp that must be filtered to either red, green and blue (RGB), or cyan, magenta and yellow (CMY).

Consider how one separates white light into color bands. If narrowband filters (notch filters) are used, the system is highly inefficient when coupled with a broadband source, because light with wavelengths outside of the notch is wasted. If one uses conventional bandpass filters, then the color gamut is degraded. Consider now the tri-band lamp. The notch filters in this case separate the three colors without gross inefficiency, because the lamp does not generate much light outside of the notch. A benefit is obtained in systems using dichroic filters as well, since the narrow wavelength range of the light from a tri-band lamp simplifies the requirements on the dichroic filter's thin-film stack. Thus it can be seen that a true tri-band lamp enables displays of enhanced brightness and color gamut.

2.2. AMLCD MANUFACTURING METHODS

To resolve display anomalies caused by established assembly techniques in very small pixel displays, manufacturing methods were developed to achieve uniform 2 μm to 6 μm liquid crystal (LC) cell gaps with hidden spacer and spacerless assembly. LC cell gaps must be reduced for smaller pixel sizes to avoid fringe field defects in display appearance. Thin displays facilitate improvements in the luminance efficiency of subtractive color displays. A stack of three displays is required for subtractive color displays which limits off axis illumination as the overall stack thickness increases.

To provide a route toward manufacture of subtractive color displays, Standish Industries developed manufacturing techniques in collaboration with Honeywell PTC. Standish developed a spacerless assembly technique which used spacer structures located outside the active display area. Uniform LC gaps were maintained across the span of the small displays. Kopin used another approach to develop pedestal spacers hidden by the black matrix pattern between clear pixel areas. The pedestals, fabricated using established IC manufacturing processes, provided very uniform LC cell gaps. Pedestals are located so that they improve display yield by protecting sensitive circuits from handling forces. Deflection of the faceplate glass by a few microns causing it to strike the active matrix circuits requires only a few ounces of pressure. Pedestals distributed over the pixel array prevent glass deflection. Manufacturing methods developed at Kopin have been adopted by Kopin's display manufacturing facility in Westborough, MA. Kopin display products and the DARPA funded displays in development are now assembled using these methods.

2.3. IC YIELD ENHANCEMENT

Integrated circuit yields increase as die sizes are reduced. Since Kopin's display circuits are fabricated using conventional IC manufacturing processes, display yields can also be increased by reducing display area. Sarnoff, Kopin and Allied collaborated on the reduction of the 1280 x 1024 pixel display area by a factor of four. To attain this goal, the pixel size was reduced to 12 μm. This allowed the 1280 by 1024 AMLCD fabrication using conventional 5x steppers because the display fits within a single stepper field. Stepper field stitching which can reduce yields is not required. Smaller die size and more displays per wafer result in higher yields and lower costs. Sarnoff made design improvements and Allied developed new processes under 1 μm design rules to achieve the aggressive size reduction and to enhance yield. Working displays with 12 μm pixels demonstrated the feasibility of these yield enhancing developments

Other Kopin display products are expected to benefit from the technology developed in this task. The reduction in display circuit chip size and the advanced circuit designs are expected to increase manufacturing yields. More display circuits can be fabricated on each wafer, thereby reducing the cost and making them suitable for a broader range of market applications. The 2560 x 2048 displays in development will have 12 μm pixels. This display technology is available for other government purposes.

2.4. COLOR FILTER DEVELOPMENT

Reduction in pixel sizes to 24 μm and 12 μm made the use of a conventional color filter plate ineffective. Even when the filter plate is perfectly aligned, the gap imposed by the display glass thickness (550 μm) between the pixel structure and the filter plate allows excessive light leakage between pixels.

If the filters are especially thin (< 1 μm), they can be placed on the face plate electrode glass under the ITO. In this case planarization is necessary to avoid effects of LC gap variations on the final display characteristics. In addition, a filter to pixel electrode alignment must be added, and liquid crystal contamination issues arise caused by the metals used to achieve color in most of the spin-on techniques.

A method of integrating the formation of the color filters with the active matrix fabrication process was developed. In this way, the red, green and blue color filters are fabricated directly onto the respective pixel electrodes. Such an approach obviates the use of color filter plates and alignments, and is also an enabling technology for small pixels which cannot make adequate use of a conventional color filter plate. The specific innovation here required the adaptation of micro-electronic processing techniques that are used for active matrix circuit formation to the deposition and patterning of color filter materials. Thus, the techniques were added to Kopin's active matrix fabrication sequence. Color filter processing steps developed are now integrated into the display manufacturing process for use in future products. Kopin displays with integral color filter have been delivered.

2.5. DELIVERABLES

The above tasks, which augmented the AMEL/AMLCD program, provided the following deliverables:

(1) Honeywell-PTC delivered 6 advanced ILC lamps, power supply and characterization data to Armstrong Laboratories for DARPA.

(2) The ILC lamp, PTC notch filters and subtractive color displays were integrated by Honeywell-PTC to demonstrate advanced color 1024 by 1280 displays.

(3) Kopin delivery of three monochrome 1024 by 1280, 12 µm pixel displays to the Army Research Laboratory, Fort Monmouth was not made. These displays conform to the electrical interface requirements of the baseline 24 µm pixel display. Failure of the drive electronics interrupted testing.

(4) All Kopin displays are now assembled using the generic manufacturing methods developed, included displays delivered to DARPA. Standish Industries delivered one subtractive color display fabricated using its production processes, as well as a manufacturing plan to address various production levels.

(5) Kopin developed a generic manufacturing technology for color filter fabrication on active matrix liquid crystal displays (AMLCDs). We have integrated the results of this work with ongoing AMLCD work at Kopin in both our commercial display program and our DARPA-funded program. Color displays delivered include the color filter process developed.

(6) Section 4 contains a final data package summarizing the additional results obtained by these support tasks. Final reports from Honeywell, Sarnoff & Allied are included.

3.0. DETAILED PROJECT RESULTS

This project included four separate tasks. Each task independently augmented the AMEL/AMLCD program. To make clear the distinctions between the tasks, each part of this report addresses the following four tasks individually:

(1) Primary color tri-band lamp development;
(2) AMLCD manufacturing methods;
(3) Active matrix IC yield enhancement;
(4) Color filter development.

3.1. TASK 1: PRIMARY COLOR TRI-BAND LAMP DEVELOPMENT

A 105 watt primary color tri-band metal halide arc lamp was developed by ILC. This lamp substantially improves the luminous efficiency of the subtractive color light valve system. It also increases the color gamut that can be attained. Lamp power requirements are reduced by a factor of three. When coupled with Honeywell's notch filter polarizers, the lamp developed yielded a fully optimized color gamut.

During the course of the primary color lamp development by ILC, experimental lamps were delivered to Honeywell for evaluation. The lamps were examined with a spectro-radiometer, a photometer, and an integrating sphere radiometer for spectral power distribution, color stability, arc stability, total power, and power stability.

3.1.1. Primary Color Lamp Principles

The AMEL/AMLCD team is pursuing LCD system technology which makes use of full-color displays for applications where increased information density, visibility, and natural color reproduction are critical requirements. In previous development efforts, the light source for these displays is a single broad-band "white" source which is used to illuminate a stack of liquid crystal cells, each containing a different dichroic dye. Typically, yellow, magenta, and cyan dyes are used to absorb selectively the blue, green, and red primary colors, creating a full color display with complete color control at each pixel.

The performance of each of the liquid crystal cells in the three-cell subtractive stack is optimum in a particular and narrow wavelength range. The input spectrum is separated into three component bands by passing the light through the dichroic dyes and filters within the tandem three cell stack. Note that an engineering trade-off is required between color gamut and efficiency. If narrow band pass filters are used the color gamut is improved at the expense of absorption of non-optimal wavelengths, thus leading to low efficiency. If wider band pass filters are used, the optical throughput increases at the expense of color gamut.

Despite the above engineering compromises, the subtractive color display developed in the preceding HMD program has high resolution, reasonably brightness, and good color control. However, it is highly desirable to improve system efficiency. Efficiency can be improved if the photon wavelength distributions can be more tightly packed around the optimum wavelength for each color band, thus eliminating the compromise between efficiency and color gamut. A lamp spectrum consisting of only three spectral peaks located at the optimum red, green and blue primary color wavelengths would be ideal. The primary colors targeted are centered about 475nm, 525 nm and 625 nm.

A primary color light source can be obtained by filtering the white light spectrum using broadband yellow, magenta and cyan filters, but such an approach is inefficient.

Alternatively, spectrally selective lamps are feasible using metal halide high intensity discharge technology. Metals can be selected having emission spectra coinciding with the dye passband. The objective of the design and development of a multi-band lamp characterized by emission in three narrow bands centered around red, green and blue.
Thus, the losses associated with broadband filters can be eliminated. The overall quality of the subtractive color optical system can be further improved by also employing selective notch filters with much less loss than would be obtained with conventional white light sources and narrow band filters.

Metal halide lamps consist of a quartz arc discharge tube contained within a quartz or hard glass outer jacket and are configured in single-end and double-end designs, depending on the location of the two electrical contacts to the lamp power supply. The source size is determined primarily by the arc length within the discharge tube. Smaller source size increases efficiency further because the smaller source spot can more easily be focused making the lamp optics more efficient. Thus power reductions achieved by the primary color lamp concept allow a shorter arc to improve efficiency even more. Linear power loading (watts/mm arc length) is limited by material thermal limits and radiation optimization criteria to the range from 10 W/mm for general illumination lamps to 30 W/mm for projection optical illumination sources. For example, a 150 W metal halide optical imaging lamp typically would have a source size of 5 mm arc length by 3 mm maximum arc diameter. Such lamps have arc luminance of about 100 cd/mm2, efficacies of about 80 lm/W and life of 500 to 1000 hours.

The primary color lamp virtually eliminates the compromise between efficiency and color gamut. Since absorption by dichroic dyes can result in efficiency losses, improved utilization of the radiance can be attained by a prime color (multi-band) light source which selectively radiates in each of the dichroic dye spectral windows. Thus energy is concentrated where the light transmission is highest and the filter is not required to reject wavelengths between peaks. A primary color lamp also has applications in other non-subtractive displays including LCD monitors and projectors in which the light is separated into red, green, and blue components, passed to separate LCD light valves, and then recombined. These systems also make engineering compromises between color gamut and efficiency and would be improved by the multi-band lamp

3.1.2. Primary Color Lamp Development

Lamp development involved collaboration between Honeywell PTC and ILC. The ILC lamp was incorporated into a Honeywell subtractive color display system.

The lamp program was carried out in three phases. The first phase included a matrix study of emission spectra, vapor pressure, and chemical stability to identify candidate metal halides. The second phase included experimental trials to select the best metal halides from among the first phase candidates. The third phase included feasibility tests of the light source system developed in the second phase optimization. An electronic ballast to drive the lamp was developed in phase three.

The objective of the Honeywell work was to define fully the lamp requirements for the subtractive color display, and to direct the ILC development effort toward that end. Honeywell was also responsible for lamp testing. Accordingly, two subtasks were completed by Honeywell PTC. The first comprises development of lamp requirements and definition of a specification in collaboration with ILC. Honeywell characterized the delivered lamps and redirected ILC efforts accordingly.

The lamp development program completed by ILC consisted of three principal subtasks. The first was choosing the lamp components and defining power supplies. The second task was the design and fabrication of lamps. System characterization of the lamp and its power supply was the third task.

First, ILC determined the radiating elements to be used in the lamp to achieve the desired three-color spectrum. Using the known properties of the chemicals involved, the most promising candidates were selected and used to produce lamps using an initial standard lamp body. Both AC and DC versions of these lamps were operated to check for feasibility and to evaluate stability. ILC constructed experimental lamps for this research, identifying the most promising chemicals and drive conditions (AC or DC).

Secondly, the basic lamp design was formulated in this subtask. The interface with the power supply was defined and the electrode and arc tube geometry was improved to provide reliable operation. ILC constructed about 50 experimental lamps during this subtask and shipped the more promising ones to Honeywell for evaluation. A drive circuit design was made, tested and improved.

The next task was the characterization of the design. Selected samples supplied to Honeywell supported lamp measurements task, where the variability of several groups of lamps were studied. Output decline and shift with operating hours and other life characteristics were measured.

3.1.3. Primary Color Lamp Evaluation Results

Primary color lamp results were compared to previous results with a broad band (white) 300 Watt xenon arc lamp used in the Honeywell Miniature Color Display (MCD) program. In this preceding DARPA program, the lamp spectrum was converted to a tri-chrominance spectral power distribution of broad red, green and blue peaks using multi layer dichroic notch filters. A 65% reduction in luminance of the Xe lamp resulted from the filtering to produce a broad color gamut. The filtered Xenon lamp (F-Xe lamp) was used to illuminate a twisted nematic subtractive color light valve which incorporated dichroic dye type polarizers to modulate color.

The primary color metal halide lamp developed by ILC is used without filtering to illuminate the light valve which uses notch filters rather than the dichroic dye type polarizers to modulate color. A 300% increase in luminance efficiency and substantially broader color gamuts than the MCD can be obtained with ILC's primary color lamp. The 105 Watt primary color lamp #89 is capable of exceeding the luminance of the filtered 300 Watt Xenon MCD lamp if the coupling efficiency into the 1/4 inch fiber optic bundle is improved. Coupling efficiency of the primary color lamp was 19% compared to 45% for the MCD. Coupling efficiency can be improved by optimizing the arc size and shape and positioning the arc more accurately within the reflector optics. ILC has achieved collection efficiencies as high as 60% in the past and predicts a 50% collection efficiency for future prime color lamps focused onto a 5mm spot. Thus the 300% increase in luminance efficiency can be realized.

Almost all of the ILC primary color lamps exhibited an undesirable yellow peak which was caused by an impurity in the gas mixture. The yellow peak was removed using a 570nm-600nm notch filter which improved the color gamut accordingly. ILC has since identified the impurity as sodium introduced by the glass envelope cleaning step. Production lamps will not have the yellow peak.

Refer to the appended Honeywell final report in the appendix for results details. Figures 5 and 6 of the report illustrate the primary color lamp spectrum and the color gamut improvements over the MCD Xenon broad band arc lamp. Refer also to the paper:
Richard O Shaffner, Characteristics of medium Arc Metal Halide Light Sources. SPIE Proceedings Vol 692, pp 622-628, 19-21 Aug 1986..

3.1.4. Primary Color Lamp Commercialization

Our plan is to commercialize the lamp developed, for both CMY and RGB tri-band lamps. ILC will provide these lamps commercially to the industry, thus providing a U.S. source for LCD lamps. ILC Technology is already a supplier of specialty lamps to U.S. industry, and also supplies space-qualified lamps for government purposes. Thus, ILC will transfer the results of the proposed work to its production facility. Kopin also evaluated the ILC lamp for potential applications and is continuing to work with ILC toward the application of a new tri-band lamp design to fit into a Kopin display. At this writing, Armstrong Labs added more funding for ILC to optimize the HMD lamp. Other application may also benefit from the additional technology developed. An addendum report will be written to cover the additional lamp developments.

3.2. TASK 2: DISPLAY MANUFACTURING ASSEMBLY METHODS

The objective of this task was the development of manufacturing techniques for the PTC subtractive color display. This task comprised a collaboration between Standish Industries, Kopin and Honeywell PTC.

The Honeywell task was mainly consulting with Standish and Kopin on methods of assembling subtractive AMLCD stacks. Liquid crystal, cell gap, polarizers, and test parameters were exchanged under proprietary data exchange agreements. This task also included tooling design and fabrication for subtractive display assembly.

Standish collaborated with Honeywell and Kopin on the development and implementation of manufacturing techniques for subtractive AMLCDs. Standish developed a perimeter spacer process in which spacer bars were placed outside the active display area. Spacer balls were eliminated along with image anomalies caused by spacers located in open pixel areas. Standish also developed methods of interconnecting the cells to the driver electronics. The baseline interconnect process adopted is a heat seal connection approach.

Standish provided two deliverables. First, Standish provided one subtractive color display fabricated using the processes developed in this effort. Second, Standish provided a plan for the manufacturing of subtractive displays at various volumes.
Kopin developed a different spacer process which uses pedestals located in the black matrix areas between pixels to maintain a uniform LC gap. Pedestals are fabricated using IC photo mask processes to fabricate pedestals. Pedestals are well suited for narrow (e.g. 2 μm) gap assemblies. Pedestal spacers eliminate image anomalies caused by ball spacers located within open pixel areas.

Spacer balls are still used for some displays; however, more resilient spacer material is used to minimize circuit damage by pressure applied through a spacer located over a circuit. Undesirable image anomalies can be minimized but not completely eliminated by using a spacer material with an index of refraction close to that of the liquid crystal material.

Kopin has integrated spacer and interconnect technologies developed into its manufacturing process and is currently delivering display products using them.

3.3. TASK 3: YIELD ENHANCEMENT

This work was an extension of the AMEL/AMLCD display development carried out in parallel. Our displays are based on the use of a single crystal silicon active matrix circuit formed using conventional IC processes. The present objective of the work underway is the formation of both AMEL and AMLCD 2560 by 2048 displays

Integrated circuit yields increase as die sizes are reduced. Since our display circuits are fabricated using IC manufacturing processes, display yields are also increased by reducing display die area. Sarnoff, Kopin and Allied collaborated on the reduction of the 1280 x 1024 pixel display area by a factor of four. The pixel size was reduced to 12 µm allowing 1280 x 1024 AMLCD fabrication using conventional 5x steppers because the display fits within a single stepper field. Field stitching which can reduce yields is not required. Smaller die size and more displays per wafer result in higher yields and lower costs. Sarnoff made design improvements and Allied developed new processes under 1 µm design rules to achieve the aggressive size reduction and to enhance yield. Working 12 µm pixel displays demonstrated the feasibility of these yield enhancing developments.

This work was carried out by Sarnoff, AlliedSignal and Kopin. Sarnoff coordinated the program within Sarnoff and between Sarnoff and the other team members. Sarnoff redesigned the 1280 X 1024 AMLCD to 5X stepper compatibility. AlliedSignal developed the stepper based process and fabricated display wafers to demonstrate the improvements. Kopin assembled displays and tested them.

The major portion of the program at Sarnoff involved the redesign of the 1280 x 1024 LCD that was designed under the current ARPA program and uses a 24 µm picture element (pixel) cell. The new design has a 12 µm cell and therefore the pitch of the scanner circuitry decreased by a factor of two. This reduction in pitch necessitated a re-layout of the scanner circuitry and subsequent re-simulation of the new layout to ensure that the new layout did not have a detrimental effect upon the performance of the scanner circuits.

AlliedSignal fabricated the displays in its foundry. Accordingly, AlliedSignal processed test lots to attain the performance necessary for attaining the display specifications in theAMEL/AMLCD program. AlliedSignal also collaborated on display design and layout improvements intended to result in higher yield. This task included generation of all masks, reticules and tooling necessary for this yield improvement task. AlliedSignal processed seven lots of 25 wafers each using the design tapes supplied by Sarnoff.

There are many advantages to fabrication of smaller displays. The related head-mounted optical system complexity and weight are reduced. The process yield is enhanced for many reasons including: smaller die (less sensitivity to defects), use of 1 µm processing, and greater number of displays per wafer. Consequently, the cost is expected to be much lower.

The most beneficial aspect of this project task is that we tested 12 µm pixels prior to the completion of the 2560x2048 design effort. Other Kopin display products benefited from this program. The reduction of the display circuit chip will allow many more of them to be fabricated on a single wafer. Higher circuit yields for these small displays will reduce the manufacturing cost, making them suitable for a broader market. This display technology is available for government purposes. Kopin Corporation shared 1/3 the cost of this task and may also at its discretion license commercial applications.

3.3.1. Design Approach to Enhance Yield

Our approach to increasing yield and manufacturability is the reduction in size from the present 1280 size of 38 x 38 mm to 23 x 26 mm. Accordingly, the size of the pixel array was reduced from 31 mm x 25 mm to 15.5 mm x 12.5 mm. Most present 5X aligners have a field of view greater than 15 x 15 mm and hence, the pixel array was exposed in a single flash on a 5X stepper. The Sarnoff Optimetrix 5X aligner which is used for to print 1.2 mm dimensions has a 17 x 17 mm field of view. The pixel array and perimeter scanner circuitry were independently flashed on the stepper and "stitched" to form the complete array. Thus, the stitch boundaries were chosen in non-critical locations so that errors between stitched fields have virtually no effect on yield. There are no stitch boundaries within the array.

The attainment of enhanced yield is of importance to the future commercialization of AMEL and AMLCD displays. One route to yield enhancement is to make the displays smaller. There are three principal advantages to decreasing the display size. Obviously, one will attain more dice per wafer. More important perhaps is that wafers with smaller die size will be less likely to be affected by distributed defects, since a bad die can be rejected without rejecting the entire wafer. Note that Kopin's ¼ inch diagonal display circuit yields are >90%. The third advantage pertains to the method of manufacturing: if the die size is sufficiently small, then stepper-based photolithography can be used. Stepper-based processes are generally characterized by much higher yield than projection-based processed; however, the AMLCDs fabricated on the current Kopin program use projection photolithography, owing to the need for large display size.

3.3.2. Processing Considerations

The process technology developed for the 1280 X 1024 AMLCD is based on a 2.0 μm design rules and Perkin Elmer projection aligners which are needed for defining the 24 mm pixel cells. While it is true that the test vehicle was processed at Sarnoff using a 5X Cannon Stepper with a resolution of about 1.25 μm, the process was not "tweaked" for 1.25 μm dimensions. The test array, however, does contain 1.2 and 1.0 μm dimensions and 12 μm pixel cells and was used to check the functionality and optical characteristics of 12 μm cells. Additional process development is needed to establish a fully operational 1.0 μm to 1.2 μm technology for producing high density 1280 X 1024 LCD's which meet all of the necessary design parameters such as brightness and contrast ratio at high yield. The funding for this additional process development effort needed to achieve all of the design parameters is part of the current 2560 X 2048 AMLCD's using the 12 μm pixel and was not part of this yield enhancement program. It was possible, however, to design and build high density functional 1280 X 1024 AMLCD's with the selected 12 μm pitch.

In parallel with this project, we fabricated test arrays which contains a number of pixel cells. Various types of pixels were contained on the test array along with their respective design rules and aperture ratio. Five different pixel designs were contained on the test array. For the case of 12 μm pixels, the test array contains four different pixels, starting with the simple Silicon Pixel and ending with the most complex Shielded Thin Poly pixel. Considering 12 μm pixels, the aperture ratio increases with increasing process complexity and also increases as the design rules decrease as shown in Table 1. Data from the pixel test arrays were used to advantage in the 2560x2048 AMLCD program.

Table 1: Aperture Ratios for AMLCD Pixels

	1.2 µm rules			1 µm rules	2.0 µm rules		
Electrode Type	24 µm	15 µm	**12 µm**	**12 µm**	100 µm	24 µm	20 µm
Silicon	59 %			**23%**		39%	
Gridded Si	59%	31%	**27%**	**23%**	87%	39%	
Shielded Si	59%	37%	**27%**	**36%**	85%	40%	
Shielded gridded Si	60%						34%
Shielded thin poly	60%	36%	**27%**	**37%**	89%	44%	34%

3.3.3. Test Results

Displays were tested at Kopin. Yields were low as expected since the process was not yet optimized for the 1 µm design rules. Process improvements were added in later lots based on test data. Scanner functionality was achieved in lot three and images were seen on displays in lot 4. A fully functional display was tested in lot 5 along with several others which displayed images with some defects evident. Lots 6 and 7 remain to be tested. Testing can be completed, if desired, by using subtractive color electronics. Luminance and contrast were low because this design did not realize the benefits of concurrent pixel test array fabrication and other display project results. Kopin's newer displays utilize more transparent pixel electrode material and a different pixel configuration for brighter, high contrast images. The DARPA 2560 x 2048 pixel AMLCD will have the new pixel.

3.3.4. Yield Enhancement Commercialization

The yield enhancement task has potential for reducing the cost of AMLCDs intended for HMDs. The manner in which the proposed work can improve yield is discussed elsewhere. Here we wish to note that in addition to the yield enhancement that results from decreasing the size of the display, certain other advantages are obtained that relate to technology transfer and commercialization. The foremost is the desire on the part of HMD designers to obtain the highest resolution possible in the smallest package size, system weight and moment which must be borne by the head. Widespread commercial acceptance of HMDs require that they be no more cumbersome than glasses or goggles.

The technology developed in the proposed program has a well-defined technology transfer path. Display designs may be implemented at AlliedSignal, GMT or other foundries and used in Kopin's commercial head-mounted display programs. These displays are now available to the industry for use in military HMD systems, as well as in avionics, medical, viewfinder (i.e. camcorder), and other display systems.

A second route to technology transfer is obtained from the establishment of small pixel designs at Sarnoff. Sarnoff provides AMLCD design services to industry. Thus, the technology developed in this program can be the basis for other development efforts within the scope of proprietary rights agreements and government use rights.

A third route to technology transfer was obtained fabrication at AlliedSignal. In this way, AlliedSignal become conversant in the processing of small pixel displays using stepper-based processing. It can be expected that the know-how obtained in this work will be applied to other circuits, including non-display VLSI circuits based on SOI materials.

Kopin is using display technology developed in DARPA projects in production displays.

3.4. TASK 4: COLOR FILTER DEVELOPMENT

Kopin was responsible for the development of novel color filter approaches. The objective of this work is the utilization of microelectronic processing techniques applied to the active matrix wafer to reduce the cost and improve the quality of the color filters. This work is applicable to AMLCD's and also to AMEL displays using white phosphors.
Various color filter materials were investigated and compatible processes to apply them to the display circuits were developed. The selected material processes color filter formation were integrated into the active matrix circuit foundry process sequence.

Finally, the work involved the identification and resolution of compatibility issues to integrate the color filter process with display fabrication process. Kopin then demonstrated the technology by applying it to AMLCD displays. Kopin's color filter process has been released to manufacturing. Displays have been delivered with the new color filter technology.

3.4.1. Liquid Crystal Color Display Background

There are presently three main approaches to make color AMLCDs: Color RGB Filtering (as developed here), Subtractive Color, and Sequential Color. The subtractive and sequential approaches have the advantage that higher resolution is attainable for a given pixel array size, since the RGB pixels are stacked or sequenced and only require a single pixel for all three colors; whereas the RGB color filter approach requires a minimum of three pixels. In this work, we developed fabrication techniques for color filter application

The use of color filters is especially advantageous for systems in which size, weight and cost are important factors, not only in head-mounted displays, but also in direct view flat-panel and projection systems. Application of color filters to displays characterized by small pixels has been problematic, owing to the need for precise alignment of the filters to the pixels, and to the necessity to have the filters in close proximity or in contact with the pixel electrodes.

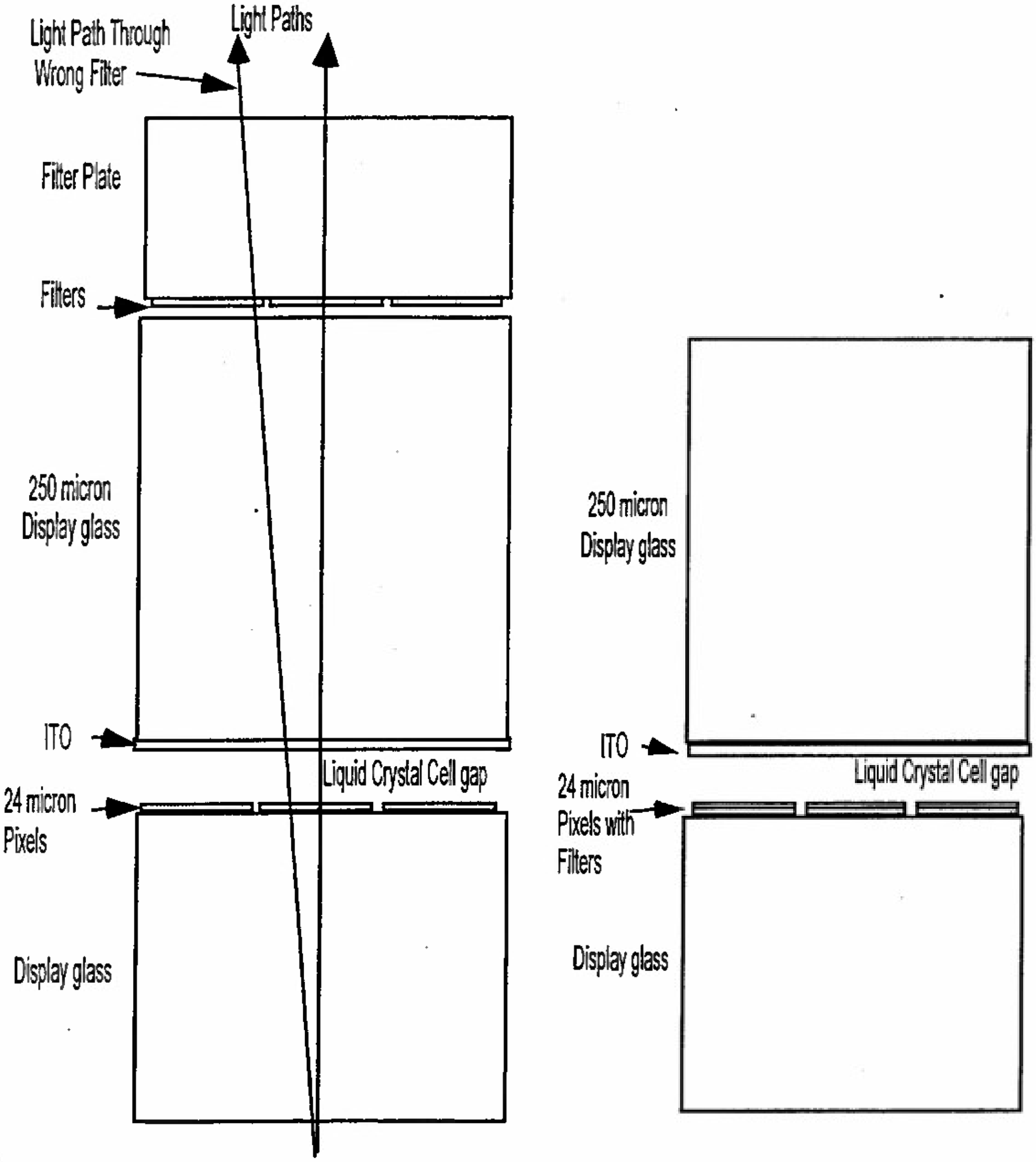
For the case of small pixels (10 to 100 µm) to be used in head-mounted displays, the color filter technology that we developed is truly an enabling technology. To show this, we first discuss the technical problem inherent to a color filter approach applied to small pixels. Consider the 24 µm pixel which forms the baseline for the AMEL/AMLCD program. Assuming that the 24 µm pixel has a 4 µm black matrix border which can mask small alignment errors, the color filter must be applied to the pixel electrode with a registration accuracy of ± 2 µm (otherwise the pixel will be illuminated by two colors). There are two components of this registration, inter-color and plate-to-plate registration. Thus the attachment of a color filter plate requires very high registration accuracy.

For systems in which the light is not highly collimated, a small (24 µm) pixel also requires that the filter be placed in close proximity to the active matrix. This requirement results from the potential for propagation of off-axis or stray light from one pixel to a filter over a neighboring pixel. This effect results in reduced viewing angle, color gamut and resolution. Note that conventionally, the filter plate is separated from the active matrix and liquid crystal by at least the thickness of one layer of glass (typically 250 µm, or ten times the pixel pitch here). Obviously, off axis illumination will cause color cross talk. For this reason, head mounted displays and other high resolution (small pixel) designs must have filters in close proximity with pixel openings. In this way, all rays passing through a pixel must also pass through the correct color filter element.

Ordinarily, a filter plate cannot be placed in intimate contact with the active matrix, as shown in Fig. 1a. Consider how the active matrix display is formed: a layer of silicon is deposited on glass or quartz which is then processed to form the active matrix circuit. The electrodes in this circuit must be in proximity to the liquid crystal, meaning that the color filter cannot be placed against the pixel electrode. The filter must therefore be placed on top of the glass. This placement introduces a gap many times larger than the pixel pitch; thus undesirable light propagation is unavoidable. It is clear that for small pixel displays, use of external filter plates is of limited utility at best

If the filters are especially thin (< 1 µm), they can be placed on the back electrode (faceplate) glass under the ITO. In this case planarization is necessary to avoid effects of LC gap variations on the final display characteristics. In addition, a filter to pixel electrode alignment must be performed by very accurate placement of the faceplate over the pixel array. Finally, liquid crystal contamination issues caused by the metals used to achieve color in the filter material must be dealt with.

The case of x-Si (single crystal silicon) transferred to glass is entirely different, as shown in the Figure 1b. Note that if the circuit is provided with a filter and then transferred to glass, the filter resides in close proximity to the pixel electrode, separated only by dielectric passivation on the order of 1 µm thick. The filter layer is effectively encapsulated between the circuit and the glass and the liquid crystal gap is on the opposite side. This approach can be applied to poly-Si (poly-crystaline silicon) and a-Si (amorphous silicon) displays, provided the circuit is transferred to make both sides of the circuit accessible.



1(a) 1(b)

FIGURE 1. ILLUSTRATION OF THE USE OF COLOR FILTERS IN THE AMLCD. (a) A filter plate is necessary in conventional AMLCDs because the filter cannot generally be imposed in the liquid crystal cell gap. For small pixels, Light through a pixel can pass through an adjacent pixel's filter. (b) The integrated filter approach is ideal for transferred x-Si AMLCDs because the illuminated side is the ideal location for a filter. Since the correct side is exposed prior to transfer, the filter can be applied in the foundry. Then the filter is encapsulated by transfer as shown here.

3.4.2. Filter Development Approach

A number of techniques were evaluated for possible use in our displays. Brewer dyed polyimide, Shipley pigmented resist, Fuji-Hunt pigmented material, Polaroid dyed resists (red and blue only), and color emulsions are techniques applied directly to the circuit. We also investigated two color filter techniques which required deposition directly on glass, and therefore a subsequent alignment to the circuit. These included Brysen Optical interference filters and Balzers interference filters. For these techniques, the color filter plate can be used as the transfer superstrate glass, separated from the pixel electrode by 5 mm of adhesive, or as the counter electrode glass. In the second case, the color filters would need planarizing prior to deposition of the ITO counterelectrode, and would be separated from pixel electrode by the ITO, LC gap and oxide layer.

In evaluating the success of each technique a number of criteria were used, including ease of processing, compatibility with the conventional CMOS circuitry which is used for the displays, adequate color, transmission and contrast, compatibility with subsequent display processing including adhesive cure, substrate lift-off, backside and LC processing, and availability in production quantities. Color chromaticity on all materials except the Polaroid were acceptable as received. Polaroid targets an internal use, subtractive color application and do not have an adequate red, blue and green resist for sale to the public.

We investigated the use of well-known color emulsion technology which is now used for photographic slide film to create high resolution color images. These emulsions can be applied by standard spin or dip coating techniques to the active matrix IC after circuit fabrication. Exposure and developing of the film in situ on the wafer provides high alignment accuracy, close proximity to the active matrix, and color gamut control at the quality level characterized by the present state of the art in color photography. The desired color is obtained by exposure of the wafer to the appropriate RGB filter master. The emulsion is then developed using conventional slide film developers. The result is an in situ filter plate formed directly upon the active matrix circuit.

We also investigated the use of thin-film dichroic interference filters that are applied in a multi-step deposition and patterning process to a glass superstrate. Dielectric film stacks are formed to produce bandpass filters. Stacks are tailored by varying thicknesses of high and low index layers to produce red, green, and blue dichroic filters that pass the desired wavelength bands while reflecting the undesired light. Absorption is very low, and transmission is very high. The sharpness of the band cutoff increases with the number of repetitions of the dielectric pair.

A number of companies make dichroic filters. The difficulty comes in patterning all three colors on one side of a substrate, at the 22 μm pixel size needed for this work. Balzers was not able to do this successfully. The optical interference filter R,G,B arrays made by Balzers are in the very initial stages of development. They can make good R,G,B filters, but they are not ready (in 1996) to achieve fine patterning in production.

On the other hand, Brysen Optical makes an excellent dichroic filter product, and with only very basic equipment, were able to produce decent inter-layer alignment and high yield on R,G,B filter arrays developed with Kopin. The advantages of interference filters are that transmission is very high and spectral cut-off can be made very sharp as illustrated by the spectral curves of Figure 2. In addition, heat and light stability are not issues. Particulates were the biggest problem here, but this is merely a matter of upgrading the laboratory environment. Pixel sizes as low as 7 μm have been demonstrated by Brysen since the 22 μm pixel size done on our demos. Initial estimates on production cost were also quite reasonable at $115 and $165 for 4 and 5 inch color arrays at the 22 μm pixel size.

The dichroic R,B,G array was a good achievement but proved difficult to use for our application since it cannot be applied directly on the circuit so must be applied to either the transfer superstrate or LC counterelectrode glass. This in turn requires a critical filter to pixel electrode alignment. Holding alignment through the adhesive curing step which is part of transfer turned out to be a non-trivial problem due to the small but anisotropic shrinkage associated with this process. If positioned on the LC counter electrode glass, this problem is alleviated, but the critical alignment to the display requires a piece of equipment not available to us at the present time. This method should not be forgotten and may be used for future applications where the alignment tool investment is justified.

Of the spin-on techniques, the Brewer Science colored polyimides turned out to be the best all around, and are now being installed in our production display facility. These materials can be applied using conventional IC fabrication processes and patterned with standard photoresist equipment and developers. The polyimide uses dye to supply the color. Dyed materials in general show superior contrast ratios to pigmented materials due to the lack of the scattering mechanism brought about by the pigments. Figure 3 illustrates the spectral curves of the red, green and blue polyimide filters.

Brewer materials presently require patterning with resist, but developing of the resist and polyimide is done in one step. A future improvement in testing now would make the basic materials photosensitive, thereby eliminating the need for resist application. The processing of these materials is very clean, with no residue problems in equipment spin bowls or on samples. Each color material is applied, coated with resist, patterned, and hard baked in sequence so that the appropriate color is positioned over each pixel as illustrated in Figure 4.

In order to simplify manufacturing, we developed the color filter process to be integrated with the IC active matrix process itself. The color filter application is the final step of the IC circuit fabrication. This approach allows better than 1 μm alignment capability, and the filter is formed directly on the pixel electrode. The colored polyimide materials were originally developed to be used on flat surfaces such as glass coverplates. In our approach, the materials are spun directly on the circuit. Due to the variation in polyimide thickness as spun over the circuit topography, the process is basically self aligning. The as-spun polyimide is thinner over the row and column lines where coverage by the polyimide is not required, resulting in a high sidewards etch rate and therefore a self-aligning effect with respect to the pixel electrode. Misalignments of 2-3 μm have very little effect on the resultant pixel coverage. Our selected approach is simple but elegant. Figure 4 is a micrograph illustrating color filters fabricated over pixels

Compatibility of the color filter formation techniques and chemicals with the CMOS circuitry was established. For transferred displays, compatibility of the filters and the transfer process adhesives was established. Since the IC circuit has been completed (no further high temperature processing), contamination of the CMOS circuit is not a problem. The final IC passivation layer prevents interactions between the circuit and the developer chemicals.

Contamination issues related to the metals used in the dyes were investigated to assure no cross contamination of equipment. SIMS analysis was performed and proved no residual metals on wafer backsides after processing, or on the backside of transferred wafers. In addition, no detrimental effect due to the addition of color has been seen on display transistor performance. We note that the interaction between the liquid crystal and the filter material which is often a prime concern, is prevented because the Kopin transfer process effectively encapsulates the circuit and color filter between the substrate glass and the passivation layer. Compatibility could be an issue if the process is applied to non-transfer displays, although encapsulation materials are available.

A further aspect evaluated was the stability of the filters during extended exposure to visible light. For the case of organic emulsions, the lifetime must be investigated to determine if stability effects are present. In the absence of ultraviolet radiation, we expect that the emulsion-based filters will be at least as stable as the liquid crystal itself. The Dichroic filters are inherently stable long term, one of the advantages of this method. The pigmented and dyed techniques all have some issue with light stability over long time exposure to light.

In the past, it has been suggested that dyes have poorer thermal and spectral stability versus pigments under similar testing. In the case of the polyimides, the color degradation due to light exposure seems to be driven by an oxidation reaction. In the absence of oxygen, the effect is extremely reduced. In our final display package, the filter layers are encapsulated by a clear polyimide layer or nitride, adhesive and glass. Another advantage of the transfer technology was realized here. In this configuration, we exposed actual R,G,B displays in a light tower outfitted with UV filtering and partial IR filtering to reduce heating. Most ports had 500 klux exposure levels. A few.concentrator positions had 2000 klux of output exposure. Samples saw temps of 70C and 100C+ respectively. After 6 x 10^5 klux-hrs of exposure, the samples were not affected. In one particular concentrated light position which was not equipped with the IR and UV filtering, we saw degradation of the colors after 2.4 x 10^6 klux-hrs, but it is not clear whether this was due to heating, UV exposure or visible light exposure. In any case, this exposure and temperature dosage was extreme to say the least. As a comparison, Fuji-Hunt quotes their light stability numbers after 1.7 klux dosage over 360 hours leading to 6.1 x 10^3 klux-hrs of exposure. In addition, samples are kept cool to separate out the possible degradation due to IR heating. We are currently subjecting displays to more controlled reliability testing including heat, light, and humidity exposures to reconfirm the excellent results we have obtained.

3.4.3. Color Filter Commercialization

The commercialization of color filter technology is taking a straightforward route. Kopin Corporation and its partners are fabricating AMLCDs using foundry-based processes and transferred silicon techniques. Color filters be integrated into the foundry process will be used in commercial products, HMDs and other military displays.

Kopin has also developed a color sequential color display technology. Two new technologies made this possible. The first is the use of single crystal silicon display circuits which are much faster than amorphous silicon and poly-crystalline silicon circuits used by other display manufacturers. The second technology is bright blue light emitting diodes (LED's). Using these technologies, Kopin has developed displays which run at a 180 Hz frame rate in synchronism with flashing red, green and blue LED back lights. Each color data is loaded into the display array, followed by the flash of its respective color LED. Color sequential color technology preserves the full array resolution by using only 1 pixel aperture per color pixel. Thus at 640x480 monochrome display is converted to a 640x480 color display running in color sequential mode. Kopin has color sequential displays in production.

Filter technology and color sequential technologies are both available for display products. Color sequential now makes sense for display arrays up to SVGA. Larger arrays such as the 2560x2048 would require even faster x-Si circuits to run at the required 180 Hz frame rate. Filter technology might also be desirable where fast moving objects within video images might cause undesirable image artifacts on a color sequential display.

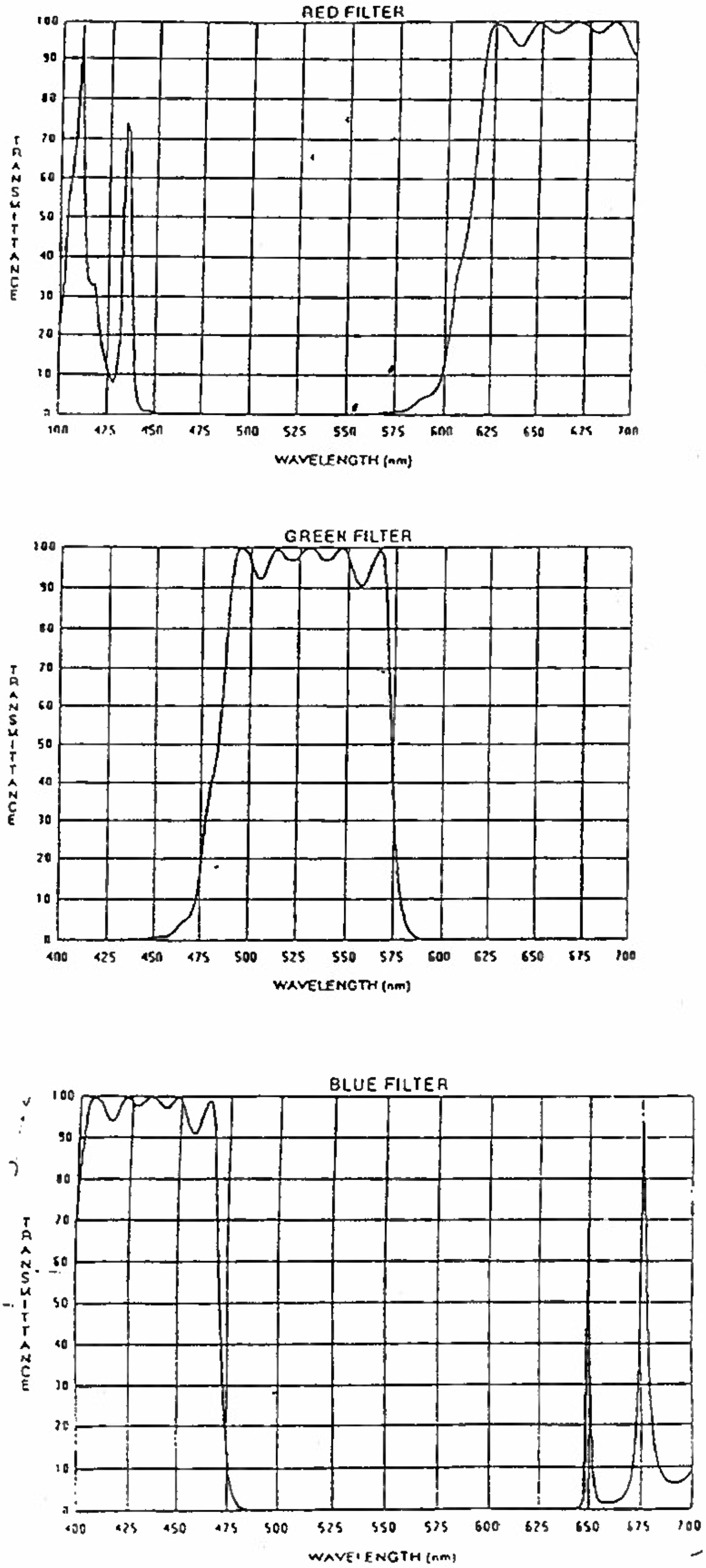


FIGURE 2. Light Transmission Curves For Red, Green and Blue Dichroic Filters

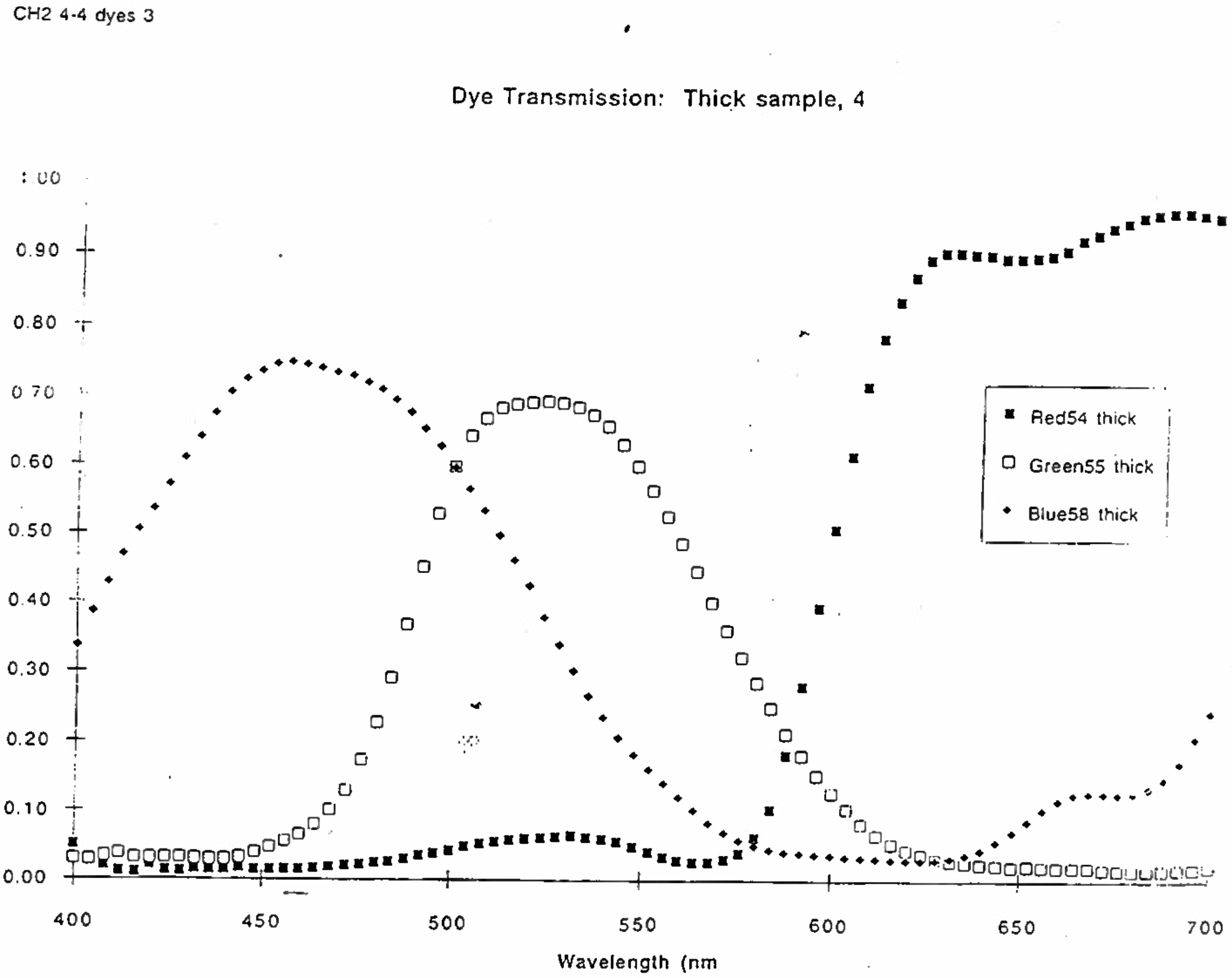


FIGURE 3: Light Transmission Curves of Polyimide Red, Green and Blue Filters.

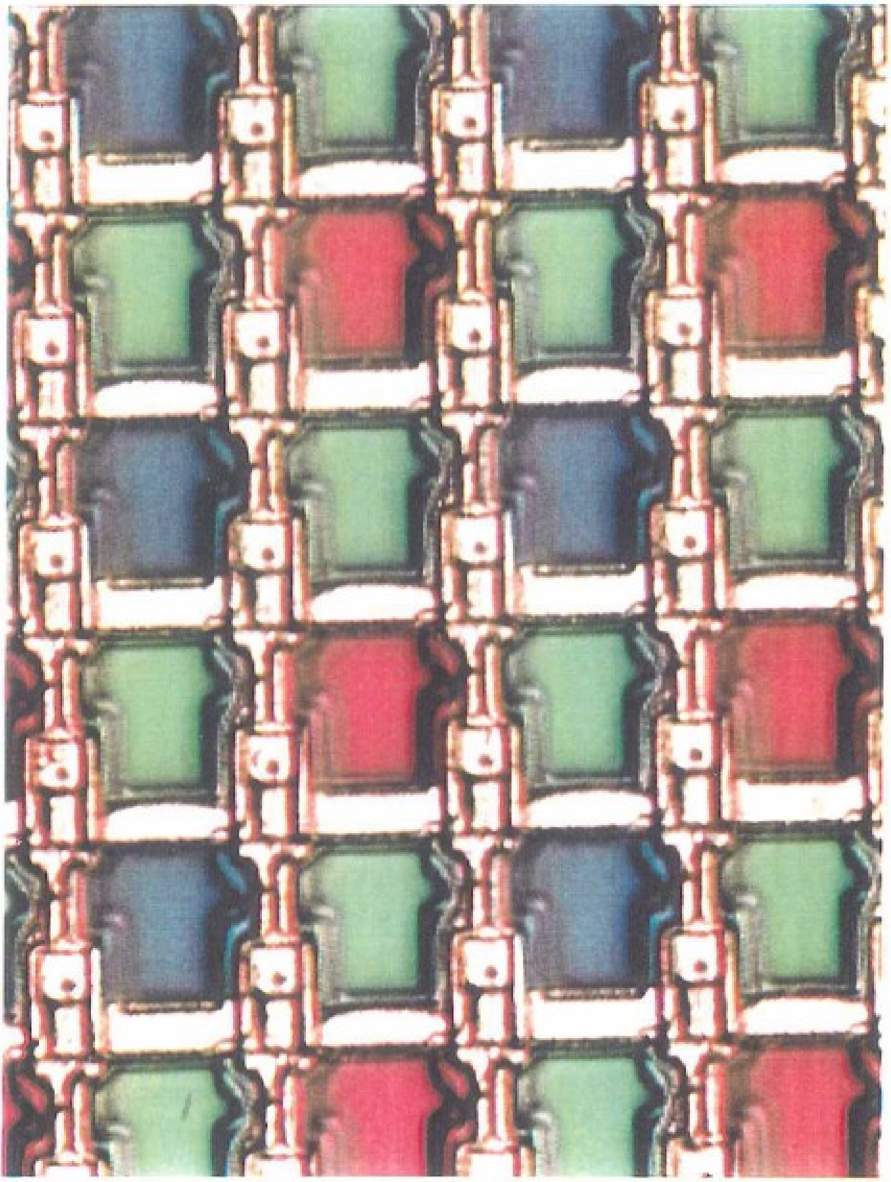


FIGURE 4: Polyimide Color Filters Fabricated Directly On To The Active Matrix Circuit, Covering the Pixel Electrodes.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-99/005 in a series of reports approved for publication.

APPENDIX A

David Sarnoff Research Center Final Report

1280 x 1024 xSi AMLCD
"SHRINK"

Final Report

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8/5/96

Table of Contents

I. Introduction

It was the object of this program to develop a 12μm x 12μm pixel, 1280 X 1024 AMLCD array using single crystal thin film transistors for applications in projection displays. During the course of this program, the Sarnoff Center was involved in the transfer of the process technology to Allied Signal and circuit re-design for this display. It was evident from measurements on larger pixel structures that the problems with small LCD pixel structures were associated with capacitive coupling between the data/select lines and the pixel electrode and with the formation of optical disclinations in the visible region of the pixel. Disclinations caused by the collapsing electric field, was a problem addressed in the 1280 X 1024 AMLCD program.

Data are input to the display via forty digital video channels. Integrated onto the display is circuitry to perform the vertical/horizontal scan functions and provide required amplification and level shifting data. The on-board data and select scanners were modified from the former 1280 x 1024 24μm design (SRI030893) to fit on the 12μm pitch. In addition to performing a re-layout for size, circuit improvements were incorporated that will be discussed later in this report.

II. Features

12μm x 12μm Pixel -----> 0.75 Inch Display Diagonal
High Spatial Resolution (1280 x 1024)
Low Voltage Digital Video (0V to 5V)
Five Volt Digital Signals
Seventy-Two Pin Interface
Built-In Scanners
Electrical Test Ports For Production Testing

APPLICATIONS

Projectors and HMD's

ABSOLUTE MAXIMUM RATINGS

|VDD - GND| +20.0V   Digital Input Voltage - GND+5.5V
|VCC - GND| +11.0V   VCC - Reference Voltage +2.2V
|VDIG - GND| +5.5V   Power Dissipation 400 mW
Storage Temperature -50 to +85 Degrees C
Operating Temperature 0 to +60 Degrees C

III. AMLCD 12 μm Process Development

The process that is used to fabricate the shielded pixel structure is shown in figure I. This process sequence requires two additional masks when compared to the unshielded process as described previously.[2] As with the standard process, the fabrication sequence begins with a formation of a thin (300nm) single crystal silicon film on an oxidized bulk silicon substrate. Implantation is used to dope the active channel regions and the silicon regions that will be used to form the storage capacitor. The silicon regions are then oxidized, contact vias are opened in the oxide and a thin polysilicon layer is deposited over the surface and implanted with boron. This thin polysilicon layer forms the shielding layer and covers the silicon electrode as well as the regions between the electrodes. In the unshielded process neither the contact via level nor the polysilicon field shield level is needed. After formation of the field shield the channel regions are oxidized and the polysilicon gate material is deposited, doped and defined. This is followed by the source/drain implantations and the deposition of the field oxide. The later steps include the opening of the field oxide and the deposition of the interconnect metallization.

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[2] J.P. Salerno et al., "Single Crystal Silicon Transmissive AMLCD, "SID Digest, Paper # 5.7, pp.63-66, 1992

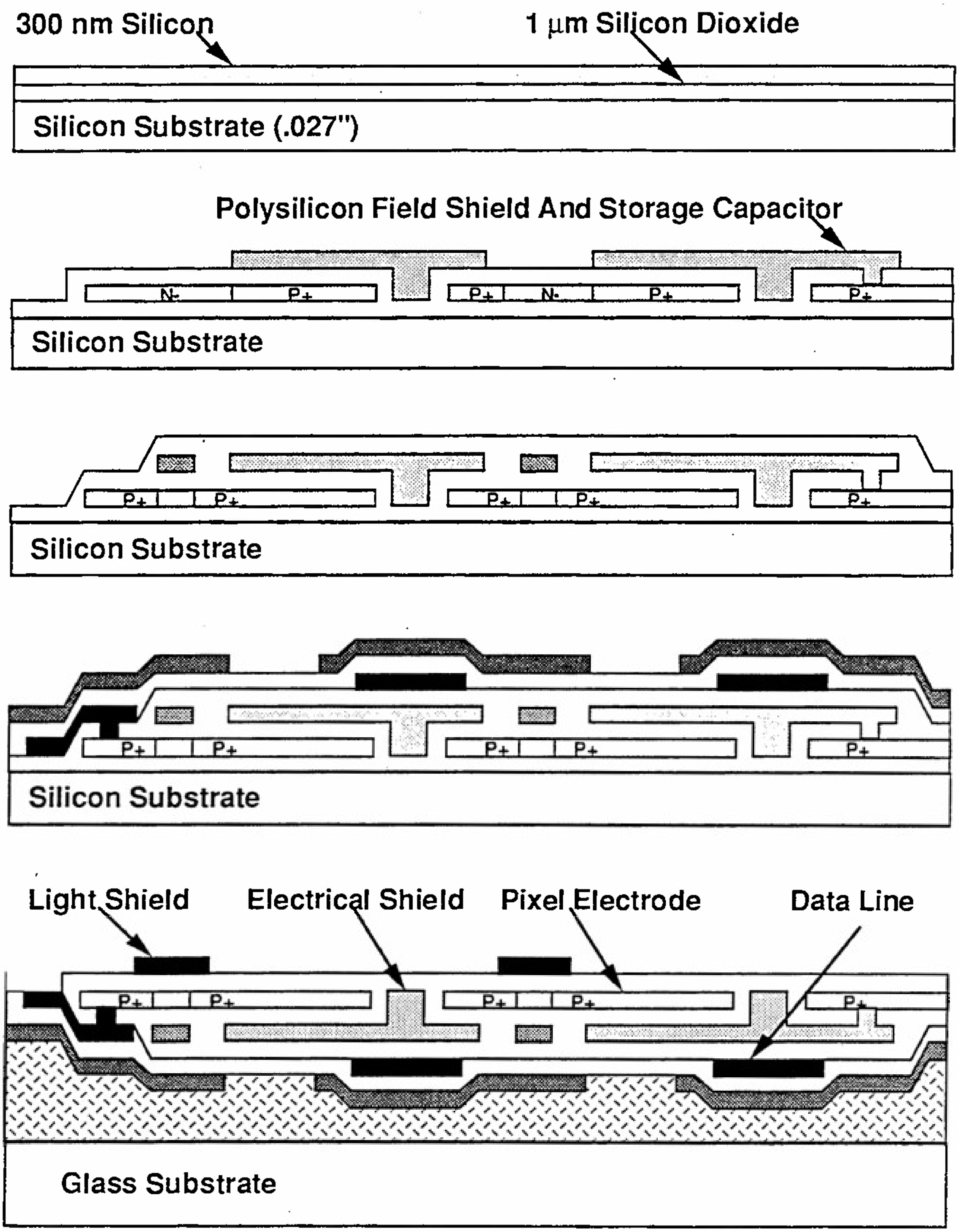

Figure I. AMLCD Shielded Process Flow

After completion of the black matrix process the wafers are shipped to Kopin for transfer. The transfer process involves the transfer of the transistor array onto a glass substrate and the removal of the handle wafer. After transfer the wafers are sent to Sarnoff for additional processing which includes the deposition and patterning of reverse light shields and the opening up of the oxide layer to permit access to the previously deposited electrical interconnect layer. This completes the array fabrication. The wafers are then sent to Kopin for liquid crystal assembly and testing.

IV. AMLCD Pixel Structure

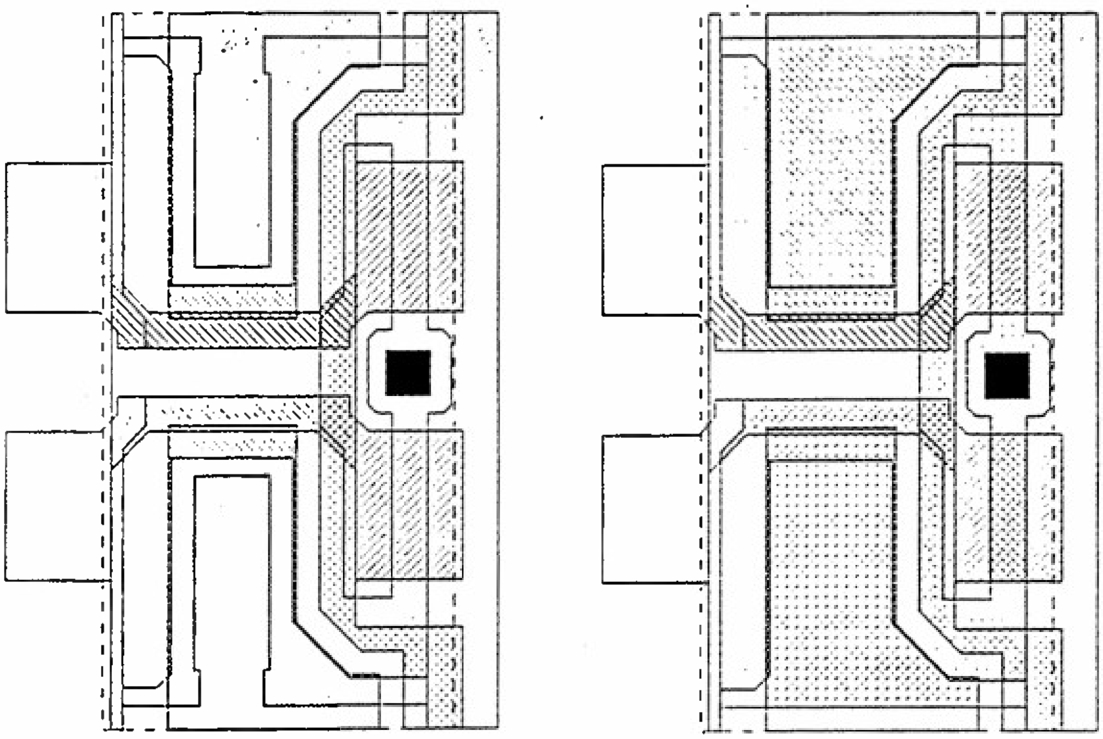

Figure II Top View of Perforated Electrode and Solid Electrode Pixel Structures

Figure II shows the 12μm x 12 μm pixel structure. In the shielded pixel structure the electrical shield covers the pixel electrode and the storage capacitor is formed between the electrode and the overlying shield which is grounded. In this structure the data line overlaps the pixel electrode so there is no open region between the data line and the electrode for unwanted light transmission.

Disclinations will form under the data line because the shield is at zero potential but this disclination will not be visible because this region is covered by the metal data line. In the vicinity of the select line a disclination would tend to form because the data line would normally be controlling the liquid crystal material but the LC material is shielded from the data line by the polysilicon gate line itself which also acts as a light shield as well as an electrical shield in this region. It is expected therefore that no disclinations will form.

To solve the problems of capacitance coupling between data lines and the electrode and also to minimize the formation of disclinations, electrical and optical shields were added to the pixel structure. The picture in figure II shows the top view of the shielded pixel structure. Adjacent pixel electrodes have been brought closely together under the data and select lines. The metal data line now completely covers the region between electrodes along the data line direction and the select line and black matrix cover the region between electrodes along the select direction. In addition, the data lines and select lines are shielded from the LC material by the shield layer and also any disclinations that form between pixel electrodes along the data line direction will be covered by the metal data line and not be visible. Disclinations that form along the select direction between electrodes will be covered by the polysilicon select line and black matrix and only be slightly visible. The opposite side of the pixel electrode along the select line direction is not covered by any light shielding layer because this area is expected to be controlled by electric fields extending from one of the two pixels.

Previous pixel performance studies indicate that the liquid crystal material can be controlled by a perforated pixel electrode. As a result of these studies two pixel options were digitized for this display, the first has a perforated pixel electrode and the second, a safer pixel, has a solid electrode. Each option has a field shield that matches the electrode type. The two structures are shown in figure II, perforated on the left and solid on the right.

V. 1280 x 1024 AMLCD Array Design

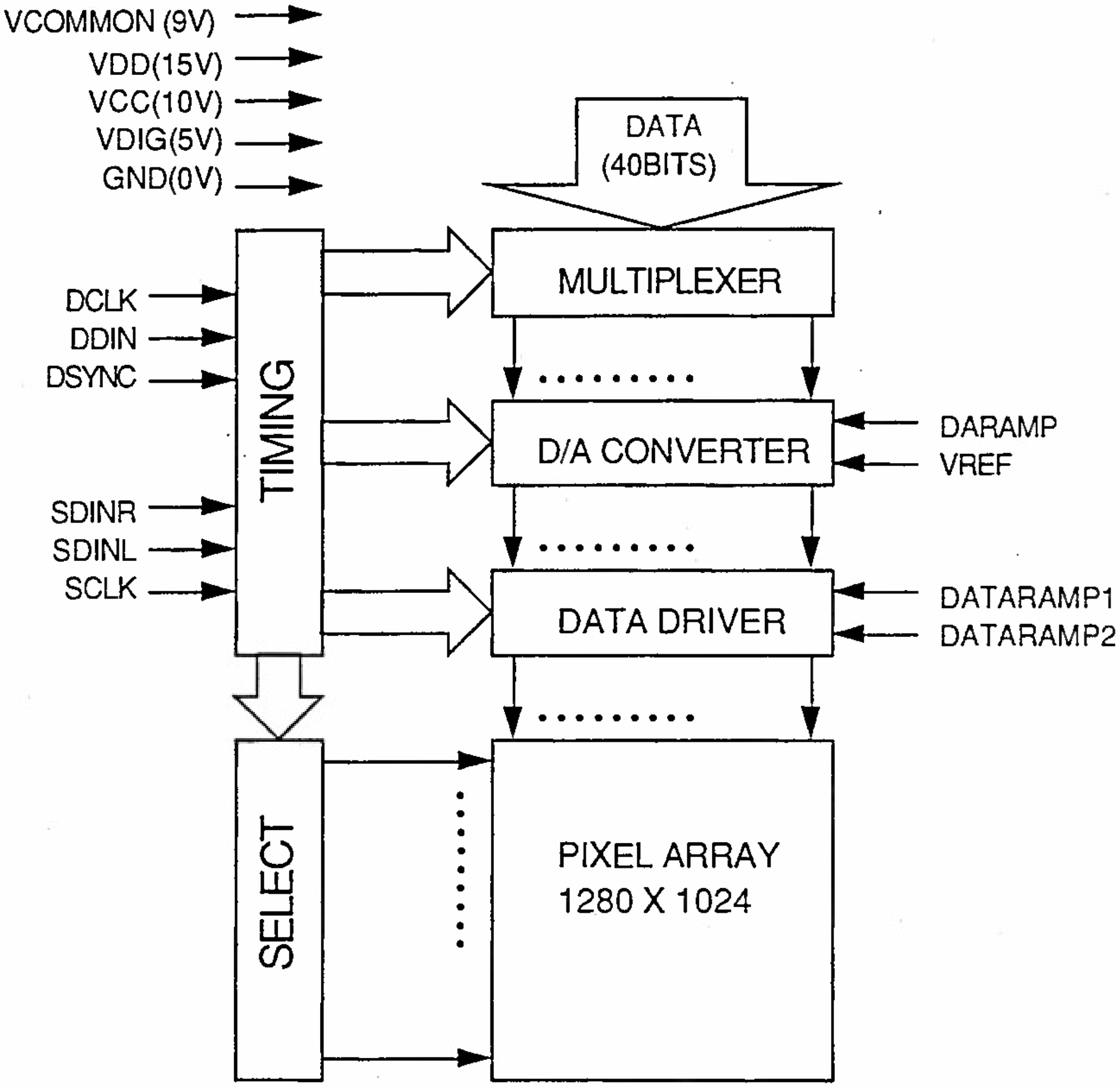

Figure III Functional Block Diagram of the 1280 X 1024 AMLCD Array

The 1280 X 1024 AMLCD array shown in figure III has several desirable design features. The Data input to the display is digital video comprised of six bits per pixel. Integrated into the display is circuitry to perform the vertical/horizontal scan functions and the required digital to analog conversion of video data. Other features of the display include a full five volt digital interface and built in data and select scanners. The expected operating power dissipation of the array is 400 mW.

Data enters the display via a forty bit wide buss connected to the input Multiplexer. When enough data to service one horizontal display line has been accumulated (7680 bits) these data are passed to the D/A Converter freeing the Multiplexer to input another line of data. A digital pipeline is thus formed between the Multiplexer and the D/A. Digital codes are converted to analog levels by the digital to analog converter and the Data Driver forces an appropriate analog voltage onto the data line. The forced voltage differs from the D/A output in a manner determined by the signals DARAMP, DATARAMP1 and DATARAMP2. Timing for the operations just described is provided by the Timing Block which also controls vertical scanning of the display by supplying the necessary signals to the Select Scanner.

Six timing inputs, DCLK, DDIN, DSYNC SDINR, and SDINL, properly sync the horizontal and vertical scanning of the display. Three power supplies with nominal values of 5V, 10V, and 15V provide the operating power. The D/A Converter reference voltage, Vref, is typically -2V relative to VCC. DARAMP is a linear ramp covering the span between VREF and VCC. DATARAMP1 and DATARAMP2 are linear ramps with settable endpoints nominally in the range of 3V to 15V. A potential is applied to the common plane through VCOMMON. Details concerning interfacing the array to external circuitry are discussed in the Interface Specifications Report.

In order to check the functionality of the array before Liquid Crystal assembly a number of test pins have been added to the array as shown in figure IV. One external pin has been added to the end of each select scanner (left and fight) for rapid testing of the select scanners. An input pulse is clocked through 1024 stages of each select scanner and should appear on the external select output pins after the 1024th clock pulse. Checks should be made at the 1023th and 1025th pulses to insure that the signal has not been distorted by the select shift registers. In addition, internal pads have been incorporated into the display at each end of the select lines for diagnostic purposes. These pads are used to check out the design and also to find and analyze internal select failure locations. In the early stages of the program photomicrographs are taken of each failure location and analyzed to insure that the failure locations do not represent design or layout errors or mask defects. In production it is only necessary to check the external select output pins to insure that the select scanners are functioning properly. Since the select lines are driven from both ends (select left and select right), it is unlikely that an open in a select line will cause a line failure and, therefore, no test circuitry has been added to the display to check for select line opens.

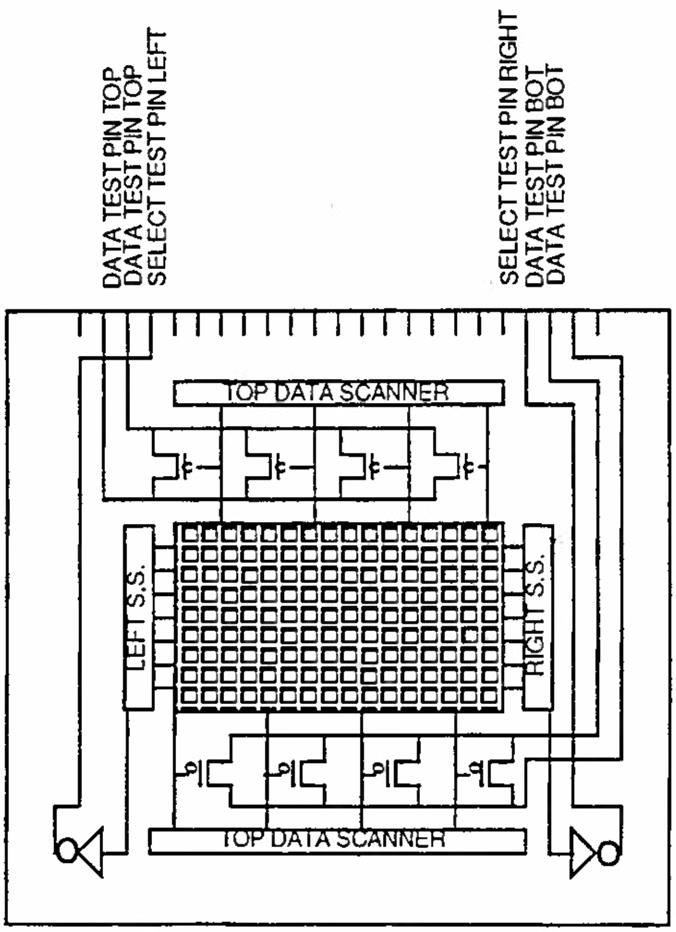

Figure IV. Diagram of External Test Pins Designed into the AMLCD Array

In order to check for proper functionality of the data scanners special switch transistors have been added to the ends of each data line opposite to the connection to its respective scanner. Again a single pulse is clocked through the data scanners and if the pulse is present at the opposite end of the data line the special switch transistor will turn on connecting the drain of the transistor to its source. Unlike the select lines, the data lines are only driven from one end and, therefore, it is necessary to check both the functionality of the data scanners and the continuity of the data lines. Internal pads are also added to the data lines in order to check out the data scanner functionality and, as with the select scanner, to check for design/layout errors and mask defects. The switch transistor technique, while useful for detecting non functioning scanner stages, will not detect shorted scanner stages and, therefore, additional testing is necessary to insure that the scanners are designed and laid out properly.

Preliminary testing of the preceding display design (1280 x 1024 AMLCD with 24μm pixels) showed a node in one of the timing circuits that was susceptible to PFETS with higher than expected leakage current. This node would tend to "droop" at high Vdd levels. The fix for this circuit was to incorporate a small feedback loop to guarantee proper operation. Other improvements include double gating of all PFETS to improve reverse breakdown characteristics, improved input protection circuitry, longer input lead length and improved buss channeling.

PIN ASSIGNMENTS

Pin #	Name	Input	Output	Function
1	VCOMMON	X		Common Plane Voltage
2	TEST		X	Top Data Scanner Test
3	TEST		X	Top Data Scanner Test
4	TEST		X	Select Scanner Test
5-14	DATA	X		Odd Data
15	GND	X		Ground
16	DCLK	X		Data Clock
17	DDIN	X		Horizontal Scan Sync
18	DATARAMP2	X		Odd Drive Ramp
19	SDINR	X		Right Vertical Scan Sync
20	SCLK	X		Vertical Scan Clock
21	VDD	X		+15V Supply
22	DATARAMP1	X		Even Drive Ramp
23	DCLK	X		Data Clock
24	VCC			+10V Supply
25-44	DATA	X		Even Data
45	DSYNC	X		Horizontal Timing
46	GND	X		Ground
47	VDIG	X		+5V Supply
48	DARAMP	X		Horizontal Timing
49	DATARAMP1	X		Even Drive Ramp
50	VDD	X		+15V Supply
51	SCLK	X		Vertical Scan Clock
52	SDINL	X		Left Vertical Scan Sync
53	DATARAMP2	X		Odd Drive Ramp
54	DARAMP	X		Horizontal Timing
55	VREF	X		+8V Supply
56	VCC	X		+10V Supply
57	VDIG	X		+5V Supply
58	DSYNC	X		Horizontal Timing
59-68	DATA	X		Odd Data
69	TEST		X	Select Scanner Test
70	TEST		X	Bottom Data Scanner Test
71	TEST		X	Bottom Data Scanner Test
72	VCOMMON	X		Common Plane Voltage

NOTES:

Pins 2 & 71 are data scanner test outputs and should be tied to VCOMMON during normal operation.

Pins 4 & 69 are select scanner test outputs and should be floating during normal operation.

There are a total of forty DATA pins.

Each DATA pin services 32 columns of pixels.

The STEST pins can be used to test the select scanner circuits. These pins are connected to the output of a CMOS inverter which are turned on by the last select scanner. By monitoring the STEST pin a voltage will be generated that toggles between GND and VDD when the last select scanner stage is turned on. This will indicate that the select scanner is working. The output waveform will have a 1/1024 duty cycle.

The DTEST pins can be used to test the data scanner circuits. These pins are connected to the drains of a series of PMOS transistors which are turned on by the data scanners. The source and drain sides of these PMOS transistors are tied to pins 2, 3, 70 and 71 and the gate is tied to the output of the data scanner (DATARAMP). By placing a voltage on the source side and a resistor from the drain side to ground, a voltage will be generated across the resistor when the data scanner turns on the test transistor. To check each data scanner individually, all the columns must be passed data to drive the pixel to white. The column being tested must be passed data which will turn the pixel black. When the DATARAMP reaches the minimum voltage, the PMOS transistor will turn on and a voltage will be generated across the test resistor to indicate the data scanner is operational.

VI. 1280 X 1024 AMLCD Array Testing

No testing of actual 1280 X 1024 AMLCD arrays was done at the Sarnoff Center. Preliminary results from the testing being conducted at Kopin Corp. indicate that the scanner circuits are operating as designed.

APPENDIX B

Honeywell PTC Final Report

Primary Color Metal Halide Lamp

Final Report

December 15, 1995

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and
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Contract Number SC921014

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Table of Contents

List of Figures

1.0 Introduction

In a previous program, Miniature Color Display (MCD), funded by Armstrong Labs, a 300 watt broad band Xenon arc lamp (Xe lamp) was converted to a trichrominance spectral power distribution of broad red, green and blue peaks, by filtering the Xe lamp with multi layer dielectric notch filters. The filtered Xenon lamp (F-Xe lamp) was used to illuminate a twisted nematic subtractive color light valve (TNSCLV) which incorporated dichroic dye type polarizers, to modulate color. A 65 % reduction in luminance of the Xe lamp resulted due to the filtering. The lamp filtering was necessary to produce a broad color gamut.

In this Natick funded contract "Primary Color Metal Halide Lamp" (PCMHL), a PCMHL was developed at ILC, for the purpose of broadening color gamut, and increasing luminance efficiency, when the PCMHL is used to illuminate a TNSCLV. The goal for the PCL was to emit a trichrominance spectral power distribution of isolated, narrow band red, green and blue color peaks. This TNSCLV, designed for PCMHL illumination, uses notch polarizers, rather than dichroic dye polarizers, to modulate the red, green and blue peaks of the PCMHL, to render a substantially broader color gamut than was achieved for the MCD. The broader color gamut is due to the enhanced spectral power distribution of the prime color lamp (narrower primary color peaks) and the superior contrast and sharper polarization bands of the notch polarizers. The PCL's were designed to operate (produce peak HMD luminance) at 105 watts, or 1/3 the power of the Xe lamp (1/3 the power because the PCMHL would produce the trichrominance spectral power distribution without filtering).

One of the 105 watt PCMHLs developed at ILC is capable of exceeding the luminance of the filtered 300 watt Xenon arc lamp (MCD lamp). The condition for this 300 % increase in luminance efficiency, is that the coupling efficiency of the PCMHL into the fiber optic bundle (FOB) will be improved. A broad color gamut, substantially exceeding the area of the MCD color gamut, was achieved with this lamp.

2.0 Results

Substantially broader color gamuts than the MCD, with a 300 % increase in luminance efficiency will be obtained with ILC's prime color metal halide lamp 89 used to illuminate our subtractive color light valves. The condition for the 300 % increase in luminance efficiency, is that coupling efficiency of the PCMHL /reflector combination into the fiber optic bundle (FOB) is improved to 45 %. A 105 watt metal halide lamp will successfully replace the filter optimized 300 watt Xenon arc lamp with no loss of luminance.

These performance improvements in color gamut and luminance will greatly benefit helmet mounted display programs such as HMS plus, as well as the projection display programs, where subtractive color light valves can be utilized.

2.1 Technical Liaison

Honeywell consulted with ILC to develop a prime color metal halide lamp ideal for illuminating a twisted nematic subtractive color light valve incorporating notch polarizers. The original goal for the lamp spectra was to produce red 625 nm, green 524 nm, and blue 475 nm with the appropriate metal halides. Another goal for the lamp was little or no inter-peak luminance so that narrow band notch polarizers could be utilized to produce a broad color gamut, with two to three times higher transmission than was obtained with dichroic dye polarizers . The higher transmission of the light valve coupled with the three time improvement of the PCL luminance efficiency predicted a net 600 % to 900 % increase in system luminance efficiency. Attempts to utilize calcium and strontium were unsuccessful for red and blue, however lithium (610 nm and 675 nm red peaks), and Indium (450 nm blue peak) were blended successfully with thallium (535 nm green peak). The 610 nm red is acceptable because photopic response and luminance to peak height ratio is greater than at 625 nm. 536 nm green also has higher photopic response than 524 nm. green, and is also acceptable. Although 450 nm blue is blue-violet, substantially broad color gamuts were achieved, to produce good human factors blues within the color triangle. Lamps were constructed with these metal halides, with the fill gas Xenon, and Mercury. The mercury was utilized in an attempt to lower the inter-peak luminance.

The prime color lamps inter-peak luminance (a luminance continuum between the peaks), was not low enough to achieve a broad color gamut with narrow band notch polarizers. However in a back up approach the prime color lamps spectral power distribution had low enough inter-peak luminance, and narrow color peaks, to result in substantially broader color gamut's using light valves incorporating broad band notch polarizers. More than a 300 percent increase in display system luminance efficiency over the MCD can be obtained by improving the lamps coupling efficiency to the FOB. The lamps tested all had an extraneous 590 nm yellow peak, probably due to an impurity. Lamp 89 had an additional yellow peak at 578 nm due to the mercury response. Minor filtering of the PCMHLs with a notch filter, to remove only the yellow spectral area between 570 nm and 600 nm was necessary to produce substantially broader color gamuts than the MCD. Only 35 % of the PCMHLs luminance is lost due to filtering . The increase in luminance efficiency of the filtered PCMHL over the filtered Xe lamp, due to less filtering of the PCMHL, is about 200 %. An additional benefit other than the prime color spectra, is that the unfiltered PCMHL lamp can have higher luminance efficiency than the unfiltered Xenon arc lamp. Therefore, the 300 % reduction in power of the filtered PCMHL 89 (105 watts) to achieve the same luminance as the F-Xe lamp (300 watts) is achievable due to the improved luminance efficiency of the unfiltered PCMHL compared to the unfiltered Xe lamp, and by concentrating most of the lamps luminance in narrow red, green. and blue color peaks, requiring less filtering for color gamut optimization with the broad band notch polarizers. The gain in light valve transmission due to the broad band notch polarizers is only 20 % compared to the dichroic polarizers used with the MCD. The real benefit of the broadband notch polarizers is the higher contrast and color gamut achievable with less required filtering of the PCMHL, with greater than a 300 % increase in system luminance efficiency (display lumens per watt).

2.2 Lamp Test and Evaluation

Six prime color lamps were delivered from ILC for evaluation.

2.2.1 Spectral Power Distribution

The lamps spectral power distribution is shown in Figure 1 a, b, c, d, e, and f. Lamp numbers 42, 69, 71, 74 and 76 are 105 watt Xenon metal halide lamps, and lamp 89 is a 105 watt Mercury metal halide lamp doped with the same metal halides. The lamp/reflector combination was not optimized for collection efficiency into the fiber optic bundle so a meaningful comparison for luminance efficiency is not possible from the measured spectral power distributions. Therefore, the spectral power distributions are normalized by assigning a value of 1 to the magnitude of the dominant peak of each lamp. The lamps can be easily compared for prime color peak ratios and inter peak luminance level (fill-gas continuum.). Lamp 89 (the mercury metal halide lamp) has the lowest inter-peak luminance. With minimal filtering with a notch filter to remove yellow, the prime color lamps produce broad color gamuts, with broadband notch polarizers. Lamp 69 gives the most saturated blue due to the stronger blue peak to red and green peaks ratio. Lamp 89 demonstrated the highest luminance. None of the lamps have low enough inter peak luminance to permit the use of narrow band notch polarizers in achieving a broad color gamut.

2.2.2 Luminance Efficiency Comparison

A separate luminance efficiency comparison of the lamps was conducted. The raw luminance (raw lumens) of each lamp reflector combination was measured without the fiber optic bundle (FOB) by removing the lamp from the housing and shinning the lamp reflector combination directly into an integrating reflectance sphere. Next the FOB luminance was measured for each lamp by mounting the FOB into the lamp housing with lamp, and shinning the FOB output luminance (FOB lumens) into the integrating reflectance sphere. By measuring the FOB transmission (50%) the collection efficiency (% focused) of each lamp into the 1/4 inch FOB was calculated. A comparison of luminance efficiency and potential luminance efficiency by optimizing collection efficiency is given in Figure 2 vs. the luminance of the 300 watt filtered MCD lamp . The comparison shows that the FOB luminance of color gamut optimized (yellow filtered out with notch filter) 105 watt prime color lamp 89, with a 45 % coupling efficiency into the FOB, will exceed the luminance of the filtered 300 watt Xenon arc lamp used for the MCD. The current unfiltered FOB luminance of lamp 89 with only 19 % collection efficiency is 2/3 of the MCD filtered 300 watt xenon lamp.

ILC believes that the yellow peak in the Xenon metal halide lamps is due to an impurity and can be eliminated by eliminating the impurity. The modeled effect of eliminating the impurity with lamp 69 (broadest color gamut) and lamp 76 (highest luminance of the Xenon metal halide lamps) is to reduce the lamps luminance only 6 %, compared to a 35 % luminance reduction due to filtering the yellow spectral area with the notch filter. The modeled spectra of lamp 69 and 76 with yellow causing impurity removed is shown in Figure 3.

2.3 Color Gamut Evaluation with Broad Band Notch Polarizers

Color gamuts for the lamps were investigated with broad band notch polarizer stack 2 which provided the highest transmission of the notch polarizer stacks developed under the Notch Polarizer contract. A single 570nm-600nm notch filter optimizes the lamps so that stack 2 efficiently polarizes the remaining spectral area. The color gamuts achieved are much broader than the broadest color gamut (stack four gamut) achieved with the filtered 300 watt Xenon arc lamp under the Notch polarizer contract. The PCMHLs yield substantially deeper blue and green primaries, and deeper violets and magentas defined by the line between blue and red.

All of the color gamuts and spectral power distributions of the stack 2 colors presented for the prime color lamps were precisely extrapolated from the measured spectral power distribution of the lamp and the measured color transmission spectra of stack 2. This technique has proven precise when compared with actual measured data.

The best lamps for color gamut optimization with broad band notch polarizers are lamps 69 and 89 and 76. Lamp 89 (Mercury metal halide) has the highest luminance. Lamp 76 is included because it has the highest luminance of the Xenon metal halide lamps.

A yellow peak is present in all of the prime color lamps. When the yellow spectral area is removed with a 570nm-600nm notch filter, the color gamut is substantially broadened. Lamp 89 has additional peaks at 436 nm blue, 546 nm green and 579 nm yellow, however lamp 89 as well as lamps 69 and 76 produce very broad color gamuts when only the yellow spectral area is filtered out with a notch filter. The 436 nm and 546 nm peaks in lamp 89 are minor in size and are usable having only a very minor effect on the color gamut. The effect of filtering lamps 69, and 89 is shown in Figure 4 and Figure 5. A color gamut comparison of the lamps 69 and 89 and the 300 watt Xenon arc lamp when illuminating broad band notch polarizer stack 2 is shown in Figure 6. The color gumut due to the Xenon lamp, shown in Figure 6, was the broadest color gamut achieved during the notch polarizer contract. The filter was considered a part of the stack. Stack 2 including the filter was called stack 4 under the notch polarizer contract. Stack 2 is optimum for the filter optimized lamps efficiently polarizing all of the spectral area. The color gamuts of the of the prime color lamps 69, 76, and 89 /broad band notch polarizer stack 2 is compared to the MCD using the filtered (two filters) 300 watt Xenon arc lamp in Figure 7. The spectral power distribution of the light valve colors RGB, and CMY, precisely extrapolated and used to calculate the chromaticities of the color gamuts, are shown in Figures 8a, 8b (lamp 69) 9a, 9b (lamp 76), and 10a, 10b (lamp 89).

The estimated effect of eliminating the yellow causing impurity in prime color lamps 69 and 76 on color gamut with notch polarizer stack 2 is shown in Figure 11.

3.0 Conclusion

The current generation of prime color lamps from ILC produce color gamuts exceeding the MCD in breadth and saturation, when used to back-light twisted nematic subtractive color light valves incorporating broad band notch polarizers.

105 watt lamp 89 with only 19 % collection efficiency has twice the luminance efficiency through a 1/4 inch FOB as the filtered 300 watt broad band Xenon arc MCD lamp through a 3/8 inch bundle or two thirds the luminance. Improvement in collection efficiency to 45% into the 1/4 inch FOB will enable the luminance of color gamut optimized filtered 105 watt lamp F-89 to equal the filter optimized 300 watt MCD lamp (F-Xe) luminance. The current FOB collection efficiency (19 %) of filtered lamp F-89 (1/4 inch FOB) produces 30 % more luminance efficiency (L/watt) than the 300 watt filtered MCD lamp (3/8 inch FOB with 2.25 X collection area of 1/4 inch FOB).

4.0 Deliverables

Six 105 watt prime color lamps to be delivered to Kopin.

5.0 Future Tasks

5.1 Optimize Reflector Resign and Coupling Efficiency into the 1/4 Inch Fiber Optic Bundle

The prime color lamps received and measured have low collection efficiencies as observed in Figure 2. Neither the reflectors, nor the positioning of the lamps into the reflectors were optimized. The lamp alignment fixture was malfunctioning when the lamps were positioned into the reflectors. The reflectors did not have the correctly designed geometry for small spot focusing. The reflectors were ceramic and have a rough surface which scatters the focused spot compared to glass. The lamp arc length was not optimized for focusing.

ILC has designed and received the corrected geometry glass reflectors and will have them metallic coated by Balzers. ILC is optimizing the arc length for focusing, and can correct the lamp positioning into the reflector. With these techniques they have obtained a collection efficiency of 60 % in the past, and predict high collection efficiencies of 50% plus for future reflectorized prime color lamps focused to a 5 mm spot (1/4 inch FOB).

5.2 Eliminate Impurity Causing Yellow Peak

ILC has strong evidence that the yellow peak in the Xenon filled prime color metal halide lamps is due to an impurity in the metal halide mixtures and can be eliminated by isolating and removing the impurity.

This can result in higher luminance than achieved via filtering. Lamp 76, for example, with yellow impurity eliminated, rather than filtering yellow spectral area produces 442 FOB lumens by modeling, which is 1.4 X MCD lamp FOB lumens at 1/3 the power.

An example of color gamut was shown in Figure 11. The color gamut is not nearly as broad as via filtering, and the merit of the higher luminance vs. the color gamut needs to be determined depending on application.

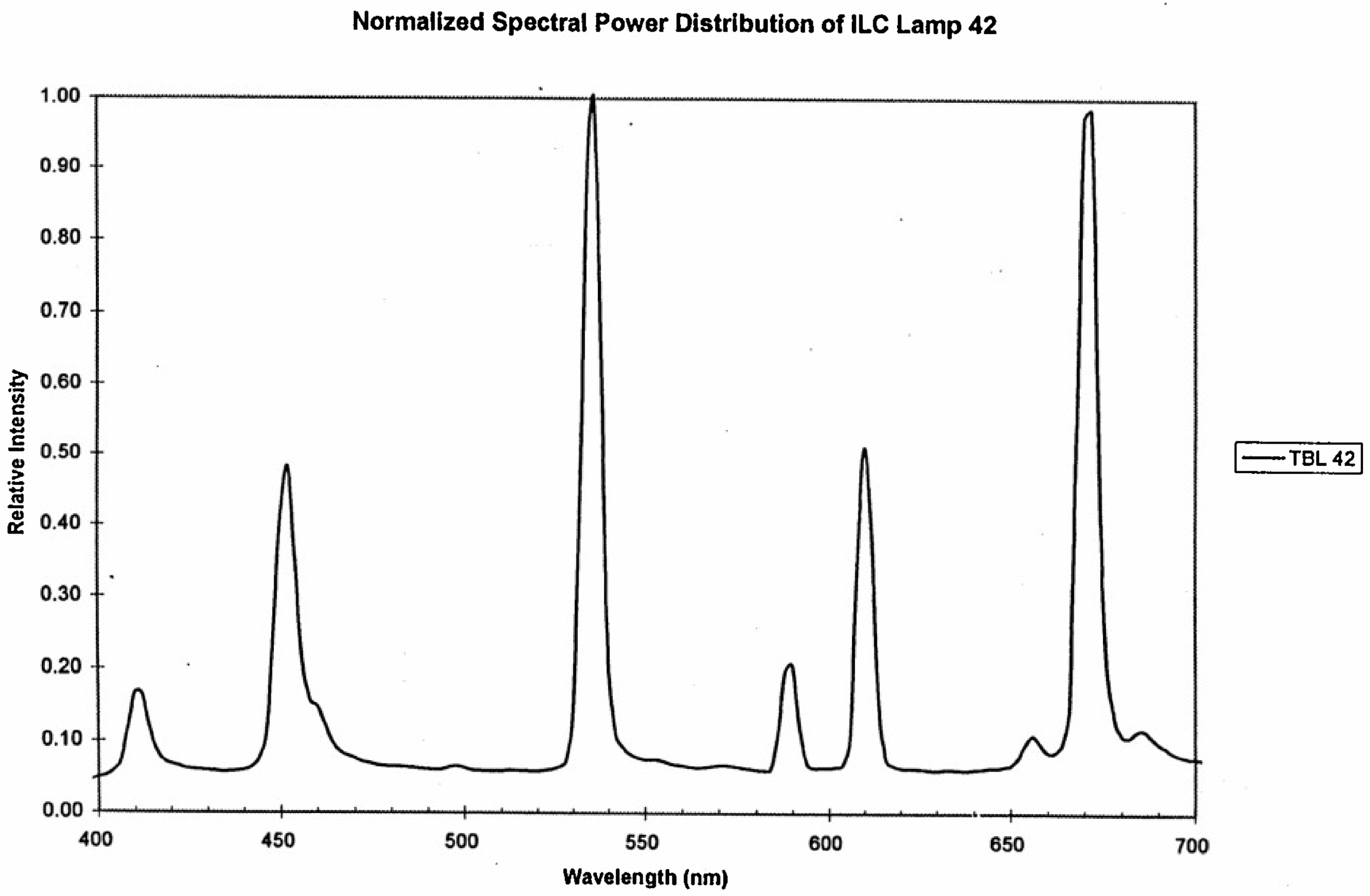
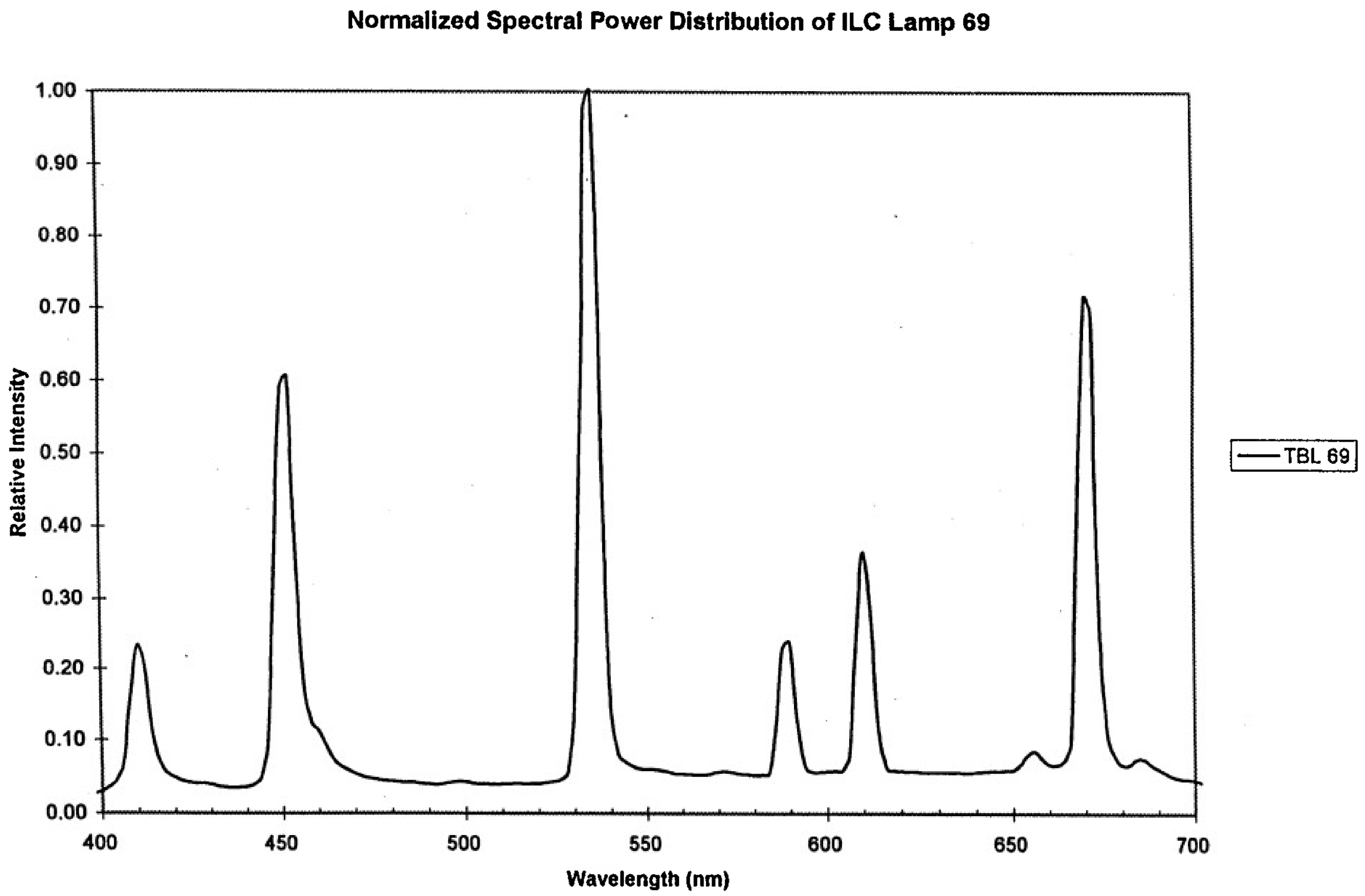

Normalized Spectral Power Distribution of ILC Lamp 42
Relative Intensity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
400
450
500
550
600
650
700
Wavelength (nm)
TBL 42

Fig. 1a


Normalized Spectral Power Distribution of ILC Lamp 69
Relative Intensity
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0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
400
450
500
550
600
650
700
Wavelength (nm)
TBL 69

Fig. 1b

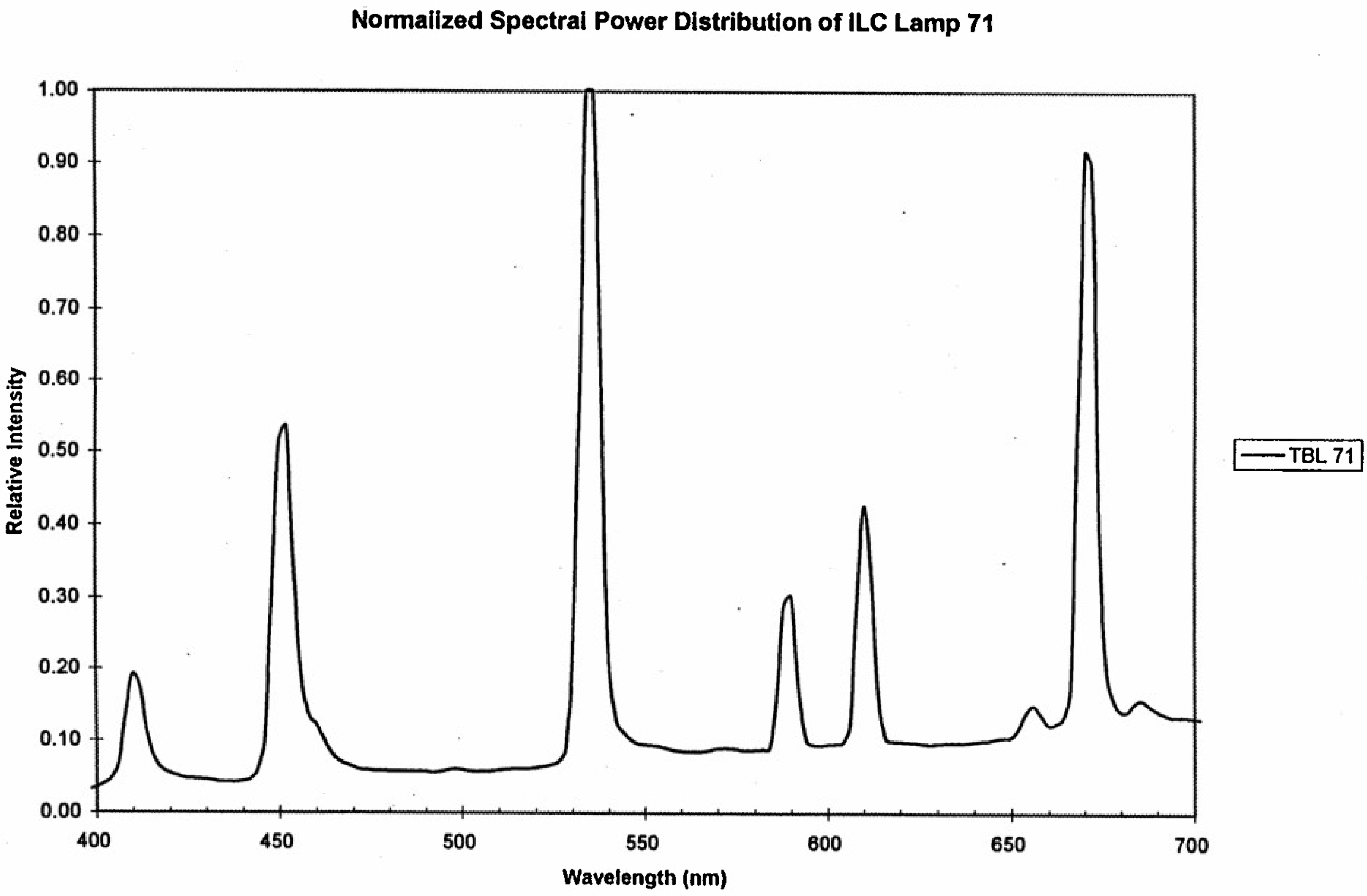

Normalized Spectral Power Distribution of ILC Lamp 71
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Relative Intensity
400
450
500
550
600
650
700
Wavelength (nm)
TBL 71

Fig. 1c

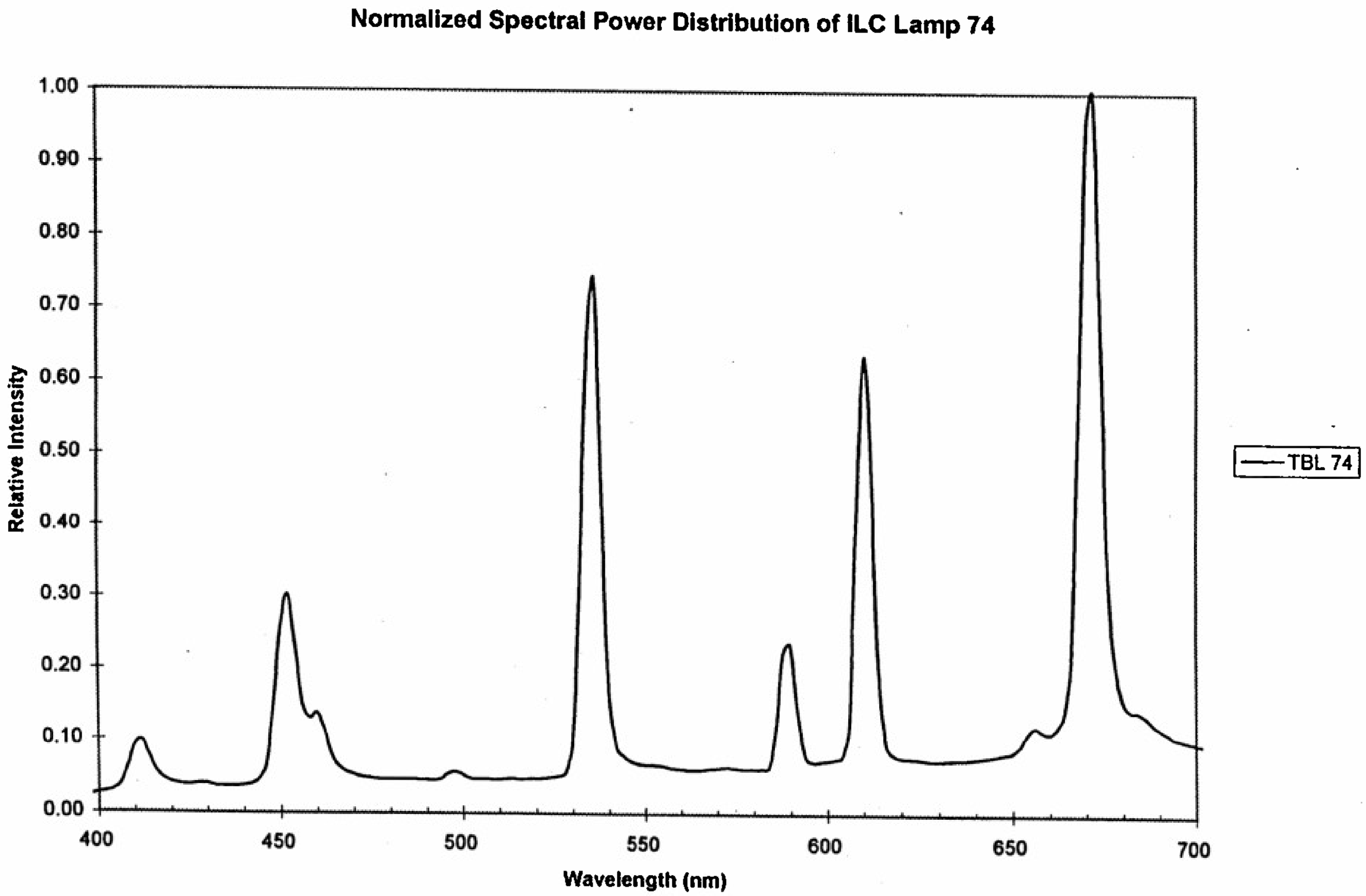
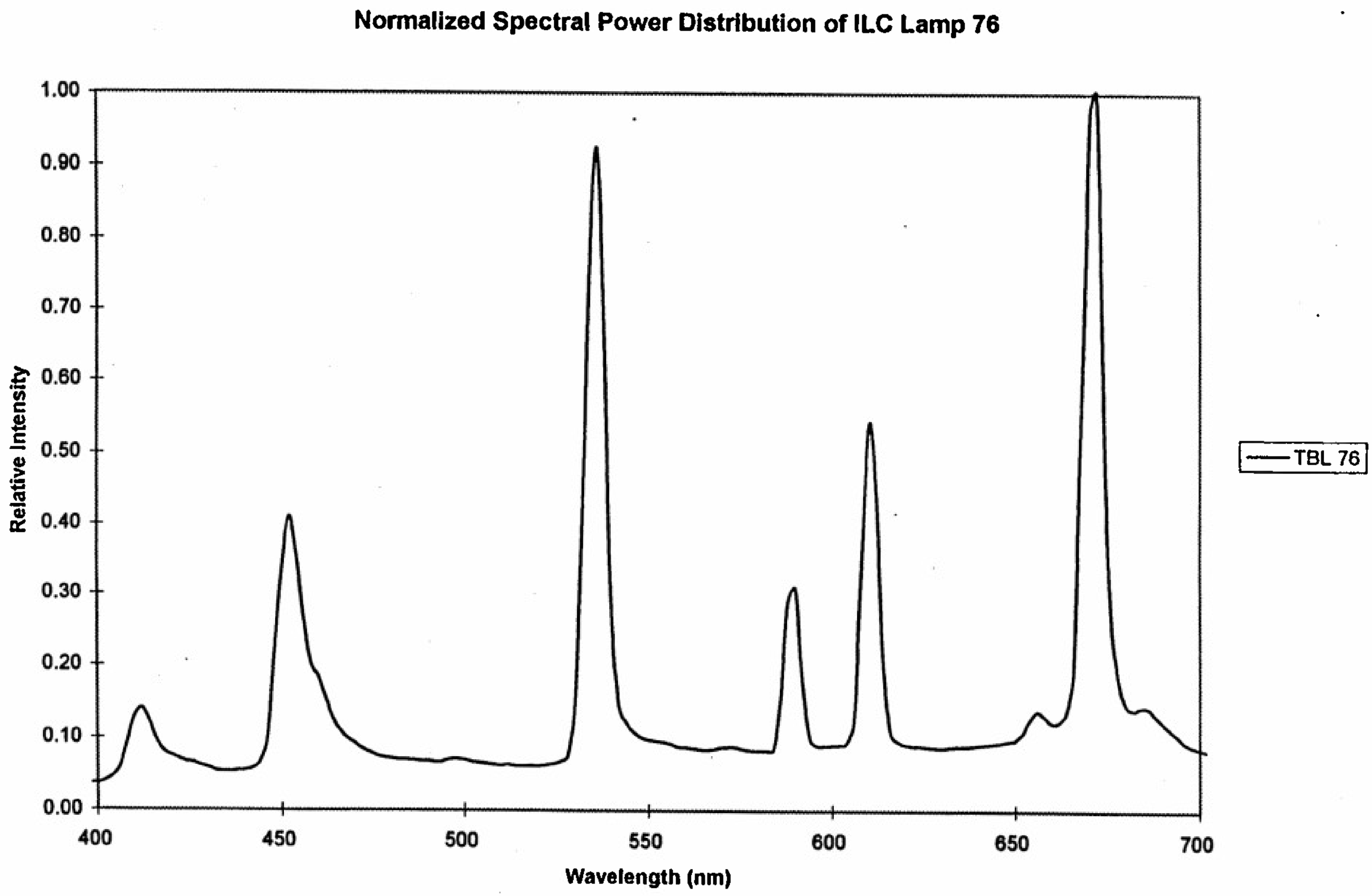

Normalized Spectral Power Distribution of ILC Lamp 74
Relative Intensity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
400
450
500
550
600
650
700
Wavelength (nm)
TBL 74

Fig. 1d


Normalized Spectral Power Distribution of ILC Lamp 76
Relative Intensity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
400
450
500
550
600
650
700
Wavelength (nm)
TBL 76

14 Fig. 1e

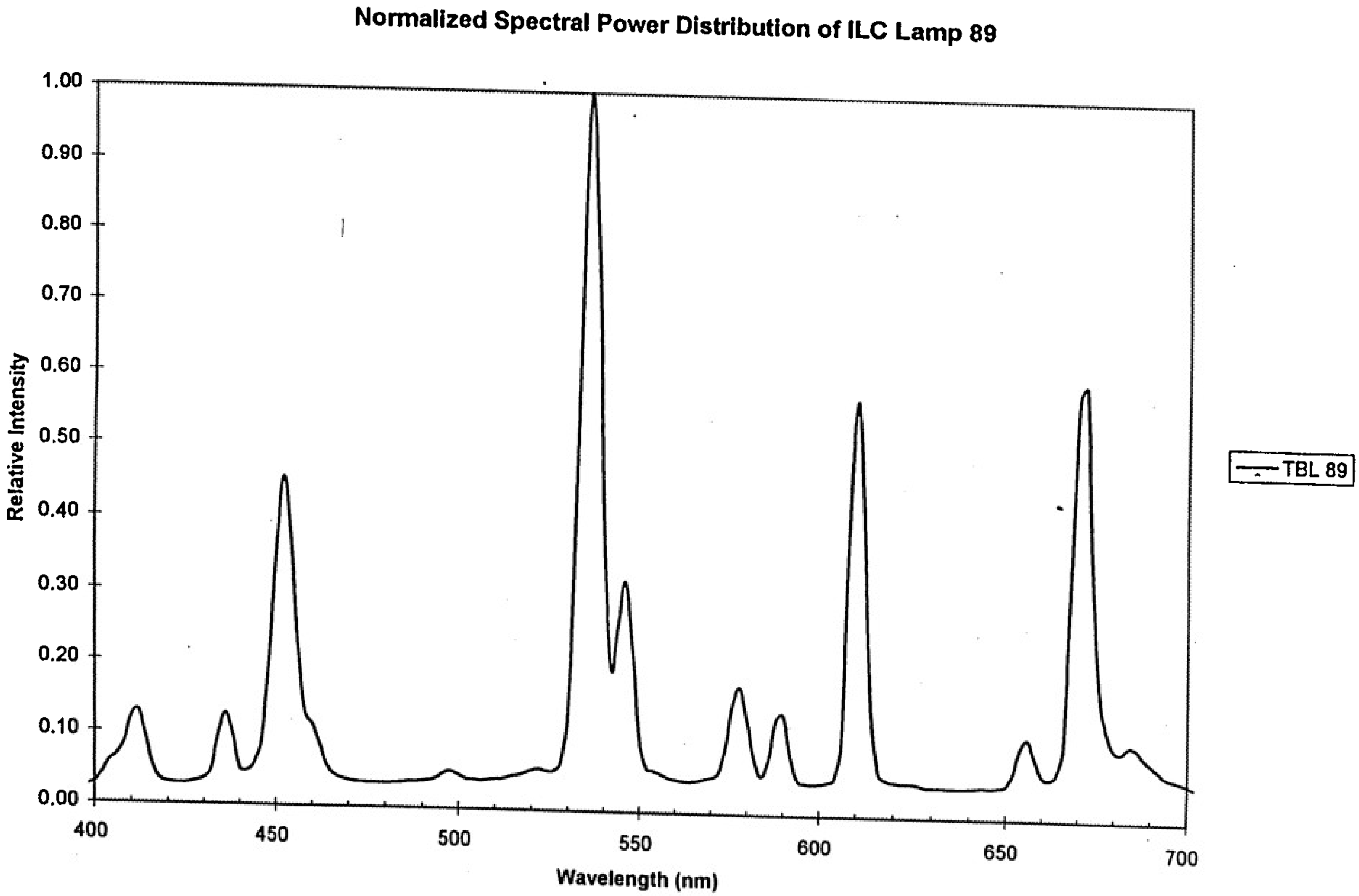

Normalized Spectral Power Distribution of ILC Lamp 89
Relative Intensity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
400
450
500
550
600
650
700
Wavelength (nm)
TBL 89

Fig. 1f

Luminance Comparison of 105 watt primary color metal halide lamps vs. 300 watt broadband Xenon arc lamp.

Lamp #		raw L	L FOB	T FOB	% CE	FOB L/watt	FOB FLTD L/watt	FOB FLTD L	FOB FLTD L at 50% CE	FOB L yellow impurity removed no filtering at 50% CE
42	105 watt	950	35	0.5	7.4	0.34	0.2	22	149	239
69	105 watt	950	52		11	0.50	0.3	33	148	237
71	105 watt	1420	86		12	0.82	0.5	51	213	355
74	105 watt	585	20		6.8	0.19	0.1	12	85	146
76	105 watt	1890	72		7.6	0.68	0.4	43	283	470
*89	105 watt	2170	210		19	2.00	1.3	137	349	
Xenon arc	300 watt	hot mirror	535			1.8	0.6	186		
Xenon arc	300 watt	cold mirror	900	MCD		3	1.1	315		

* 89 is a Mercury metal halide lamp
and only prime color lamp with elliptical
reflector

no reflector/lamp combinations are optimized
for collection efficiency.

Key
L = lumens
T = transmittance
CE = Collection Efficiency to FOB
FLTD=lamp filtered for optimum color gamut
FOB = Fiber optic bundle output

Fig. 2. Luminance comparison of six primary color metal halide lamps from ILC, showing raw lumens, FOB output lumens (LFOB), FOB transmittance, collection efficiency to FOB, FOB output luminance efficiency (FOB L/watt), Color gumut optimized (filtered) luminance efficiency (FOB FLTD L/watt), color gamut optimized lumens from FOB (FOB FLTD L), and color gamut optimized lumens output from FOB when collection efficiency is improved to 50 % (FOB FLTD L at 50% C). The comparison shows that 105 watt lamp 89 luminance from 1/4 inch FOB at 50% CE excedes the luminance of 300 watt filtered MCD lamp form 3/8 inch FOB.

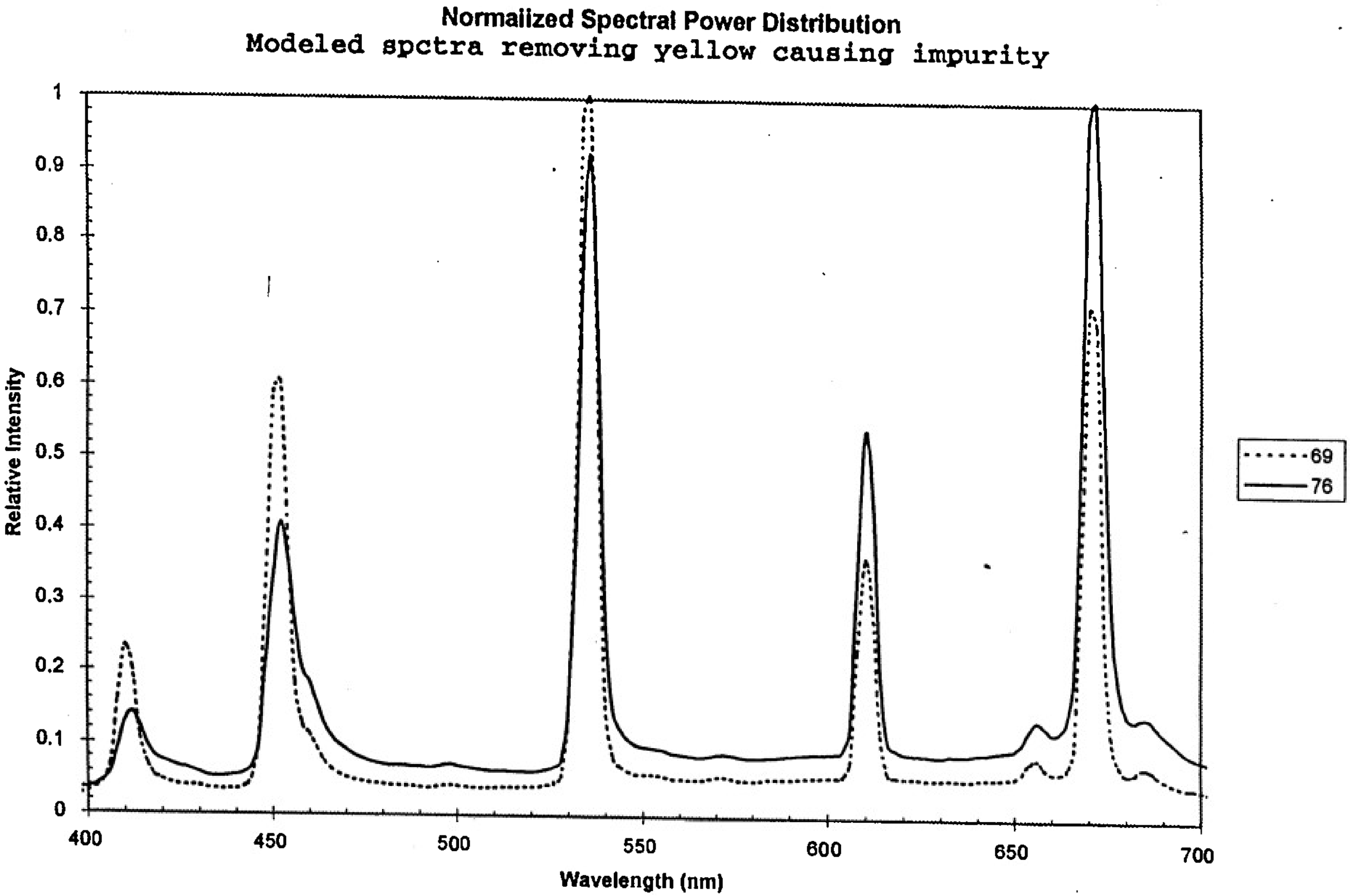


Fig. 3 Simulated spectral power distribution of Xenon metal halide lamps 69 and 76 showing estimated effect of removing impuity causing yellow peak. Yellow peak is replaced with yellow interpeak luminance.

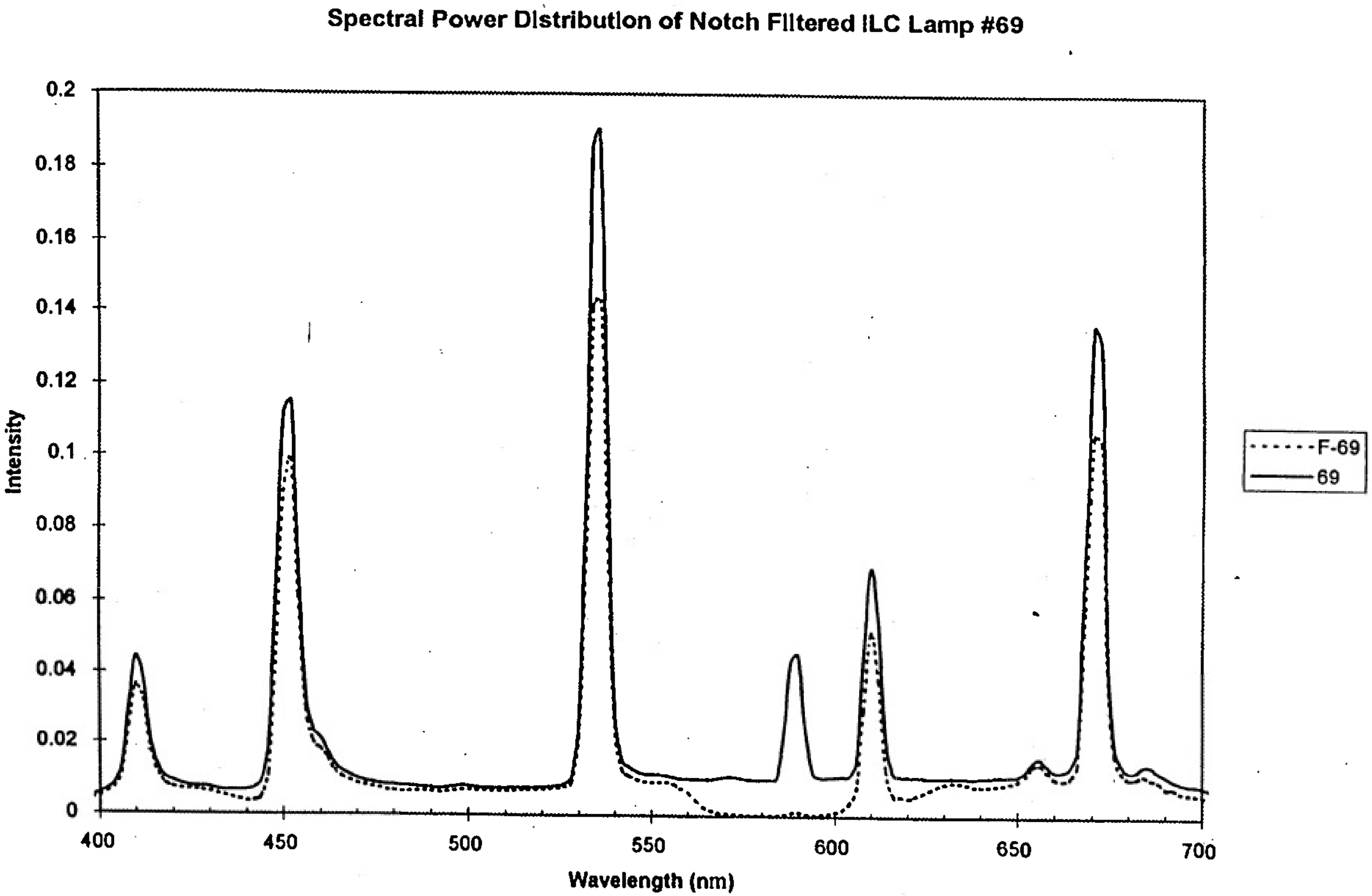


Figure 4. Effect of Notch Filter on Spectral power distribution of ILC lamp #69... Unfiltered (69) and filtered (F-69). The filter removes yellow peak as well as interpeak yellow baseline luminance and yields the broadest color gamut (Fig. 4B).

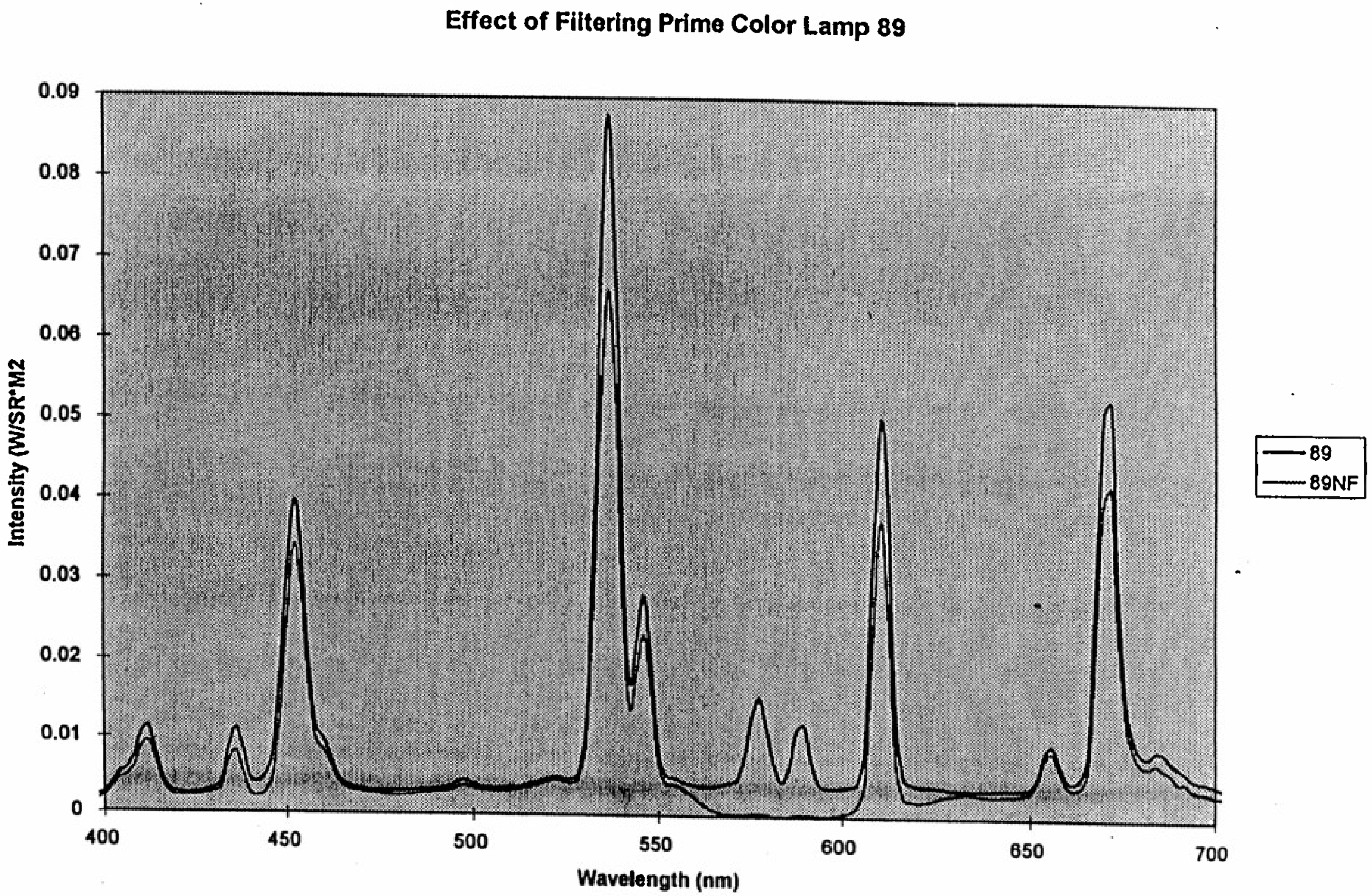
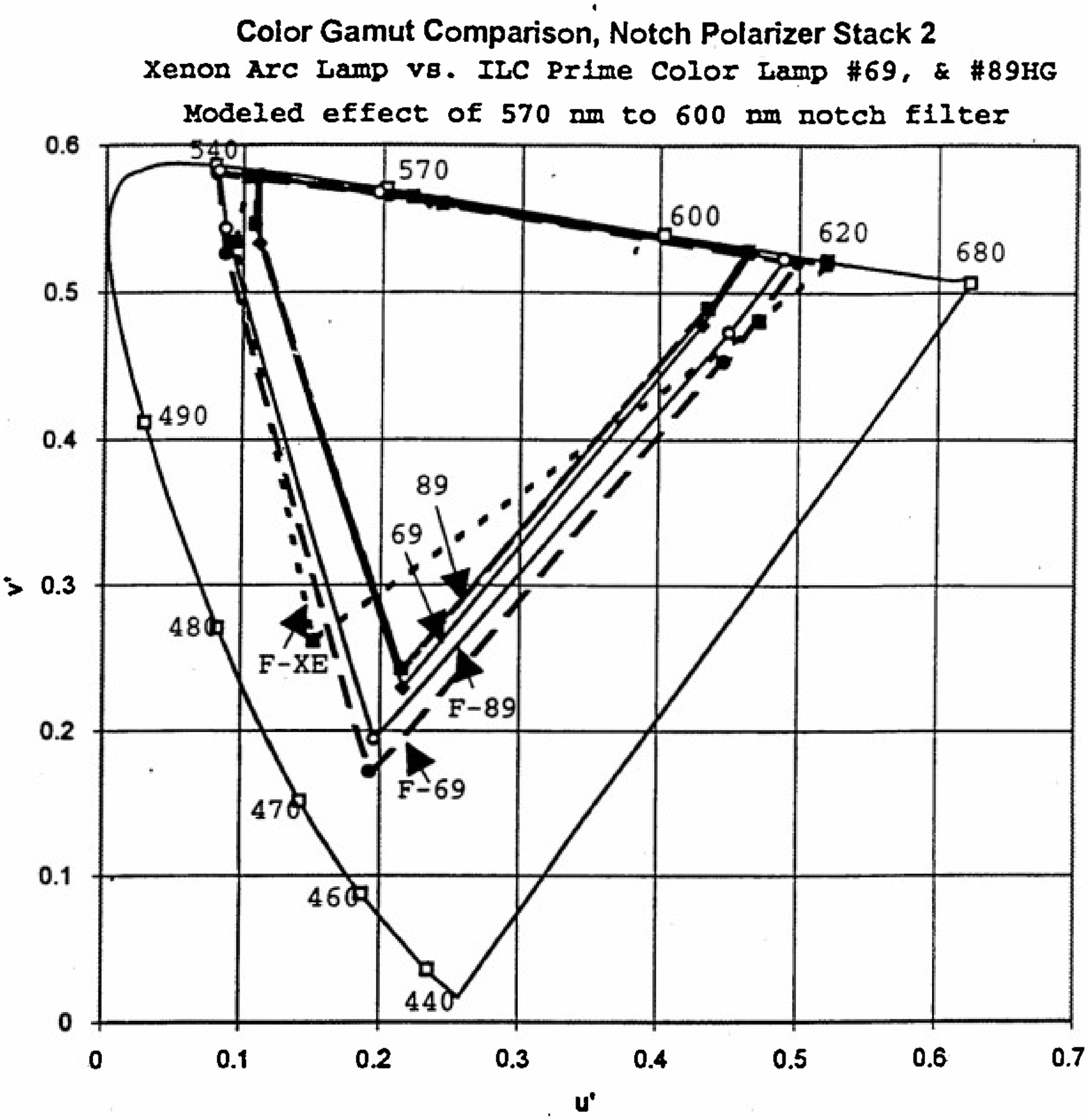


Figure 5. Spectral power distribution of ILC Mercury filled metal halide prime color lamp #89 , with (89NF) and without (89) 570nm - 600nm notch filter.

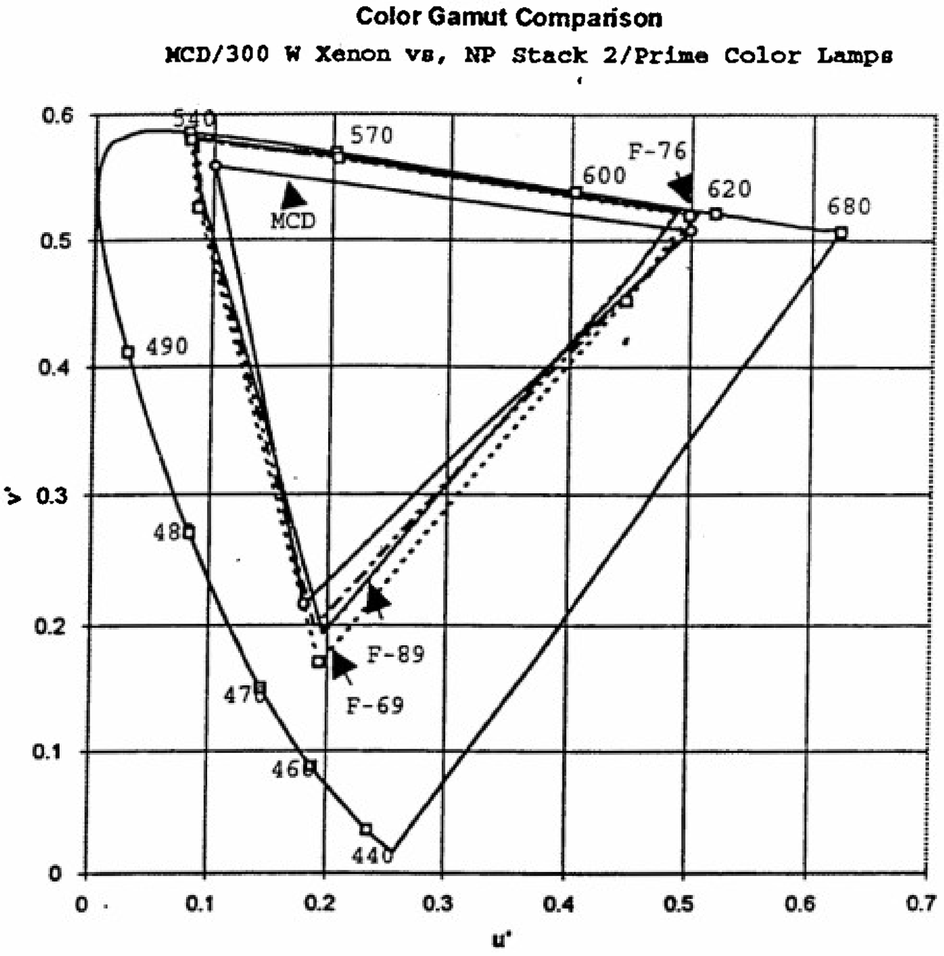


Color Gamut Comparison, Notch Polarizer Stack 2

Xenon Arc Lamp vs. ILC Prime Color Lamp #69, & #89HG

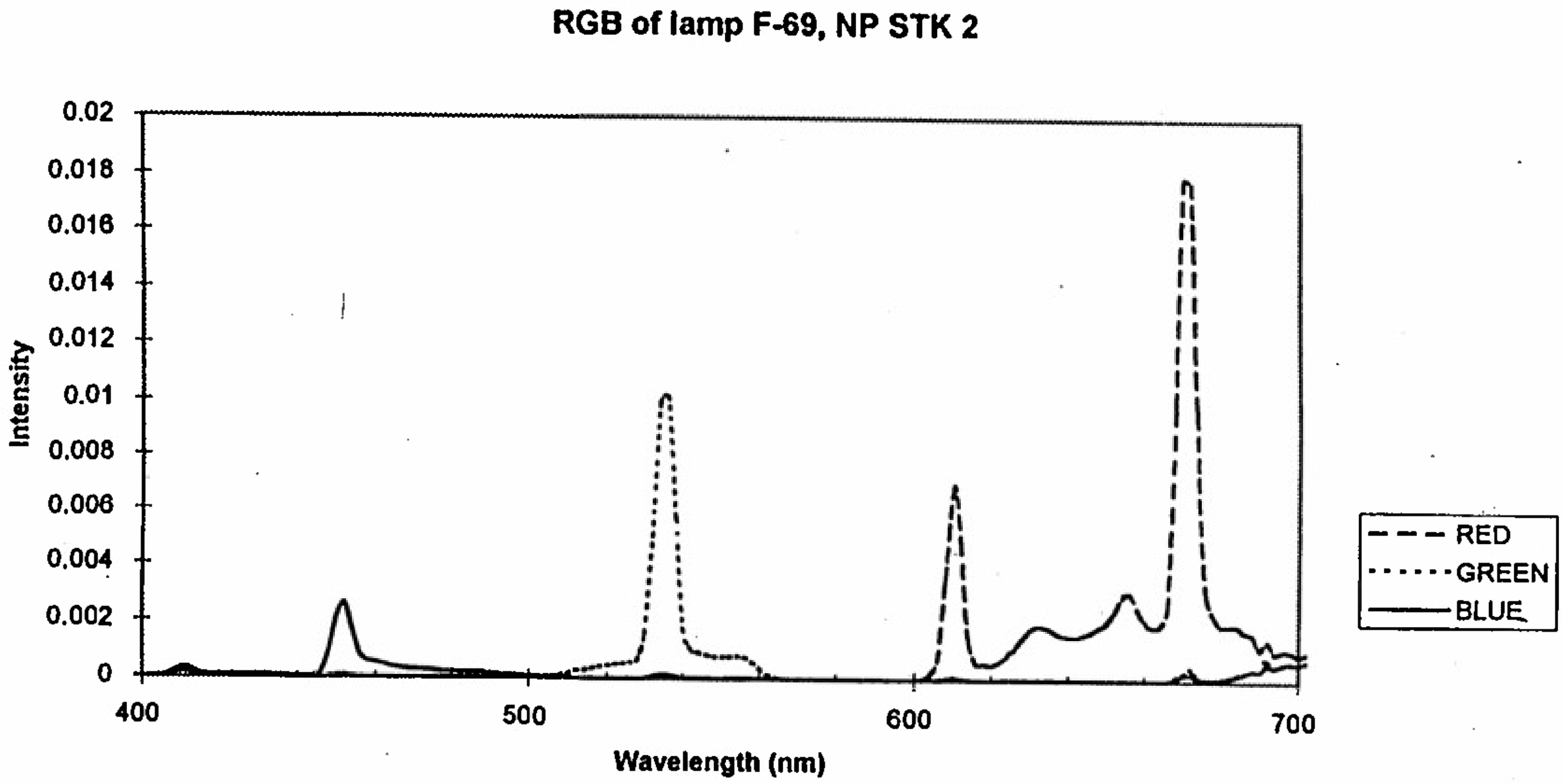
Modeled effect of 570 nm to 600 nm notch filter

Figure 6. Color gamuts obtained with notch polarizer stack 2 when illuminated with ILC lamps 69 (XE) and 89 (HG) and broad band Xenon arc lamp, with (F-) and without 570nm - 600nm notch filter used to eliminate yellow spectral area..



CIE 1976 UCS CHROMATICITY DIAGRAM

Figure 7. Color Gamut results with subtractive color light valve incorporating broad band notch polarizers, illuminated with filter optimized (yellow removed) 105 watt prime color lamps 69 (F-69), 76 (F-76), and 89 (F-89) vs. MCD light valve illuminated with filter optimized (cyan & yellow removed) 300 watt Xenon arc lamp.



.Figure 8a. Relative spectral power distributiom of notch polarizer stack 2 Primaries illuminated with notch filtered prime color lamp 69 (Xenon metal halide. Extrapolated.

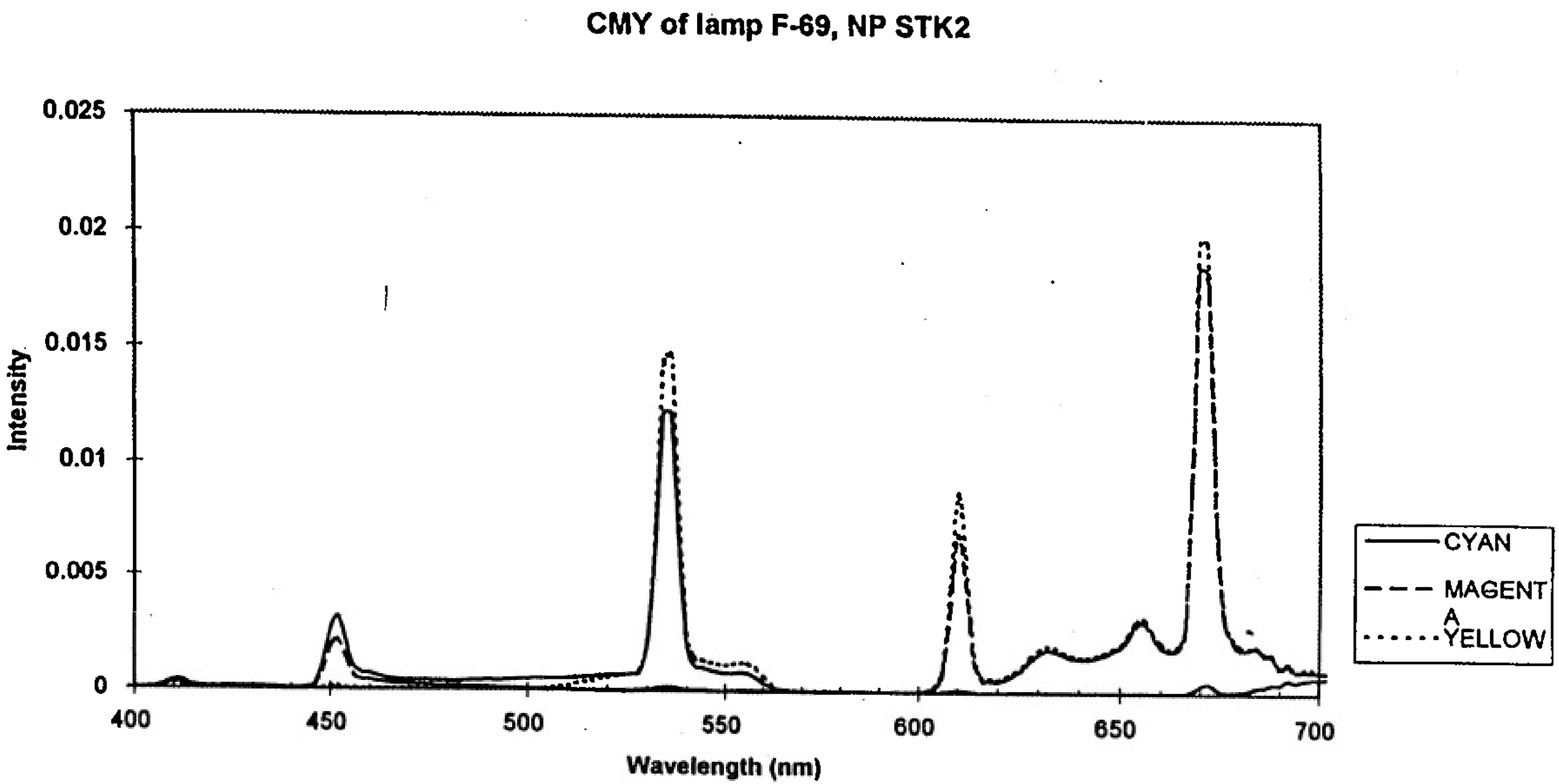


Figure 8b. Relative spectral power distributiom of notch polarizer stack 2 CMY illuminated with notch filtered ILC prime color lamp 69 (Xenon metal halide). Extrapolated

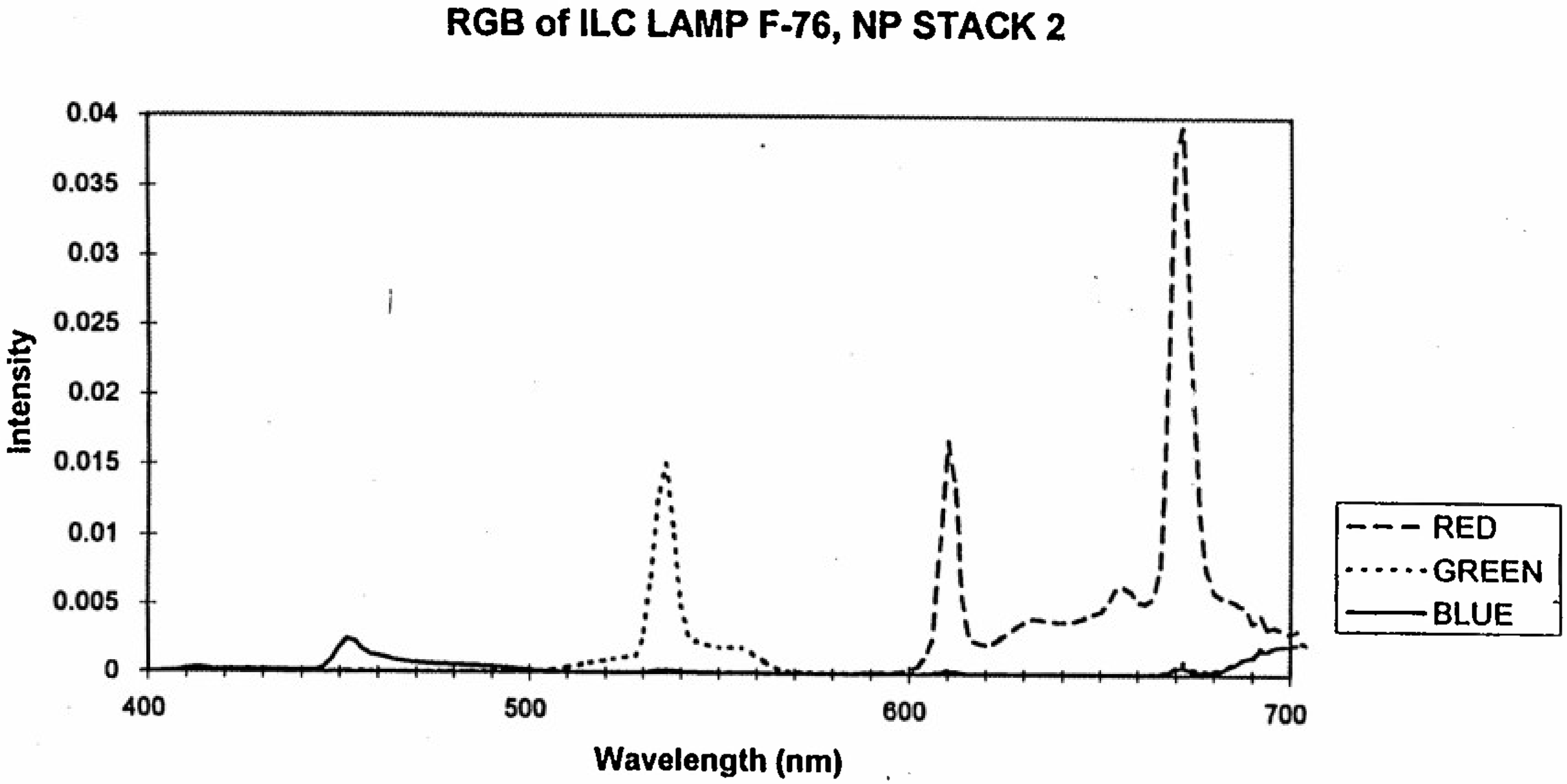


Figure 9a . Relative spectral power distribution of primaries of notch polarizer stack 2 illuminated with notch filtered ILC prime color lamp 76 (Xenon metal halide). Extrapolated

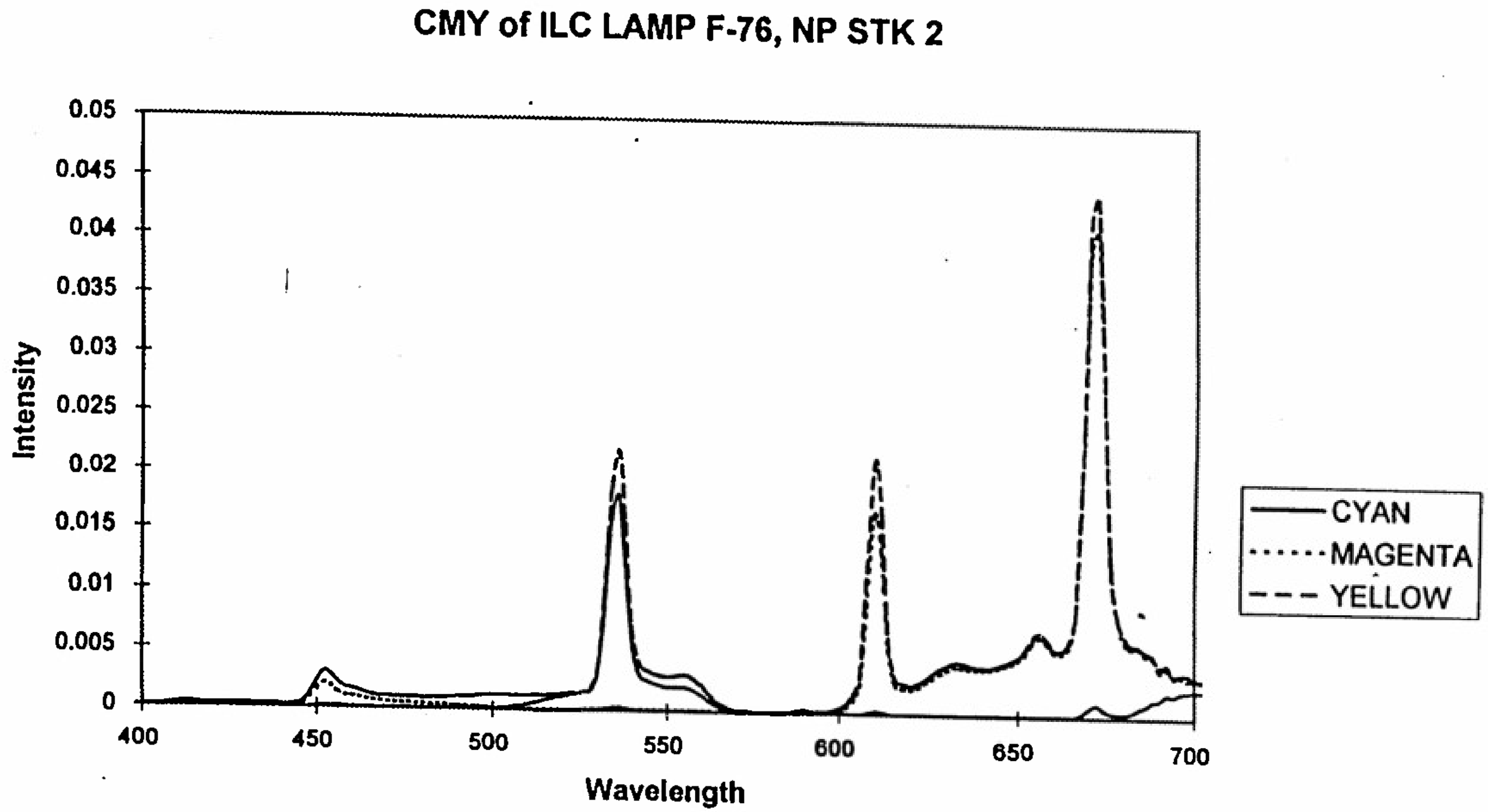


Figure 9b . Relative spectral power distributon of CMY of notch polarizer stack 2 CMY illuminated with notch filtered ILC prime color lamp 76. Extrapolated.

RGB89F

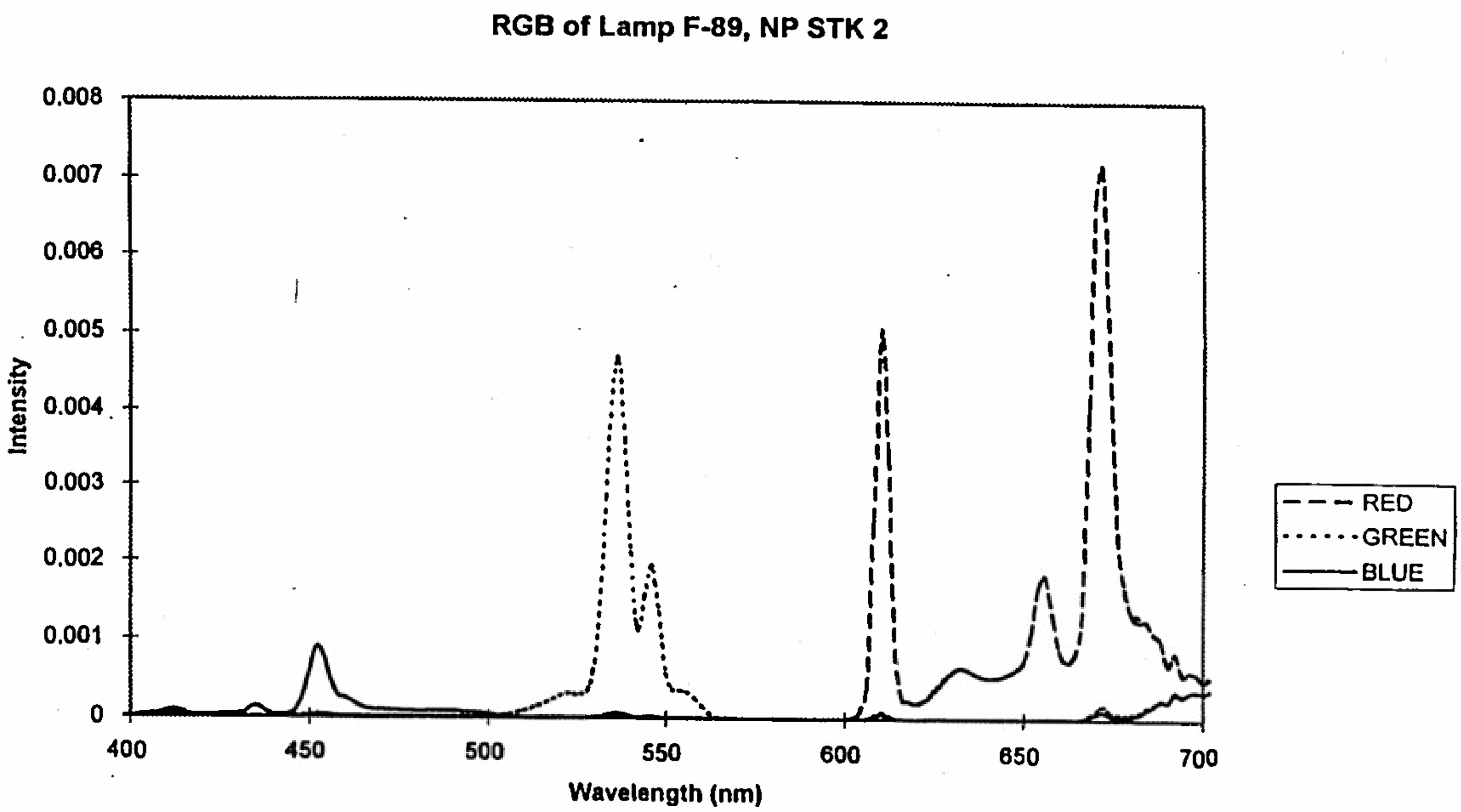


Figure 10a . Relative spectral power distribution of Primaries of broad band notch polarizer stack 2 primaries illuminated with notch filtered ILC prime color lamp 89 (Mercury metal halide) to remove yellow spectral area.

CMY89F

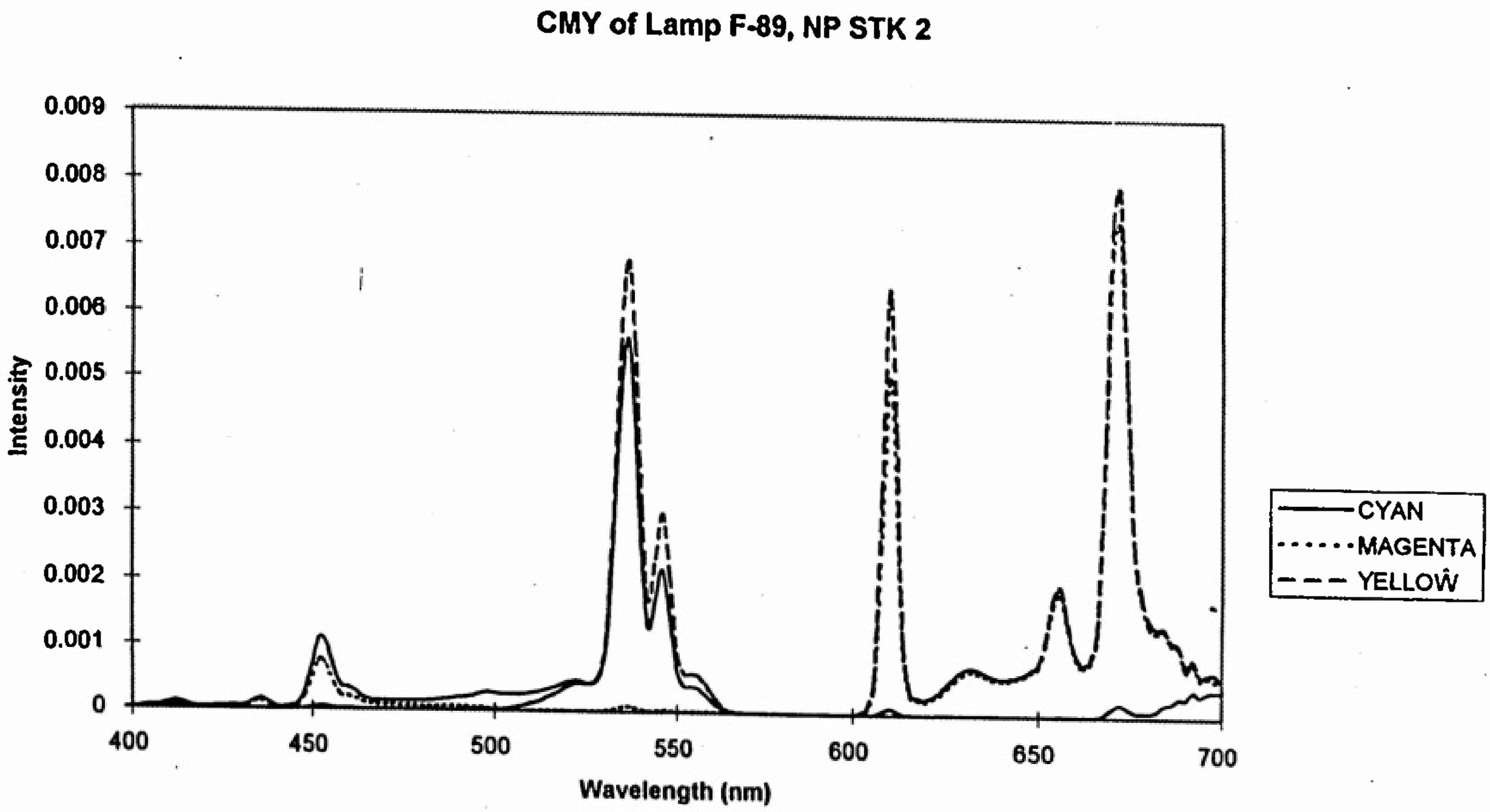


Figure 10b. Relative spectral power distribution of CMY of notch polarizer stack 2 illuminated with Notch filtered prime color lamp 89. Precisely extrapo0lated.

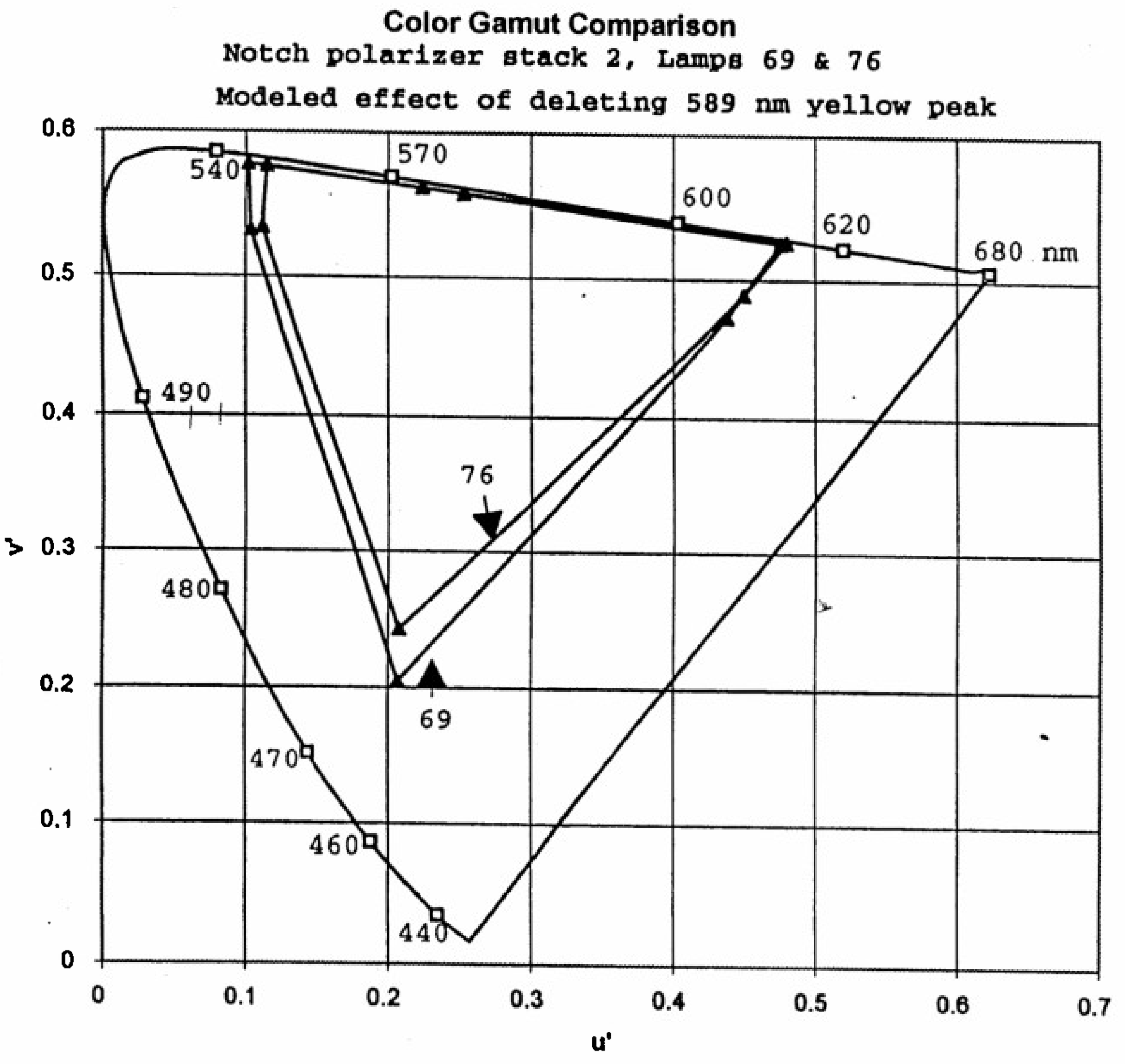


Fig.11. CIE 1976 Chromaticity Diagram. Color gamut comparison showing the modeled effect of removing the impurity causing yellow peak by replacing the yellow peak in the spectral power distribution with the average inter peak xenon response continuum between green and red.

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